EXTREME EVENTS IN HUMAN EVOLUTION: FROM THE PLIOCENE TO THE ANTHROPOCENE

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EXTREME EVENTS IN HUMAN EVOLUTION: FROM THE PLIOCENE TO THE ANTHROPOCENE

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Editorial: Extreme events in human evolution: From the Pliocene to the Anthropocene

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Editorial on the Research Topic
Extreme events in human evolution: From the pliocene to the anthropocene

Introduction

This volume of *Frontiers in Earth Science* brings together ten contributions on the topic of *Extreme Events in Human Evolution: From the Pliocene to the Anthropocene*. It features perspectives from archaeology, the earth sciences, and other related disciplines to explore a variety of extreme events and how they have impacted human societies at various points of the past. In studies of the contemporary world, extreme events–rapid climate change, drought, floods, tsunamis, landslides, volcanic eruptions, and earthquakes–are much discussed. Such events, many of which are exacerbated by anthropogenic climate change, are widely predicted to become more common, severe and costly in the future (IPCC, 2021). This is putting lives, livelihoods, and a trajectory towards sustainability in jeopardy (Reichstein et al., 2021; Thiery et al., 2021). Understanding extreme events in the deep past is not only of intrinsic interest and scientific importance, but also provides baseline data and perspectives which can help societies adjust to future challenges on our unstable planet.

From the Pliocene to the Anthropocene

Ranging from the deep past to the future, the contributions to this collection explore both the character and physical impacts of extreme events, and their impacts on societies.

This provides a way to understand past human societies and their responses, and also to bring long-term evidence to bare in discussions about future sustainability and risk reduction.

A useful entry point to the topic is Stewart et al's. systematic review of the diverse ways in which extreme events are understood and operationalized across different disciplines and periods of interest. They randomly selected 200 papers on the topic from the biological, societal, and earth science literature for evaluation. While this found a high level of variability, it also identified a number of commonalities in how researchers think about extreme events, which may be useful for more integrated and comparative research across spatial and temporal scales.

Patalano et al. take us deep into early hominin evolution. They explore the conundrum that while climate shifts are often inferred to have impacted hominins, the temporal and spatial scale of data to evaluate such claims is limited. There is, for instance, often an assumption of uniform regional changes in climate. In this article, they propose a microhabitat variability framework and link this to the evolution of the adaptability shown by the genus *Homo*. This ability to utilize microhabitats provides both a general adaptive mechanism but also a way of dealing with abrupt environmental changes.

Staying in the Pleistocene, Nicholson et al. focus on the relationship between human societies and the climatic/environmental fluctuations of the Saharo-Arabian deserts, a topic of considerable recent scientific interest. One of the challenges has been precisely dating periods of abrupt climatic change, particularly the periodic northwards incursions of the African and Indian Ocean monsoons into Arabia. In this paper the authors compare the most recent wet phase, the Holocene Humid Period, with the Last Interglacial (MIS 5e). This highlights the extreme character of MIS 5e, yet, as the authors argue, human adaptability and resilience complicate simplistic inferences from climate records.

Nyland et al. now take us into the Holocene, specifically to one of the climatic episodes argued to have been a systemic tipping point (Brovkin et al., 2021) and which has been used to subdivide the Holocene (Walker et al., 2019): the 8.2 ka event. In this context, they investigate how a broadly contemporaneous extreme environmental event–the major Storegga tsunami–may have affected societies already under pressure. They evaluate the possible impacts of this tsunami on Mesolithic societies, and emphasize the different ways in which the tsunami would have been experienced and human impacts would have been generated.

Groucutt et al. move on to yet another prominent climate event, and one coinciding with the transition from the middle to late Holocene: the 4.2 ka event. The collapse of the iconic Maltese 'Temple Period' and the 4.2 ka event seemingly occurred simultaneously, yet as this paper explores, we have to be cautious about superficial (e.g. wiggle-matched) correlations. The paper explores how while climatic deterioration may have been involved in the downfall of the Temple Period, so might a variety of other aspects such as a plague epidemic. The paper therefore presents itself as a case study on how to consider processes with different drivers, providing an exemplar of how quantitative analyses can help disentangle the influences of multiple drivers.

Riris and de Souza stay with quantitative analytical approaches. The notion of resilience is often highlighted in discussions of extreme events and their impacts, both here and elsewhere. The authors bring a quantitative perspective to resilience (the capacity of a system to absorb disturbances), in contrast to the rather subjective way the term is often used. They present resilience metrics, drawn from ecology, and highlight their utility for archaeological research through a series of case studies. In particular, they apply their resilience-resistance framework to prehistoric eastern Brazil, and argue that it is useful in evaluating aspects of demographic change in the region.

Working in a similarly quantitative manner and taking us into the Common Era, Carleton et al. take a precise look at a fascinating example of human-environment interactions: The second millennium CE in Europe is well known for being a period in which highly violent conflict and a variety of climatic extremes (such as the Little Ice Age) coexisted. Carleton and colleagues present a Bayesian regression model to explore whether conflict and climate extremes correlated. They found no evidence for correlation, and therefore argue that extreme climate conditions alone were seemingly not the drivers of conflict.

Lavigne et al. explore the reasons for periods of apparent crisis in the 15th century CE Tu'I Tonga kingdom in West Polynesia. By evaluating various sedimentary and archaeological aspects, they argue that the kingdom was severely impacted by a large tsunami, which inundated large areas. This contrasts with previous views which have tended to emphasise models like internal politics. Their study highlights the possibly significant role of single, large-scale natural disasters (rather than climate change) in altering socio-political trajectories.

Kavková et al. likewise focus on a punctuated event, namely the Tunguska explosion that occurred in Siberia in 1908. Through the analysis of sediments from two cores, the authors evaluate whether the Suzdalevo Lake was created by a meteorite impact and resulting explosion. They found that the lake existed before the explosion. Their multiproxy analysis of the sediments, however, indicates significant changes in the landscape that may relate to the explosion, with the catchment and lake system taking more than 50 years to return to its normal state.

Finally, Blong explores the character, likelihood, and risks of four major global catastrophic events–sea level rise, a large volcanic eruption, a global pandemic, and a geomagnetic storm. While focusing on the Anthropocene future, the paper highlights the diverse characteristics of different extreme events, many of which would have also occurred in the past. Blong's paper also demonstrates the importance of studying extreme events through a societal filter. For instance, while a geomagnetic storm is unlikely to cause much harm to a society reliant on stone tool technology, it is a different story for one reliant on satellites and other vulnerable technology.

Closing comment

The suite of papers in this collection highlights the diverse ways in which extreme events can be understood and studied. The importance of quantitative analyses emerges as a key theme, but so does the importance of evaluating diverse forms of human vulnerability and resilience. Lamentably, a serious consideration of extreme events and their impacts on human societies is more timely than ever (Kemp et al., 2022). Studying the impacts of extreme events in the past brings both a time depth and a human element to evaluating future hazards and challenges.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Four Global Catastrophic Risks – A Personal View

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Global catastrophic risks (GCRs) affect a larger than hemispheric area and produce death tolls of many millions and/or economic losses greater than several trillion USD. Here I explore the biophysical, social-economic, demographic and cultural strands of four global catastrophic risks – sea level rise, a VEI 7 eruption, a pandemic, and a geomagnetic storm – one human-exacerbated at the least, one geological, one biological in large part, and one from space. Durations of these biophysical events range from a day or two to more than 100 years and the hazards associated range from none to numerous. Each of the risks has an average return period of no more than a few hundred years and lie within a range where many regulators ordinarily demand efforts in the case of less extreme events at enhancing resilience. Losses produced by GCRs and other natural hazards are usually assessed in terms of human mortality or dollars but many less tangible losses are at least as significant. Despite the varying durations, biophysical characteristics, and the wide array of potential consequences, the aftermath at global (and at more granular scales) can be summarised by one of four potential futures. While this assessment considers the present and the near future (the Anthropocene), much of this appraisal applies also to global catastrophic risks in the Early Holocene.

Keywords: global catastrophic risks, sea level rise, pandemic, VEI 7 eruption, geomagnetic storm, economic losses, anthropocene

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INTRODUCTION

Here I offer thoughts on the likelihood of occurrence, character, and consequences of four global catastrophes (hereafter, often shortened to GCR). I will come back to a definition of a GCR shortly – for now a global catastrophe has at least hemispheric consequences with major effects lasting at least several years and economic losses totalling several USD trillion or at least 1% of global GDP.

In these terms, since the beginning of the 20th century there have been at least five global GCRs: the 1914–1918 war (WW1); the 1918–1919 Influenza pandemic; the 1930s global depression; the 1939–1945 war (WW2); and, in 2019–2021, the COVID-19 Coronavirus pandemic. This suggests a 1/25 years average return period; that is, the chances of another GCR in the next decade or two are moderately high. There may even be a cascading GCR where the impact of the next GCR is influenced by the occurrence and consequences of COVID-19 (cf. WW1 and the 1918–19 influenza pandemic).

The four GCRs I focus on here are Sea Level Rise (between now and 2100), a pandemic equivalent to the 1918–1919 influenza pandemic, a Volcanic Explosivity Index (VEI) 7 eruption (similar in magnitude to the 1815 eruption of Tambora), and a geomagnetic storm roughly equal in scale to the 1859 Carrington event. These four global catastrophes/natural hazards – one human-exacerbated at the least, one biological in large part, one geological, and one from space – can be expected to produce consequences for the global economy, for multiple countries, and a large proportion of the global population. Each of these GCRs is described in more detail below.

In truth there are a number of catastrophes with global consequences that could meet the short list of criteria for a GCR above – a war, especially a nuclear war, climate change, a gamma ray burst, a meteorite impact, a cyber hack, antimicrobial resistance, a plant disease, and a few of the hazards and consequences listed by the World Economic Forum in annual reports (WEF, 2021). Infectious diseases appear on the WEF Top five to seven Global Risks for the first time in 2021 and it is possible that some of the other four global GCRs considered here are subsumed under “Natural Disasters” or “Natural Catastrophes” which have been included in the top five risks in most years since 2012 (WEF, 2021).

Inevitably, given the scope of this introduction, incomplete vignettes of likely consequences are considered, sometimes moderated by what we think COVID-19 has so far taught us and/or modified by what we thought we knew. While Donald Rumsfeld, former US Secretary of Defense, popularised the expression “Known Unknowns” in a 2012 speech, this assessment of four global catastrophes is much more about “Unknown Knowns” – things we think we understand, but we haven’t thought about their impact and consequences nearly enough or nearly clearly enough. None of these four global GCRs are Black Swans. As Taleb (2008) noted, a black swan event has three attributes: First, it is an outlier, as it lies outside the realm of regular expectations, *because nothing in the past can convincingly point to its possibility* [my italics]. Second, it carries an extreme impact. Third, it has retrospective (though not prospective) predictability. The four GCRs considered here fail all but the second of these attributes.

Below I define what is meant here by a global catastrophic risk and review briefly potential losses and loss estimation, emphasising the broad range of biophysical, social-economic and cultural strands that should be considered in loss estimation. A range of the physical characteristics of each of the four selected GCRs – sea level rise, a pandemic, a VEI 7 eruption and a severe geomagnetic storm – is considered together with some of the likely potential losses. Some of the similarities and differences between the four GCRs are discussed and a broad semi-quantitative view of the magnitude of potential losses is outlined within a framework that considers the myriad of potential losses. Finally, the four possible pathways that follow from the impact of a GCR are outlined and a brief comparison is drawn between GCRs in the Early Holocene and the Anthropocene.

GLOBAL CATASTROPHIC RISKS

Many studies of global catastrophic risks focus on outcomes that take the lives of a significant proportion of the human population potentially leaving survivors with reduced resilience (e.g. Avin et al., 2018). Others have focused on Global Catastrophic Biological Risks – risks of purportedly unprecedented scale that could cause severe damage to human civilisation at a global level, magnified by a rapidly-changing interconnected world, political instability, urbanisation, climate change, and rapid technological advances which allow the easier, cheaper and faster engineering of pathogens (GHS Index, 2019, p5).

My concern here broadly follows the definition of Bostrom and Ćirković (2008, p1-2): *a catastrophe that caused 10,000 fatalities or 10 billion dollars of economic damage (e.g., a major earthquake) would not qualify as a global catastrophe. A major catastrophe that caused 10 million fatalities or 10 trillion dollars worth of economic loss (e.g., an influenza pandemic) would count as a global catastrophe, even if some region of the world escaped unscathed. As for disasters falling between these points, the definition is vague*.

Others have focused on existential risks which threaten human survival, a subset of Bostrom and Ćirković (2008, p3) global catastrophic risks. Or, like Turchin and Denkenberger (2018), associate global catastrophic risks with a death toll of one billion. My present concern is with more than just human health, extending also to all forms of economic activity and to human and environmental wellbeing. COVID-19 exemplifies well the scope of the global catastrophes with which we are concerned – the final human death toll may be less than 10 million, but the accumulated costs to the economies of the world easily exceed several trillion dollars, and there have been marked downturns in employment, in lifespan, and in well-being in a significant number of countries.

Figure 1 illustrates the reach of global catastrophes. The concern is not just with human health or with the biophysical hazard per se, but also with the associated biophysical hazards that cascade from the initiating event – secondary associated hazards such as storm surge, pyroclastic density currents, tsunami, ground deformation, and/or atmospheric warming or cooling. Biophysical impacts extend to terrestrial and marine ecosystems, agriculture, food and feed supply, and water quality and availability. Built environment impacts occur on buildings, infrastructure and networks with cascading consequences potentially extending to biomass and energy prices, transport and financial markets and clean-up and restoration. Human impacts include not only morbidity and mortality but also disease, and the possibility of unemployment, changes in equality, marginalisation and migration. In turn, societal impacts may include social conflicts at household, community and country levels with the possibility of new government regulations and expenditures. In a longer time frame cultural impacts include the establishment of memories or commemorations of the event and its aftermath, adjustments to political, democratic, religious and legal systems, and ultimately alter the pace and nature of adaptations and innovations. As implied in **Figure 1** there are interconnections, cascading consequences and feedbacks between the biophysical, human, economic, social and cultural strands.

Equally, as the risks considered here are global catastrophes but less than existential, the range of impacts or consequences for one community, country, region, or continent may differ markedly from those in adjacent communities/continents.

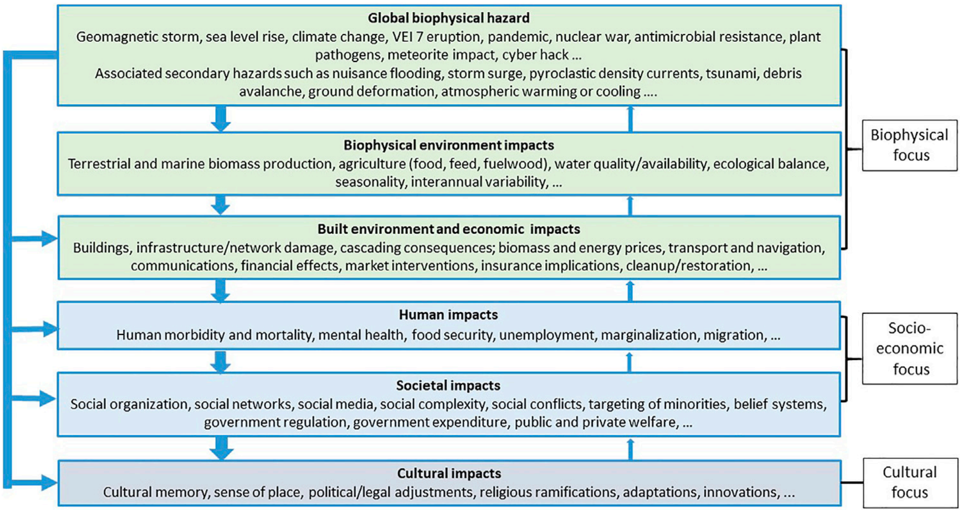

FIGURE 1 | The biophysical, social-economic and cultural strands of a global catastrophic risk (based on Luterbacher and Pfister (2015), Torrence (2019)).

POTENTIAL LOSS AND LOSS ESTIMATION

A review article assessing the costs of natural hazards based on the views of 60 experts reveals just how complicated assessing losses is Meyer et al. (2013). These authors settle on dividing losses into tangible and intangible (non-market) losses with each of these categories subdivided into damage costs – Direct, Business interruption, and Indirect – and Risk Mitigation costs (also divided into Direct and Indirect). This division results in 10 cost categories though the category Indirect Intangible Risk Mitigation costs contains no examples. A sizable proportion of the impact strands in **Figure 1** would fall into intangible categories.

Further, using the value of property damage as a key metric for summing losses and/or devising mitigation strategies biases the view of damage towards the wealthy – measuring damage as a percentage of total value or losses as a share of household wealth can present a different view of risk (Hino and Nance, 2021).

Reinsurers also provide a view of the losses associated with extreme events, though their concern is entirely with tangible losses and, usually, only with the insured portion of dollar losses. In 2016 terms the world's biggest insurance loss event to date had been Hurricane Katrina, with estimated losses around USD 81 billion (Swiss Re, 2018).

In the 2017 Berkshire Hathaway Annual Report (p8), Warren Buffett noted "We believe the annual probability of a U.S. mega-catastrophe causing $400 billion or more of insured losses is about 2%. [i.e., an average 50 years return period]. No one, of course, knows the correct probability." Vijay Padmanabhan (Vice President of Marketing at Applied Insurance Research - AIR) ran AIR models and estimated that a $400 billion insured loss in the United States had an Annual Exceedance Probability between 0.1 and 0.01% (i.e., a return period between 1,000 and 10,000 years)[1]. AIR's 2017 Global Modeled Catastrophe Losses (AIR, 2017) indicates a global insured loss of USD 325 billion has a 250 years return period (p.6).

Warren Buffett and AIR may well be talking about different things (insured losses versus modelled insured losses). AIR certainly exclude insured life losses while it is unclear whether Warren Buffet included these or not. Both Buffett and Padmanabhan were referring just to the United States; neither considered losses that occur from events that span more than one continent.

Swiss Re uses "insured losses" to refer to insured losses excluding liability. The term also excludes insured life loss, though this is not stated. "Economic losses" are losses due to property damage and business interruption that are directly attributable to major events. Insured losses are a subset of, and are included in, economic losses (Swiss Re, 2018), Sigma, 1/2018. For the more than 90 catastrophe events included in Sigma reports for 2015–2017, insured losses average 48 ± 25% of economic losses with a range extending from 1.5 to 82.5%, the range reflecting not only variations from region to region and from peril to peril but also, no doubt, the quality of the estimates of economic losses. In a very approximate sense we can regard economic losses, on average, as roughly twice insured losses. Hence my interest here in global catastrophes that produce economic losses of several USD trillion. As global GDP is a little under USD90 trillion[2] my interest focuses on catastrophic risks that produce losses exceeding 1% of annual global GDP.

Clearly, assessing the losses stemming from global catastrophic risks is difficult; estimates in dollar or GDP terms are likely to be only very approximate. Methods and divisions commonly employed for assessing losses in extreme events either by researchers or reinsurers seem problematic and far from complete. Further, such measures capture only part of the

[1]https://www.air-worldwide.com/Blog/Why-Warren-Buffett-Is-Almost-Certainly-Wrong-about-Cat-Risk/.

[2]https://data.worldbank.org/indicator/NY.GDP.MKTP.CD.

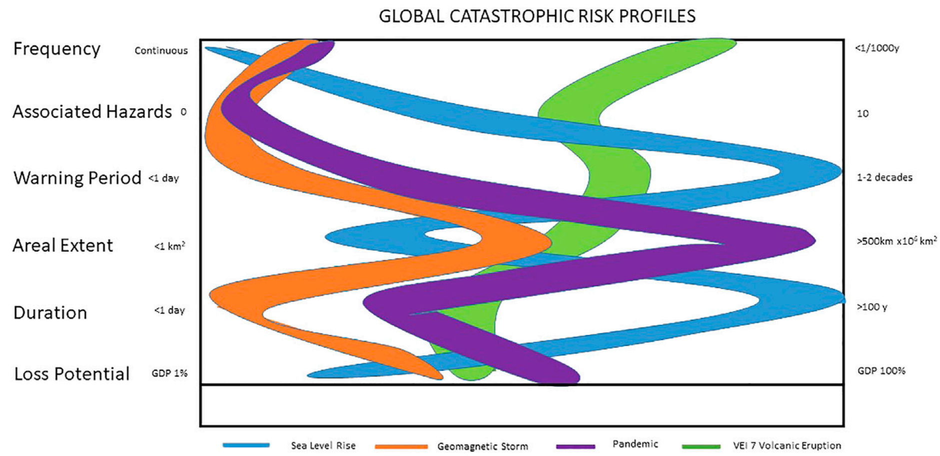

FIGURE 2 | Global Catastrophic Event Profiles based on selected physical characteristics. Expected values are indicative rather than prescriptive.

losses – as implied in **Figure 1** measures as diverse as a gauge of food security, the proportion of the population above or below the poverty line, changes in average lifespan, or even a happiness index, may be equally appropriate for evaluating the consequences of global catastrophic risks. Torrence (2019, p259) provides a list of 13 key variables invaluable for assessing impacts, vulnerability, and resilience – many of these have been incorporated into **Figure 1**.

FOUR GLOBAL CATASTROPHES - PHYSICAL CHARACTERISTICS

In their 1978 book *The Environment as Hazard*, Ian Burton, Robert Kates, and Gilbert White – co-stars and icons of early natural hazards research – recognised the difficulty of comparing the magnitude, severity, intensity, or damage potential of different natural hazards. They 'profiled' three hazards – drought, blizzard, and earthquake – using a continuum for each of six characteristics (Burton et al., 1978):

- Frequency — Frequent – Rare
- Duration — Long – Short
- Areal Extent — Widespread – Limited
- Speed of Onset — Slow – Fast
- Spatial Dispersion — Diffuse – Concentrated
- Temporal Spacing — Regular – Random

Subsequent studies (e.g. Leroy, 2006; Riede, 2019) have improved little on this physical characterisation (although a range of societal characteristics/impacts have been added), thus emphasising the difficulties in comparing very different hazards in a quantitative framework. Here I also offer limited improvements in characterising the four global catastrophes. **Figure 2** provides a shorthand assessment of expected physical characteristics of four "average" or moderate global GCRs (rather than extreme geophysical risks). The focus is on the first box – Global Biophysical Hazard – in **Figure 1**.

Frequency is simplified on a (logarithmic) scale ranging from "Continuous" – as is more or less the case for sea level rise – to "<1 event/1,000 years." A VEI 7 volcanic eruption has a frequency of roughly twice in 1,000 years, while both pandemics and geomagnetic storms of the magnitude discussed here occur approximately once in 100–200 years on average.

Associated hazards refers to physical events that are associated with the primary hazard or are a direct physical consequence of the initial event. The scale varies, nominally, from 0 to 10 associated hazards. For example, sea level rise has four associated hazards – an increase in the scale and frequency of nuisance flooding and an increase in the height and frequency of storm surges, coastal erosion, and groundwater rise. It is not directly relevant here that nuisance flooding and storm surge may (or may not) increase in frequency as a result of other consequences of global warming – these potential changes are not under consideration here. Neither geomagnetic storm nor a pandemic are considered to have any direct associated physical hazards[3]. On the other hand a VEI 7 eruption is likely to have four or more additional physical effects. The eruption itself, characterised by the occurrence of pyroclastic density currents (PDCs), airfall tephra (volcanic ash), and atmospheric shock waves (all with a duration of less than a week) may be preceded by or followed by smaller eruptions which could continue for years. The main eruption is likely to be preceded by ground deformation and earthquakes large enough to damage nearby physical property. The collapse of the eruption column or the collapse of a sector of the volcano itself in a coastal locale is likely to produce tsunami experienced on coasts possibly extending across half the globe. Redistribution of volcanic ash by lahars, wind and rain is likely to continue for several years. Most significantly, the megatons of sulphur dioxide injected into the upper atmosphere is likely to induce global cooling with

[3]It could be argued that the declines in health programs targeting the incidence of Tb, measles and polio and in elective surgery are associated hazards of the COVID pandemic – see below.

potentially severe consequences for half or more of the globe for 3–5 years.

Warning Period is shown on a scale ranging from <1 day to 1–2 decades. We have known about the current rate of sea level rise for several decades while, with current technologies, we are unlikely to have more than a few days' notice of the arrival of a major geomagnetic storm. Similarly, there are likely only a few weeks warning that an incipient epidemic could become a global pandemic. A VEI 7 volcanic eruption is likely to provide a year or two of increased earthquakes, raised fumarole temperatures, and ground deformation before the eruption begins; however, the period in which it is clear that these precursors herald a very large eruption rather than just an eruption is likely to be only weeks rather than years.

Warning Period here refers to a specific event. In a general sense, because each of these four global catastrophes has an average return period of less than a few hundred years, we have already been warned to expect the not infrequent occurrence of these global catastrophes – that seems to have escaped the attention of almost everyone with executive authority. As noted earlier, these catastrophic risks are not black swans.

Areal Extent is shown on a scale ranging from <1 km^2 to >500 million km^2, the latter roughly the surface area of the earth. A pandemic is likely to affect almost all land areas of the earth, though this could be discounted by areas that are barely populated (Antarctica for example). The direct physical effects of sea level rise in most areas are unlikely to extend more than a few hundred metres to a few kilometres inland from the coast – a relatively limited portion of the earth's surface area. The area directly affected by a geomagnetic storm depends, in part, on the duration of the storm and the earth's rotation. Further, Areal Extent is not a particularly appropriate measure of the direct impact of a geomagnetic storm as some of the direct effects will occur in space (on satellites, and possibly, aeroplanes). Similarly, areal extent is problematic for a VEI 7 eruption; the direct physical effects of a less-than-1 week-long eruption, including pyroclastic density currents, ash fall, and possible tsunami, are likely to impact less than 3–5 million km^2. Redistribution of the massive volume of erupted products by erosion and lahars will occur over several years over an area of just a few tens of thousands of square kilometres. However, atmospheric cooling induced by the injection of vast amounts of sulphur dioxide into the upper atmosphere will likely last several years, with direct effects on a half or more of the earth's surface (**Figure 2**).

Duration refers only to the duration of the physical event; the likely enduring economic, social and cultural consequences of the event are not considered. The duration scale extends from <1 day to more than 100 years. Thus a severe geomagnetic storm is likely to last less than a few days, while sea level rise will continue beyond 100 years – even if greenhouse gas emissions were suppressed to pre-industrial levels immediately, the slow response of the thermal mass of the oceans will ensure that sea level will take even longer to return to early 20th century levels. While the duration of a VEI 7 eruption, or at least the truly catastrophic part of the eruption, is likely to last less than a week, direct physical effects resulting from lahars (volcanic mudflows),

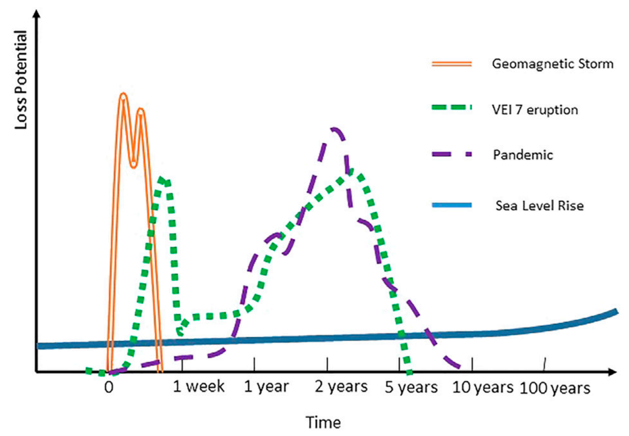

FIGURE 3 | 4 Global GCRs – a schematic of the duration of the physical event initiating four global catastrophes and loss potential. Note the time intervals per unit width on the X-axis vary from 1 week to 90 years. The Y-axis Loss Potential scale has no units here; it encompasses the potential consequences in the five lower boxes on **Figure 1**.

rain and wind erosion of volcanic deposits and a period of atmospheric cooling are likely to continue for several years or more. The direct physical impact of a global pandemic, as COVID-19 has shown, is likely to last at least several years.

Loss Potential is little more than a general concept and provides only a broad view of Severity or Intensity of the consequences of each of the global catastrophes. On **Figure 2** Loss Potential is shown on a scale ranging 1–100% of Global GDP, the latter roughly USD 90 trillion. Loss potential is intended here to represent the consequences of a "middle-sized" global catastrophe rather than an "extreme" GCR event. It is a general summation of all the consequences that might arise from the impact of the hazard across seven broad sectors – human health, social impacts, buildings, infrastructure, agriculture, other economic activity, and the environment – or, more generally, as shown on the lower five boxes on **Figure 1**.

For a pandemic loss potential might be dominated by human morbidity and mortality or the effects on economic activity. For a VEI 7 eruption the majority of the damage potential might lie with a decline in global agricultural production and the effects, including human deaths, following from that decline. The loss potential of both geomagnetic storms and sea level rise might initially result from the effects on infrastructure and economic activity. More particularly, loss potential extends across all five lower boxes in **Figure 1**; it is likely that the bulk of the losses are indirect and/or intangible.

Figure 3 considers, in a schematic way, variations in loss potential with time as each global catastrophe and associated hazards play out. It is important to recall that I am dealing here only with the direct physical impacts of a GCR.

Only broad patterns are represented on **Figure 3**; note the varying time scale on the X-axis. The severity of global sea level rise has already begun, increases inexorably, and continues beyond the 100 years' timeframe shown here. A geomagnetic storm may have several peaks (possibly affecting different parts of the world) but is unlikely to last more than a few days. A pandemic may also exhibit several waves, affecting different parts of the world, and last 3–5 years or longer. As noted earlier, the main phase of a VEI 7 eruption producing widespread PDCs and extensive ash fall is unlikely to extend longer than a week, will possibly include a tsunami with near-hemispheric consequences, but will be followed by i) redistribution of the ash by lahars, rain and wind across tens of thousands of square kilometres during the next year or two; and ii) atmospheric effects including cooling and anomalous weather across large portions of the globe likely to continue for 3–5 years.

While the relative durations of each of these direct physical effects is likely to vary considerably from those portrayed, the relative loss potential of each of these GCRs is likely to be even less constrained both in time and space. Implicit in the scale of loss potential are questions about whether this is a measure of human deaths, hospitalisations, building and/or infrastructure damage, the growth in unemployment, restrictions on mobility, some measure of economic loss, a range of social factors including inequality and happiness, or some combination of these and other outcomes. The human, societal and cultural impacts (lower three boxes on **Figure 1**) are likely to continue long after the direct physical impacts have retreated into the background.

Sea Level Rise

The physical characteristics of sea level rise can be summarised as continuous rather than rare to frequent, with a very slow onset but a very long duration, and limited to a narrow but concentrated area. Temporal spacing hardly applies. This combination of physical characteristics suggest sea level rise is different to other global catastrophic risks (**Figures 2**, **3**).

Sea level has been rising slowly over the last century. Global mean sea level (GMSL) is expected to rise between a minimum of 30 cm and a maximum of 280 cm by 2100. A rise of 50 cm has a probability varying 49–96% depending on which model is used (US Global Change Research Program, 2018). About 45% of the rate and about 90% of the acceleration in the altimeter (GRACE) record is due to ice mass loss from Greenland, Antarctica, mountain glaciers and small icecaps with the rest due mainly to thermal expansion Nerem and Fasullo (2019). Relative mean sea level rise on individual coastlines can vary considerably from GMSL depending on water temperature, nearby ice melt, strength of ocean currents, fluid extraction (water and oil), storm tracks and storm frequency, El Niño Southern Oscillation phase, Pacific Decadal Oscillation phase, and continuing isostatic-tectonic adjustments from the last glacial maximum.

1900–1990 global mean sea level rise is regarded as 1.1–1.5 mm/y, but for the last 25 years the rate has been about 3 mm/y (Bamber et al., 2019). Extrapolation of these rates to 2100 suggests a rate of ~10 mm/y by the end of the century (Nerem and Fasullo, 2019). Since the US Global Change Research Program, 2018 report appeared, it has become clear that East Antarctica outlet glaciers are melting at a hitherto unsuspected rate, suggesting the min and max limits above may need to be raised. The largest mass contribution to sea level rise (SLR) since the 1990s has been ice sheet melting, but this is also the largest source of uncertainty; global total SLR >2 m by 2100 for a high emission scenario lies within the 90% uncertainty bounds developed using structured expert judgement (Bamber et al., 2019). More extreme scenarios may be more realistic than recently supposed.

While the direct consequences of sea level rise are limited to a narrow coastal zone, often less than a few hundred m in width, a 2019 estimate of the global population at risk from sea level rise by 2100 reached 190 million people (Hino and Nance, 2021). Hooijer and Vernimmen (2021) estimate the land below 2 m + Mean Sea Level at 1.05×10^6 km^2 (just over 1% of the land area of the Earth) and the population in this zone at 267 million. Populations and economic activity are often concentrated on the littoral, particularly the tropical littoral. For example, in California only 0.3% of the state's land area but 6% of the State's GDP will be impacted by 2100 by dynamic sea level rise including sea level rise, tides, waves, storm and coastal change (beach erosion and cliff retreat) (Barnard et al., 2019). Thus, indirect consequences are likely to have a near-global effect, with the consequences for human health, buildings, infrastructure, agriculture, other economic activity, and the environment increasing over time.

Nuisance flooding refers to low levels of inundation that pose few significant threats to human safety but disrupts daily activities and causes minor damage to property and infrastructure (Moftakhari et al., 2018). In the context of global sea level rise, nuisance flooding can be expected to increase in frequency with associated increases in riverine flooding near the coast, enhanced salting of soils and enhanced salt water damage through groundwater rise to infrastructure, equipment, property and other assets.

Based on NOAA gauges, the return period for nuisance flooding at San Francisco was about once in 3–10 years in 1950, but once in 3–6 months in 2012, increasing to 4–5 days per month in 2100 under the trend scenario, to more than 20 days per month under more extreme but realistic scenarios (US Global Change Research Program, 2018, p348). In Annapolis, Maryland (on Chesapeake Bay) current high tide flooding reduces visits to the historic downtown area by 1.0–2.6% measured by variations in parking meter revenue. A 7–30 cm sea level rise would reduce visits by 3.6–24% respectively, with increases in both flood height and flood duration reducing parking revenue (Hino et al., 2019).

Barnard et al. (2019) have shown the importance of combining the relatively minor rises in sea level and spring tide by 2040 with the same conditions exacerbated by the 100 years storm in California. The economic costs of future projected flooding is about an order of magnitude greater than the two most expensive natural disasters in California's history – the 1989 Loma Prieta earthquake, and the 2017 wildfires, and roughly equal in cost to a repeat of the 1861–62 ARkStorm which today would cause more than $300 billion in property damage (Porter et al., 2010). Further this cost estimate doesn't include ripple effects across economic sectors resulting from closure of ports, disruption of transport and goods, business closures and impairment of infrastructure (Barnard et al., 2019).

Sweet et al. (2013) put the widespread damage and functional disruption to critical infrastructure including mitigation from

Hurricane Sandy (October, 2012) at USD60.2 billion. Hurricane Sandy provides a fine example of the impact of a storm surge, fairly extreme in terms of the damage wrought, but an illustration of the numerous storm surges that occur globally each year. The storm surge coincided with peak high tide at Battery Point on the southern end of Manhattan (Sweet et al., 2013) with the surge reaching 4.3 m above mean lower low water (Rosenzweig and Solecki, 2014). While Sandy was only a Cat 1 hurricane with a central pressure of 940 mb combined with a slow forward speed of 18 km/h (Tennis, 2013) the area hit accounts for 23% of national GDP (Tennis, 2013).

The return period for Hurricane Sandy's flood height at Battery Point has been estimated for various time frames – once in ~1,200 years in 1800, once in ~400 years in 2000, and once in ~90 years in 2100 (the latter estimate varying from ~23 to ~130 years depending on the climate model utilised). Alternatively, a flood with Sandy's estimated return period of 398 years in 2000, would have reached only to 2.3 m in 1800, but 3.7 m in 2100 but varying 3.5–4.3 m when storm climatology is also accounted for Lin et al. (2016).

The major impacts of Hurricane Sandy on human health, buildings, infrastructure, other economic activity and the environment have been detailed by Rosenzweig and Solecki (2014), Smythe (2013), and Platt (2013).

Without adaptation 0.2–4.6% of the global population will be flooded annually by 2100 with a 25–123 cm GMSL rise. Expected annual losses range 0.3–9.35% global GDP (Hinkel et al., 2013), though these estimates rely on lesser sea level changes than now expected. Others have interpreted sea level changes of less than a 1 m rise could place USD21-210 trillion in global assets in the 100 years flood zone by 2100 (Goldstein et al., 2018).

More recently, Kirezci et al. (2020) have produced what they call a "first pass estimate" which assesses assets currently at risk from coastal episodic flooding at USD6.4–9.1 trillion, approximately 9–13% of global GDP. The RCP 8.5 (high emissions) scenario would increase the land area at risk of episodic coastal flooding by 48% by 2100 for the 1/100 years return period event. These estimates assume no coastal defences are in place so they indicate the scale of the investment required to offset the increase in risk. They attribute 32% of the increase to sea level rise, 63% to tide and storm surge and 5% to wave setup, noting that most of the world's flooding associated now with the 1/100 years event could occur as frequently as 1/10 years in 2100.

A Pandemic Equivalent to the 1918–1919 Influenza Pandemic

The annual risk of a pandemic similar in scale to that of 1918 is often considered to be in the range 0.5–1.0%, an average recurrence interval of once in 100–200 years (Burns et al., 2008; Fan et al., 2018). However, Marani et al. (2021), identify 217 epidemics with known occurrence, duration and number of deaths between 1600 and 1945 and use a generalised Pareto distribution to show that that the mean recurrence time of a pandemic with the same intensity as the 1918 pandemic is about 400 years. They also show a pandemic similar in intensity to COVID-19 (with a death toll of 2.5 million at the time of writing), has a probability of occurring in one's lifetime of about 38% - a probability that may double in coming decades (Marani et al., 2021).

Eisenberg (2020) suggests death totals for previous pandemics:

Black Death	1342–1351	200 million.
Smallpox	1520	56 million.
Great plague	17th century	3 million.
Spanish Flu	1918–1919	40–50 million.
HIV/Aids	1981-Present	25–35 Million

Additionally, the Spanish invasion of Mexico produced epidemics of smallpox, measles, typhoid, and mumps in Mexico between 1520 and 1590, killing an estimated 19–21 million people[4] (Gamble et al., 2021). This suggests there have been seven or more significant pandemics (including COVID-19) that have killed at least a few million people in the last 700 years; as global population has increased from about 400 million to about 7.5 billion in that time, all the preceding pandemics have had much higher death rates than COVID-19[5].

The 1918–19 pandemic killed around 50 million people (Short et al., 2018) at a time when global population was less than 2 billion; some estimates suggest total deaths were much higher. Pre-COVID scenarios envisaged that a pandemic similar to the 1918–19 influenza pandemic would spread around the world in about 180 days, infect up to 35% of the global population, kill perhaps 2.5% of the infected population (that is, about 65 million people, though some authorities put the likely death toll at more than 200 million). The lower estimates assume that efforts to limit the spread of the virus are no more effective than in previous epidemics (Burns et al., 2008; Fan et al., 2018). On the plus side our understanding of viral, genetic, and immune factors has advanced enormously; however, lifestyle, lifestage, underlying diseases and infections complicate the pattern of severity and transmission (Short et al., 2018).

The complex interplay of three groups of factors influence the severity and transmissibility of a pandemic influenza virus (and, presumably, of other viruses): Viral factors include low-high pathogenicity, transmission routes from animals to humans, reassortment, human-to-human transmission, and subsequent changes in virulence. Host factors include lifestage from the naïve young to the immune-senescent old, lifestyle (e.g., pregnancy, obesity), underlying diseases and immune status. External factors influencing severity and transmissibility encompass underlying infections, lifestyle (living conditions, mass gatherings, mobility), pharmaceutical interventions (antivirals, vaccines), and non-

[4]Koch et al. (2019) put the population decline in the Americas in the 100 years following Columbus at ~90%. Intriguingly, they estimate that secondary succession on the abandoned land led to a 2.3–5.1 ppm decline in global CO_2.

[5]See the summary of population estimates by a range of authorities at https://en.wikipedia.org/wiki/Estimates_of_historical_world_population. As Eisenberg and Mordechai (2020) point out, both these death tolls and accounts of the role of pre-20th century pandemics driving social, political, and cultural transformation need to be regarded critically.

pharmaceutical interventions including facemasks, quarantine, and handwashing (Short et al., 2018).

While it is still too early to assess how COVID-19 compares with the influenza pandemic of 1918–19 two trends seem likely – even assuming the global death toll doubles or triples before the end of 2022, this pandemic, in terms of human deaths (the most common measure of pandemic severity), is roughly an order of magnitude less severe than the 1918–19 event. For example, Fan et al. (2018) place the excess death rate from the 1918–1919 pandemic at 1.1%, though they believe it was probably considerably higher than that. This suggests that a 2020–2022 repeat of the 1919 pandemic would produce a death toll of at least 86 million, an outcome that, in the COVID-19 world of mid-2021, seems unlikely.

However, COVID-19 appears to have produced knock-on effects with global disruption to other health services. Roberts (2021) notes that WHO estimates an additional 0.5 million people have died from Tb as prevention and treatment regimes have been disrupted by closure of clinics, reassignment of health workers to fight COVID, and delays in shipping medicines and devices. Programs targeting measles and polio have also been disrupted.

Secondly, in terms of economic and social effects, COVID-19 is certainly a multi-trillion dollar event – probably an order of magnitude (or more) greater than that of the 1918–1919 pandemic.

Whether pandemic severity is measured by human deaths, by economic losses, or by some combination of consequences (**Figure 1**), influences estimates of the frequency of pandemics similar is severity to the 1918–19 influenza pandemic. Here I assume that both the 1918–19 and the COVID-19 pandemics are roughly one-in-100–200 years events. However, we note that changes in Viral, Host, and External factors such as increased animal-human contacts, increased and older populations, globalisation, and greater mobility may more than offset improvements in pharmaceutical interventions so that the potential for severe pandemics may be increasing (as Marani et al., 2021 suspect).

As **Figures 2**, **3** suggest a severe pandemic is likely to have a duration of several years, possibly five or more years, before the rate of viral infections returns toward background levels. Given the mobility of a section of the global population, sometimes less than effective leadership, incomplete compliance with lockdowns and other measures designed to reduce transmission, the speed of onset reaches the stage where large proportions of the globe will be affected within a few weeks to months. While some sections of the earth may resist infections for as much as a year or two (e.g., Antarctica), eventually the infection will be truly global – a characteristic which may differentiate pandemic from the other global catastrophes considered here (**Figure 2**).

As we have discovered with COVID-19, the principal impact is not mortality but morbidity, leading to a reduction in consumption of many goods but stockpiling of others, restriction of movement with major effects on tourism, travel, hospitality, entertainment, transport, journey-to-work, exports and imports. Perhaps the most striking impact is in increases in inequality. Furthermore, about 10% of people infected with COVID experience long COVID with the most common symptoms including fatigue, post-exertional malaise, and cognitive dysfunction sometimes for a year or more (Marshall, 2021).

Mortality is also likely to be but a small part of the costs of a pandemic. Burns et al. (2008) suggest only 12% of the economic impact of a pandemic will be due to mortality, 28% to illness and absenteeism, and 60% due to efforts to avoid infection. Keogh-Brown et al. (2010) modelled the macroeconomic impact of an influenza pandemic on the United Kingdom, France, Belgium and the Netherlands. Their modelling suggests limited effects on agriculture with the rest of the economy experiencing a 5–7% decline, assuming 13 weeks of school closures and 4 weeks of prophylactic absenteeism from work averaged across the four countries.

The US Congressional Budget Office estimates the macroeconomic effect of a severe influenza pandemic similar to the 1918 Spanish flu to be a loss of 4.25% of GDP. By comparison, during the Great Recession (2007–2009), the U.S. economy contracted by approximately 3%[6]. Recent analysis from the World Bank suggests that the annual global cost of moderately severe to severe pandemics is roughly USD 570 billion, or 0.7% of global GDP; a very severe pandemic like the 1918 Spanish flu could cost as much as 5% of global GDP, or nearly USD 4 trillion[7]. Cutler and Summers (2020), working on the (possibly erroneous) assumption that the COVID pandemic in the United States will be largely contained by the fall of 2021, placed the economic cost of the pandemic (to the United States) at USD16.1 trillion. This total includes USD7.6 trillion in lost GDP from unemployment and subsequent business revenue declines, USD4.4 trillion in the cost of premature death (allowing a conservative USD7 million for each death), USD2.6 trillion in long-term health impairment, and USD 1.6 trillion in mental health impairment. In total these costs, effectively summed over 2 years, reach about 90% of US annual GDP.

It is probably impossible (and pointless?) to compare any of the above estimates. However, the available literature pre-COVID-19 can be interpreted to suggest a decline in global GDP of 5–6% in the event of a severe pandemic. With global GDP at about USD90 trillion, this suggests an economic loss of USD5 trillion. While it is too early to forecast global GDP decline due to COVID-19 there are indications that it will be much larger than 5–6%. In any case, economic consequences seem poorly related to the death toll, or the severity of the outbreak, and more to governmental concerns and responses. Large economic losses are driven by human behaviour (which is very hard to model) – affected by people's valuation of their own health status, family, relationships, work, social activities that affect decision making

[6]https://www.air-worldwide.com/Publications/AIR-Currents/2018/What-the-1918-Flu-Pandemic-Can-Teach-Today-s-Insurers/.

[7]https://www.air-worldwide.com/Blog/A-Pandemic-Emergency-Facility-to-Protect-the-Poorest-Countries/.

and exposure to disease[8]. Human actions are often not predictable, but they are interconnected (NAS, 2018, 35ff).

A VEI 7 Volcanic Eruption

A Volcanic Explosivity Index (VEI) 7 eruption produces at least 100 km^3 of eruptive product, primarily ash fall and pyroclastic density currents (Newhall and Self, 1982). The most recent VEI 7 eruptions were from Tambora (Indonesia) in 1815 and Samalas/Rinjani (also in Indonesia) in 1,257. Proximal to the volcanic source (say, within 100 km), pyroclastic density currents and thick tephra (ash) falls obliterate all life and the built environment. Tephra, drifts downwind with deposits as thin as a few mm at a distance of up to 1,000 km damaging plants/crops and animals/livestock, and producing relatively minor building and infrastructure damage. The area proximal to the volcano is likely to be further devastated in the years following the main phase of the eruption by erosion and redeposition of the PDCs and airfall tephra (**Figure 3**). VEI 7 eruptions inject megatons of sulphur dioxide into the atmosphere, creating sulphate aerosols which circle the globe and backscatter incoming solar radiation. The reduced solar radiation generates surface cooling, altered atmospheric and oceanic circulation patterns linked to semi-global phenomena including the Atlantic meridional overturning circulation, ENSO, the Pacific Decadal Oscillation, tropical monsoons and associated variable direct and indirect consequences at regional scales (Brönnimann and Krämer, 2016).

The atmospheric perturbations of the 1815 Tambora eruption, for example, resulted in crop failure in parts of Europe and the northeastern United States, the latter often described as the "year without a summer" (1816). A range of other possible global consequences have been elucidated by Wood (2014). It seems likely that the Samalas/Rinjani eruption in 1,257 triggered the onset of the Little Ice Age with subsequent VEI 6 eruptions sustaining it for several centuries (Newhall et al., 2018).

VEI 7 eruptions occur on average about twice in a thousand years, possibly a little more frequently as the magnitude of some large eruptions in the last few thousand years remains unclear. Additionally, some VEI 6 eruptions have produced similar atmospheric effects; for example, the twenty largest volcanic eruptions in the last 2000 years have produced summer temperature anomalies in the northern hemisphere of >0.4°C and lasting for about 5 years (Büntgen et al., 2016). Newhall et al. (2018) have identified 125 volcanoes around the world that appear capable of producing VEI 7 eruptions.

The magnitude of deaths and economic losses around the world are hardly quantified. Deaths on Sumbawa and neighbouring Indonesian islands resulting from the Tambora eruption have been placed at 92,000, mainly from PDCs and subsequent starvation. Deaths probably also occurred in the north eastern United States and in Europe as a result of poor harvests. Some authorities maintain mass deaths occurred in India following a cholera epidemic were occasioned by the eruption (e.g., Wood, 2014). The 1,257 eruption of Rinjani has been associated with cold summers in Europe and parts of Asia (Stothers, 2000); mass deaths in Europe have been attributed to poor harvests but there is also evidence that the poor harvests and deaths began before the eruption (Campbell, 2017; Ludlow, 2017).

Whatever the consequences of past VEI 7 eruptions, we can be fairly certain that the area within about 100 km of the source (that is, an area of about 30,000 km^2) of future eruptions will be completely devastated by PDCs with temperatures of several hundred degrees Celsius moving at velocities of us to several hundred km/hour, burying the built and/or natural environments under tens of metres of pyroclastic flows and tephra falls. In volcanic source areas such as Japan, the west coast of North America, the Philippines and Italy the human deaths might be in the tens of thousands or more and economic losses would likely be in the trillions. For some source volcanoes in parts of Alaska, eastern Russia, and Papua New Guinea the losses might be comparatively minor. Recovery, if possible, may take decades; the area of Katmai National Park, Alaska devastated by the Katmai-Novarupta VEI 6 eruption in 1912, and the area around the former US Clark Air Base in the Philippines destroyed by the 1991 VEI 6 of Pinatubo provide examples (Griggs, 1922; Newhall and Punongbayan, 1997).

The area affected by downwind tephra fall ranging in thickness from as much as a metre to just 1 mm may exceed 400–500,000 km^2. Unpublished data suggest human death rates ranging from about 5% from a 40 cm tephra fall to about 0.02% for a fall of 1–2 mm. Similarly, building and infrastructure losses averaged across the whole area of tephra fall might average 3–5%. Crop losses are likely to be much more substantial ranging 20–100% in areas receiving more than 10 cm of tephra to 0–20% in areas receiving more than 1 mm of ash with actual losses very dependent on crop type, growth stage, the aerosol components attached to the tephra, subsequent rainfall, and the effects of the tephra on beneficial and predator insects. Moreover, as Wilson et al. (2015) indicate a fall of more than 30 cm of tephra is likely to result in the retirement of agricultural land for at least several years.

However, it is the longer term climatic consequences of a VEI 7 eruption that are of major interest, particularly those shown to produce summer temperature anomalies across the globe and over a period of 4–5 years (Büntgen et al., 2016). Much of the evidence is anecdotal with actual consequences dependent on prior conditions as well as the actual temperature anomaly. Puma et al. (2015) have modelled the potential impacts of seven historical eruption on contemporary wheat, maize, rice, and soybean harvests. They show, for example, that the potential annual production losses from the Laki fissure eruption (Iceland, 1783; a VEI 4 eruption) are equivalent to the annual food consumption of 2.9 billion people on a caloric basis, assuming the world average diet of 2,940 kcal per capita per day for 2015. Estimated annual production losses for a repeat of the Tambora

[8]Ferguson (2021, p139) refers to the dual pandemic – the biological and the informational; something we can all relate to in 2021; however, Ferguson was writing about Daniel Defoe's Journal of the Plague Year, about the 1665–6 bubonic plague in London, though published in 1722. Given 2020 attacks on healthcare workers, destruction of 5G towers etc., it is also interesting to note that nakedness, fish contaminated by Germans, dirt or dust, unclean pajamas, open windows, closed windows, old books, and "cosmic influence" were all popularly posed in 1918–19 as causes of influenza (NAS, 2019, p12).

eruption are equivalent to the dietary intake of about 2 billion people, Samalas 0.7 billion people, and for Huaynaputina (1601, Peru, a VEI 6 eruption) about 2.6 billion people[9]. These results should be regarded as preliminary; further research is required to confirm the magnitude of these potential losses, explore the potential consequences for other food crops, and to ascertain the longevity of such shortfalls in the current environment where global food production and global food demand are finely balanced.

While VEI 7 eruptions appear to have an average recurrence interval around 500 years, VEI 6 eruptions occur around twice per century. Eruptions capable of producing possibly enormous death tolls and economic losses of substantially more than USD 1 trillion may well have average recurrence intervals closer to once in 100–200 years.

Geomagnetic Storm

Space weather describes variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere. While a range of space weather events could produce global catastrophic risks, the most important are Coronal Mass Ejections (CMEs) – massive high speed bursts of charged particles and magnetic fields ejected from the sun with strong south-pointing magnetic fields intensifying electric currents that flow within the magnetosphere causing rapid changes in the earth's magnetic field (Lloyds, 2010; Oughton, 2018). The 1859 Carrington event was a CME with visible aurora recorded at geomagnetic latitudes as low as 20^o (Oughton et al., 2017). Chapman et al. (2020) suggest a Carrington class storm has a 0.7% chance of occurrence per year. It is possible to forecast CMEs 6–8 h before they reach the Earth, though the warning period would be less for a fast CME in a superstorm. CMEs are the most important space weather events where long-term damage is the concern (Oughton et al., 2017)[10]. Solar radiation storms (solar energetic particle events) are bursts of charged particles at very high energies capable of damaging electronics and power systems in satellites and disrupting digital systems in aircraft. They can pose a significant health risk for airborne humans (Lloyds, 2010). Büntgen et al. (2018) believe the 774–775 AD event recorded as anomalies in ^{14}C in tree rings and as anomalous levels of ^{10}Be, ^{36}Cl and other cosmogenic radionuclides in ice cores resulted from a solar energetic particle event. Frolov et al. (2018) calculate the particle fluence in the 775 AD event had to be tens – hundreds times greater than in the modern powerful solar particle events in 1956 and 1972.

Solar radiation bursts are strong bursts of natural radio emissions that occur, for example, during CMEs. They have the potential to interfere with modern wireless technologies such as satellite navigation, wireless internet, mobile telephones, and short-range device controls (such as SCADA – Supervisory Control and Data Acquisition – systems, which are everywhere today in lifelines, industry, and even homes) (Lloyds, 2010).

Solar flares are spectacular explosions on the Sun's surface sometimes associated with CMEs. The effects on Earth are limited (perhaps 10–20 min), absorbing HF radio waves across the whole sunlit side of the earth. GPS receivers can calculate positions that may be wrong by several metres (Lloyds, 2010). Absorption of HF radio waves is probably becoming of less significance as more communication is satellite-based (Hapgood, 2017).

As Oughton (2018) notes: *When these primary forms occur in combination, the time line of impacts is likely to unfold as follows. Earth may first be bombarded with initial radiation (such as X-rays) from a solar flare approximately 8 min after the event on the surface of the sun. A second barrage of very high-energy solar particles (SEPs) may then arrive some 10s of minutes later. Finally, a large CME may reach Earth somewhere between 1 and 4 days later, depending on the speed of travel through interplanetary space. The magnetic field in the CME is likely to lead to a geomagnetic storm that may also last for multiple days as it drives huge electrical currents, especially at high geomagnetic latitudes, leading to bright auroral displays. Often two CMEs may be released in quick succession, and analysis of past events suggest that this dual occurrence often leads to the most extreme impacts, as indicated by aurora occurring at low latitudes.*

A severe geomagnetic storm (also known as a space weather event) on the scale of those in September 1859 or May 1921 would be likely to instantaneously disrupt modern life across a large area, with failure of the electrical grid, potentially damaging large transformers which can take months to years to replace[11] (**Figure 4**). Loss of electric power would shut down most transport services, if not immediately, then within a few days when it became necessary to pump fuel. This failure would also affect water supply, sanitation, heating/cooling, medical services, and communications (including mobile phones, internet services, and financial services). Back-up generators will only work until they need refuelling. Food supply would dwindle as supermarkets and other retail outlets rely on electronic transactions and fuel for transport of goods. "Sustained loss of power could mean that society reverts to 19th century practices" (Lloyds, 2010, p15). As so much of western society relies on just-in-time services, it is hard to see many societies maintaining current norms for much more than a week; civil unrest, in various forms, should be expected.

[9]While the temperature anomalies and the food security consequences produced by a VEI 7 eruption are very likely to be both smaller and shorter than those resulting from a regional nuclear conflict, there are similarities (Jägermeyr and Robock, 2020).

[10]A wide range of indices are used to measure changes in the Earth's magnetic field. The time rate of change (dB/dt per unit time) best represents the threat to Extra High Voltage (EHV) transformers and the electricity transmission network via Ground Induced Currents (GIC) (Oughton et al., 2017). The intensity of a geomagnetic storm can also be measured by counting the number of solar charged particles that enter the Earth's magnetic field near the Equator – Disturbance storm time (Dst) (Masters, 2009).

[11]There appear to be two schools of thought about potential damage; some believe that the potential damage would not be large, with disruptions lasting only a few hours or days; others believe extensive damage to equipment produces blackouts that would last days, months or even longer as the globally manufacturing capacity for large-scale transformers is too small to cope with damage to dozens or hundreds of Extra High Voltage transformers (Oughton et al., 2017; Oughton, 2018). While the second view seems more likely for Carrington-size superstorms, some governments and some grid operators seem to be alert to the issues involved.

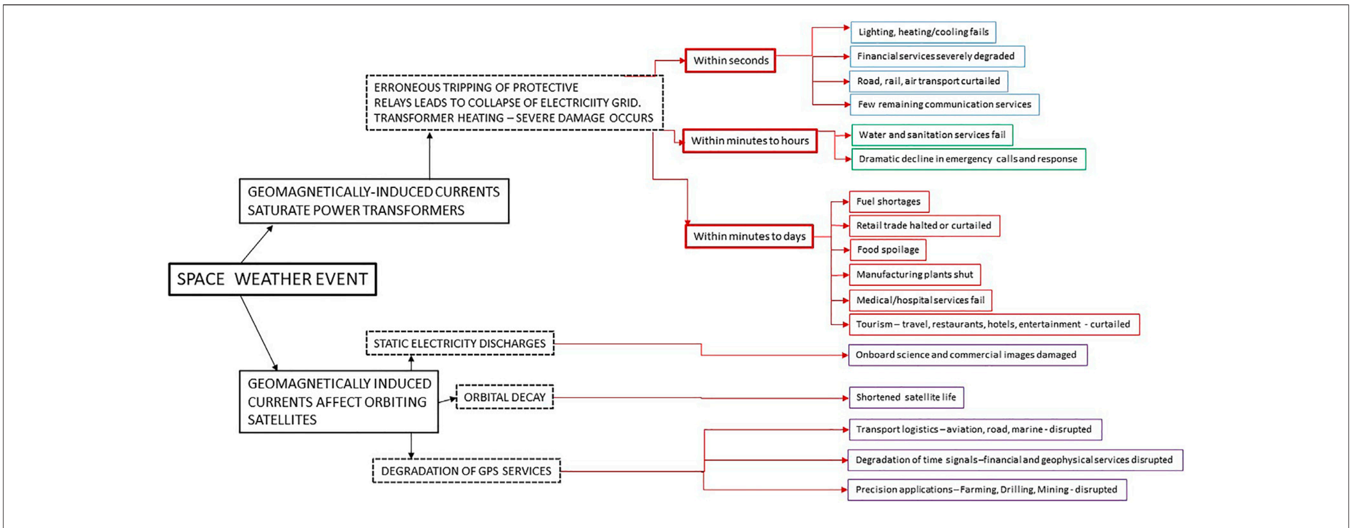

FIGURE 4 | The cascading effects of a geomagnetic storm.

Apart from the potentially severe effects on electrical grids induced currents can be created in pipelines and railway networks. Satellites are vulnerable to radiation damage and electrical charging (**Figure 4**). Transpolar aviation routes will experience disrupted communications and navigation issues, and aircrew and passengers are subjected to increased radiation.

Several attempts have been made to estimate the costs of severe space weather. Oldenwald and Green (2007) indicate losses to satellite operators of about US30 billion in a repeat of the Carrington event. A US National Academy of Sciences report published in 2008 (NAS, 2008) estimated the economic costs of a repeat of the 1921 event for the US alone at USD1-2 trillion for the first 4 years but with full recovery taking up to 10 years. While the basis for this estimate has been questioned (Oughton, 2018), a study for Lloyds (2013) found that a Carrington-level storm affecting 20–40 million people for between 16 days and 1–2 years the total economic cost is estimated at between USD0.6–2.6 trillion; this study does not consider international trade (Oughton, 2018). Schulte in den Bäumen et al. (2014) perform three scenarios with storms equivalent to the Quebec 1989 storm centred over the United States, Europe and Asia. They take into account direct impacts, international trade, and interrupted supply chains concluding storms would reduce global consumption by 3.9–5.6% and impact every industry and every sector of society.

Oughton et al. (2017), examine the direct and indirect macroeconomic costs of four scenarios affecting the United States at different geomagnetic latitudes; they fail to assign average return periods to any events though the largest (S4) appears to have a footprint smaller than a Carrington-sized event. The S1 event produced a blackout affecting 8% of the US population with a loss equal to 15% of daily US GDP plus an additional international loss from flow-on effects of 13% of the daily US loss. The largest S4 event, affecting 66% of the US population produced a loss equal to 100% of daily US GDP with an additional international loss equivalent to 18% of daily US GDP. They note that their estimates suggest about 49% of the losses occur outside the blackout zone and that the loss estimates still exclude losses of perishable products, damage to fixed capital equipment and damage resulting from any civil unrest (Oughton et al., 2017, p71, 79). More recently it has been suggested that while many of these studies model an 80^{o} latitudinal and a 8^{o} longitudinal electrojet size, zones of extreme activity have significantly smaller footprints (Oughton, 2018) perhaps indicating that these estimates produce losses that are on the high side.

The most sophisticated (and presumably the most accurate) analysis of the potential costs of space weather has been undertaken for the UK considering geophysical risk, asset vulnerability and the critical network infrastructure (Oughton et al., 2019). In their detailed analysis a Carrington-sized event has a 71% probability of producing very intense substorms with a 50% likelihood of a single very intense storm disrupting the power grid and a 21% likelihood of two very intense substorms. Two storms, with no forecast available increases the probability of "significant power grid difficulties, increasing the likelihood of a national grid collapse" (Oughton et al., 2019, p1039). The economic costs of a storm of this intensity is moderate at GBP15.9 billion on Day 1 with no forecasting ability falling to GBP2.9 billion with the current forecasting ability (which appears to be on the decline)[12]. We do not know what multiples of these estimated losses would occur in the other parts of the world affected by the modelled storms.

While Lingam and Loeb (2017) provide no details they estimate that a superflare with energy of 10^{34} ergs with produce damage roughly equal to global GDP with an average return period of about 2000 years. Furthermore, a superflare with

[12]It is difficult to make comparisons between the various studies made available but the potential losses modelled by Oughton et al. (2019) seem to be at odds with the study of Schrijver et al. (2014) who assessed the cost of non-catastrophic impact of non-extreme geomagnetic disturbances on the US through insurance claims for industrial electrical equipment for the period 2000–2010 calculating an average economic impact of USD 7–10 billion per year (Schrijver, 2015).

energy 10^{36} ergs has ~10^{-4} chance of occurring in the next century, approximately equal to the chance of a 2 km diameter asteroid hitting the earth in the same time frame.

DISCUSSION

The relentless slow but quickening rise in sea level destroys both built and natural environments and creates refugees through the rise of saline groundwater and the destruction of perched freshwater lenses on atolls and other small, low-lying islands. And these processes continue for decades.

The major consequences of a pandemic at first appears to be dominated by human mortality with potential pandemic deaths reaching a few hundred million, but the long-continued drama of mental health, the growth in inequality, and issues similar to long-COVID may change that view over a decade. One can also see that the costs and consequences for individual nations experiencing a pandemic depends in part on the national psyche, regulation, and leadership – or the lack of the latter.

Despite the near-vent total destruction resulting from a VEI 7 eruption, the threat to food security provides the most compelling vision of this future global catastrophe.

With urban populations almost totally reliant on electricity at some stage in the provision of lighting, heating/cooling, transport, communications, medical services, and food distribution it is difficult to imagine that any urban society would maintain its current level of law, order, social justice and harmony for more than a few days in the aftermath of a geomagnetic storm. On the other hand, parts of the affected area dominated by subsistence agriculture and/or a spirit of self-reliance might well remain relatively unaffected. While a geomagnetic storm provides perhaps the bleakest view of the aftermath of a global catastrophic risk, it also provides opportunities for ameliorating future consequences through warning systems and hardened electrical infrastructure – opportunities that are more difficult to envisage or implement in the case of the other three risks.

Quantifying GCR Losses

Clearly, the costs of global catastrophic risks is not solely about dollars and mortality. As **Figure 1** implies there are myriad other costs, direct and indirect, tangible and intangible, and it is difficult to see how to account for these. Here I make an attempt to interpret the variety of losses; I take as examples 15 of the numerous types of losses implied in **Figure 1**, loosely grouping the fifteen into seven broad categories – Buildings, Infrastructure, Human Health, Agriculture, Other Economic Activity, Environment, and Social Impacts (**Figure 5**). Each potential loss is expressed as a proportion of the assets at risk. For example, Pandemic Mortality is expressed as a percentage of global population; in most cases this is likely to be less than 10% of global population but, based on Puma et al. (2015) exploratory work, the global death toll from food scarcity in the aftermath of a VEI 7 eruption could reach more than two billion lives.

Obviously the views contained in **Figure 5** are those of the author alone, conditioned both by wide reading and, no doubt, by vast ignorance of many issues. A more satisfactory account would depend on the views of many, from a range of disciplines, more rigorous definition of categories, the magnitude of the GCRs, narrower bands of percentage losses, and some form of expert elicitation (cf. Aspinall, 2010; Bamber et al., 2019).

This form of "analysis," here applied globally, could also be applied to a specific community, nation, or continent.

Trends

The pathway and the shape of the post-GCR future likely depends on innumerable factors including the intensity of the impact, the resources available, outside assistance, resilience, the availability of cheap finance, leadership, and the trust of the populace in that leadership. Luck may well play an important part in shaping the future. Haldon et al. (2018) remind us: ". . . correlation is not causation and that it is a coalition of external and internal factors that generate crises." In 2020 we might argue that COVID-19 has accelerated trends in domestic violence, work-from-home, xenophobia, inequality, migration, on-line shopping, the availability of seasonal workers, the value of larger houses and apartments – but we are (largely) in the dark as to whether these trends will endure. It would be intriguing to review changes that are still with us from the 1918–19 pandemic, the Great Depression, even the world wars? Certainly, the future will be reshaped, but for how long?

Whatever character or pathway a global catastrophic risk takes and whatever the influence of leadership possible futures can be characterised as one of four (**Figure 6**):

1) Post-GCR growth – where a rapid decline, the depth of which probably depends on both pre-existing conditions and resilience, is followed by a return to a trend or a future not too different to that characterising the pre-GCR period;
2) Post-GCR innovation – where the rapid decline is followed by a future characterised by innovation, new technologies, collaboration and/or a decline in adversaries;
3) Post-GCR decline – where the rapid decline is followed by only a partial recovery where the pre-GCR trajectory never recovers; this GCR produces a deviation-amplifying event;
4) Post-GCR extinction – the rapid decline leads to a worsening situation, no recovery occurs and extinction eventually follows.

Several possible attributes are shown on the Y-axis on **Figure 6** – Gross Domestic Product (GDP), Food security, Lifespan, Happiness[13], or the Proportion of the population above the poverty line. Others attributes could be substituted or added, reflecting the breadth of the potential consequences shown in **Figures 1**, **5**.

The four possible futures might apply to the world, to a continent, a country or just a few communities. It is possible that different, even adjacent countries or continents, have

[13]Happiness might sound like a nebulous concept but Helliwell et al. (2021) provide a Happiness ranking for 149 countries based on the sum of six factors – GDP per capita, social support, healthy life expectancy, freedom to make life choices, generosity, perceptions of corruption – plus dystopia (the estimated life evaluation in a mythical country with the lowest observed values for each of the six variables (Helliwell et al., 2021, p23). This year's report is particularly apposite as it takes into account the effects of COVID in 2020.

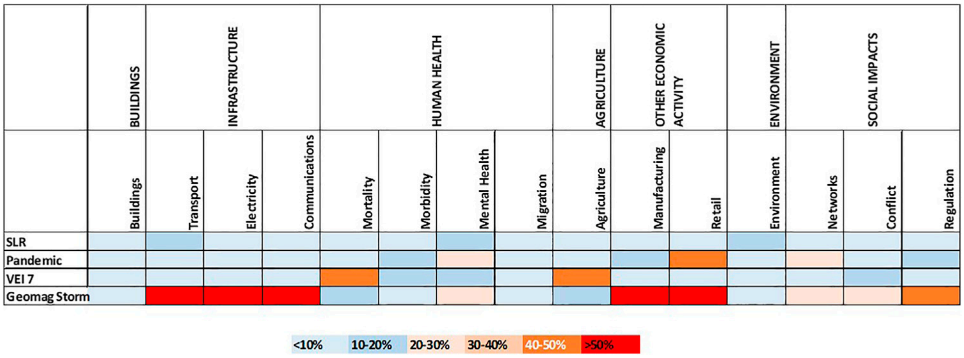

FIGURE 5 | 15 GCR losses shown as broad percentage bands, selected from the many noted in **Figure 1**, expressed as a proportion of the assets at risk. See text for fuller explanation.

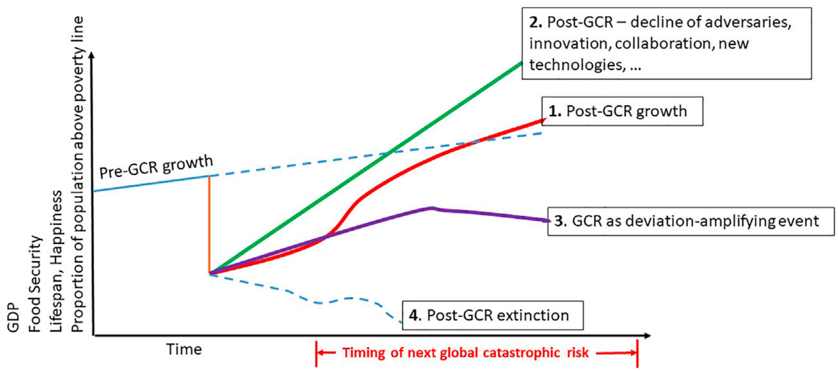

FIGURE 6 | Four possible futures following the occurrence of a global catastrophic risk (based on ideas in Brunsdon et al. (2013), Ratti (2017), Baum et al. (2019)). While the timing of the next global catastrophic risk is uncertain, it is quite likely to occur before recovery from the most recent one is complete.

substantially different futures. And it is certainly possible, even quite likely, that the next GCR will occur before the myriad enduring consequences of the present one have played out.

Perhaps as COVID-19 has shown (at least for the near term), leadership is an important influence on the shape of the future. For COVID, science-based leadership seems to have (so far) produced the best outcomes for individual countries and populations. Intriguingly, science-based leadership seems much less popular in relation to looming global catastrophic risks including climate change and anti-microbial resistance.

A 2016 report, based on interviews with top leaders around the world, found: *"A proliferation of "unthinkable" events has revealed a new fragility at the highest levels of corporate and public service leaderships. Their ability to spot, identify and handle unexpected, non-normative events is … perilously inadequate at critical moments … Remarkably, there remains a deep reluctance, or what might be called "executive myopia" (my emphasis), to see and contemplate even the possibility that "unthinkables" might happen, let alone how to handle them"* (Gowing and Landon, 2018).

Ferguson (2021), p60) puts it less subtly in words evocative of the 1980s UK TV series Yes Minister: *The decision makers may be captives of diffuse responsibility, "agenda inertia," regulatory capture, intellectual inadequacy, ideological blinkers, downright "cowardice," or bureaucratic pathologies such as "satisficing" (addressing a problem but not solving it or withholding vital information). And the "chorus" – not so much public opinion as expert opinion – can fall victim to a different set of biases: the craving for certainty (randomized control trials, peer-reviewed papers), the habit of debunking any novel theory, or the sunk cost of being invested in "settled science," not to mention the temptation to make countless false prophecies on opinion pages and talk shows.*

The Anthropocene and the Early Holocene

It is intriguing to consider these four global catastrophic risks in two time periods – the Anthropocene and the Early Holocene (say, 12–8 ka).

Whether we consider the Anthropocene to have begun with the Industrial Revolution or after 1950 (Lewis and Maslin, 2015; Subramanian, 2019), it is clear that geomagnetic storms have become a truly global catastrophic risk only in the latter part of the Anthropocene as satellites, the internet and electronic paraphernalia have come to dominate the everyday existence of a large proportion of global population. It may also be correct to assert that the speed of a pandemic's potential onset has accelerated during the last few decades as global travel has become more and more common, and viral and host factors compete to enhance risk despite medical and epidemiological advances. While the average frequency and consequences of a VEI 7 eruption have hardly changed for thousands of years it may be that the declining proportion of the global population involved directly in agriculture and the continuing rise of just-in-time food security for the ever-growing urban masses has increased human vulnerability during the Anthropocene. As the rate of sea level rise will likely continue to accelerate over the next few decades perhaps the trend of increasing risk is characteristic of all four of the extreme perils considered here.

During the Early Holocene rates of sea level rise were higher than at present. Lambeck et al. (2014) estimate a near uniform rate of rise of ~15 mm/y for the period 11,400 to 8,200 years cal BP, with a reduced rate from 8,200 to 6,700 years cal BP. More recently, Chua et al. (2021) have shown the average rate of rise for Singapore from ~9,500 – 8,000 years cal BP to be 8.4 ± 2.6 mm/y. These Holocene rates are all substantially above current rates of sea level rise, though Nerem and Fasullo (2019) extrapolate current rates to about 10 mm/y by the end of the present century. The Early Holocene rates, extending over thousands of years, translate to kilometres of retreat of the land-sea margin on many continental shelves and the drowning of some islands in island chains. Furthermore, marine and terrestrial responses to the warming trend and sea level rise may have been out of phase; together changes in the proportions of muddy, sandy, and rocky coastal and marine habitats may have produced constraints on, or abundance in, food and other resources such as water, stone tools, fibres, timber, and shelter (Graham et al., 2003). Such changes may have encouraged migration, created refugees, and likely conflict with adjacent populations.

Early Holocene VEI 7 volcanic eruptions presumably occurred at roughly the same rate as in the present day[14]. Total destruction would have been wrought on areas of much the same size, up to about 30,000 km^2, with tephra fall declining in thicknesses over additional areas of several hundred thousand square kilometres. Within the areas of total destruction extinction of local communities may have occurred and landscapes changed irrevocably by redistribution of tephra by rain and lahars. Reoccupation of these lands would almost certainly not occur for several generations, emphasising the time timeframes for recovery are an order of magnitude or more longer than the duration of the physical impacts. Vanderhoek and Nelson (2007) point out that the area buried by PDCs in the 1912 Katmai-Novarupta VEI 6 eruption in Alaska was still largely unvegetated 90 years later. In tropical New Britain where five VEI 5 or 6 eruptions occurred from Witori and Dakataua volcanoes in the period 6,000 to 1,000 years ago archaeological sites which received more than 50 cm of tephra fall remained unoccupied for 200–250 years after each eruption (Torrence and Doelman, 2007). Similarly, archaeological research suggests that reoccupation after the ~7,300 cal BP VEI 7 eruption of Kikai-Akahoya in southern Japan was delayed until the ecology recovered up to 900 years after the eruption (Machida and Sugiyama, 2002; Grattan, 2006). While it is possible that some communities left areas close to volcanoes before the peak phase of the eruption this implies an understanding of the warning signs and strong networks with other communities stretching across a large area. While migration to adjacent areas is certainly possible, the extent of the area where tephra fall is likely to severely curtail food supply and other resources is so large that a migration of 100 km or more may mark no difference in the level of resource destruction or food availability.

Pandemics depend on global spread. COVID has shown just how rapid that can be in the Anthropocene. Even a few hundred years ago the rate of spread was considerably slower with bubonic plague taking years to spread across a significant portion of the globe in the 17th century. In the Early Holocene a pandemic seems unlikely, though local epidemics could have been more frequent and more deadly.

Sea level rise, a VEI 7 eruption, or an epidemic/pandemic in the Early Holocene may have enhanced increased mobility or migration, driven by decision-making in small groups possibly with wide kinship ties. While mobility may encourage new ideas, new world views, access to new resources and changes in material culture, dislocation may also exacerbate inequality, poverty, famine, malnutrition and/or violence. Early Holocene trends to a more sedentary agriculture and more complex societies may also have encouraged the spread of infectious diseases (Sheets, 2016; Riede et al., 2020; Gamble et al., 2021). If migration followed a pandemic or a volcanic eruption, a return to the homeland may have been possible within years to decades (except near to the source of a VEI 7 eruption), but migration resulting from sea level rise prevented return and altered any "sense of place"[15].

While geomagnetic storms may well have the severest repercussions for modern society at this stage of the Anthropocene, in the Early Holocene such storms probably passed with only a lively discussion about the associated aurora.

While I have made no attempt to compile a complete list of GCRs a short list includes, in addition to the four considered here, war, especially a nuclear war, climate change, a gamma ray burst, a meteorite impact, a cyber hack, antimicrobial resistance, plant pathogens (Raistaino et al, 2021) and a few of the hazards and consequences listed by the World Economic Forum in annual reports. While it is disconcerting to observe that the Anthropocene list is substantially longer than that for the Early Holocene, this is not to suggest that life is now more risky than in the Early Holocene

[14]However, Satow et al. (2021) have shown that the frequency of eruptions on volcanic islands can be influenced by sea-level change with Santorini showing a much higher eruption rate when sea level falls below -40 m. Conversely, deglaciation and continental lithospheric unloading leads to increased continental magmatic, volcanic, and degassing activity (Sternai et al., 2016).

[15]Sandweiss and Quilter (2012) draw important distinctions between collation, correlation, and causation in an archaeological context, distinctions that make it troublesome to state categorically that an eruption or a pandemic "caused" migration or a cultural change. Often, a GCR may only be a contributory "cause" with events during previous decades encouraging a decision to finally "do something." It will be interesting in the coming decades to ponder which changes we think were caused by COVID-19.

– in fact, the increase in average life expectancy from about 20 to 30 years to 70+ years suggests otherwise.

CONCLUSION

Global catastrophic risks have the potential to kill hundreds of millions, even billions, and can produce damage to infrastructure and economic activity in the many trillions though none of the four considered here are likely to do both; possibly, a VEI 7 eruption with the vent near a densely populated region has some potential to achieve both.

Loss potential measured by just human mortality or just by economic losses, or just by both, seriously underestimates the scope and duration of consequences. Our perspective might change markedly if we focussed more on consequences for mental health, human happiness, and the environment.

Most GCRs, except meteorite impact, a VEI 7 eruption, and a gamma ray burst, result largely from human ingenuity and neglect. Serious adverse consequences from GCRs are much more likely in the Anthropocene than they were in the Early Holocene.

As COVID has shown, human behaviour has a big influence on consequences and loss potential. This likely to be even more true in the aftermath of a Carrington-sized geomagnetic storm than in the repercussions of other GCRs.

For all GCRs, not just the four considered here, leadership at global, regional, country, and community levels may have more influence on both the magnitude and the scope of the losses and on the shape of the aftermath than any other variable.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

The author confirms being the sole contributor of this work and has approved it for publication.

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A Song of Neither Ice nor Fire: Temperature Extremes had No Impact on Violent Conflict Among European Societies During the 2nd Millennium CE

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The second millennium CE in Europe is known for both climatic extremes and bloody conflict. Europeans experienced the Medieval Warm Period and the Little Ice Age, and they suffered history-defining violence like the Wars of the Roses, Hundred Years War, and both World Wars. In this paper, we describe a quantitative study in which we sought to determine whether the climatic extremes affected conflict levels in Europe between 1,005 and 1980 CE. The study involved comparing a well-known annual historical conflict record to four published temperature reconstructions for Central and Western Europe. We developed a Bayesian regression model that allows for potential threshold effects in the climate–conflict relationship and then tested it with simulated data to confirm its efficacy. Next, we ran four analyses, each one involving the historical conflict record as the dependent variable and one of the four temperature reconstructions as the sole covariate. Our results indicated that none of the temperature reconstructions could be used to explain variation in conflict levels. It seems that shifts to extreme climate conditions may have been largely irrelevant to the conflict generating process in Europe during the second millennium CE.

Keywords: Bayesian time series analysis, conflict, climate change, extreme events, Europe

INTRODUCTION

"Winter is coming", the motto of House Stark in George R.R. Martin's *A Song of Ice and Fire* series of epic fantasy novels, is an ominous metaphorical portent of difficult times to come. The novels were inspired by the historical events of the Wars of the Roses (DiPaolo, 2018), a series of conflicts in Late Medieval England that began in 1455 CE (Hicks, 2012). These conflicts erupted shortly after the onset of the Little Ice Age, a period during which average temperatures in the Northern Hemisphere dropped by around 0.5°C in a few decades and then remained low for centuries (Mann et al., 2009). In light of these connections to historical events, the Stark's motto can be read as an allegorical reference to the twin threats of anthropogenic climate change and the violent conflicts it may ignite (DiPaolo, 2018).

The idea that anthropogenic climate change will lead to more conflict has received increasing attention in recent years. It has been endorsed by a number of major policy organisations including the Inter-Governmental Panel on Climate Change (IPCC) (Adger et al., 2014), the US Department of Defense (2010), and the European Commission (2013). There has also been intense scientific interest in climate-conflict dynamics. Dozens of case studies have been published reporting quantitative analyses of conflict records and climatic variables. The conflict records include events ranging in scale and intensity from cattle raids to political uprisings and civil wars that occurred during various sub-intervals of the 20th and early 21st centuries CE. Surprisingly, though, results have been mixed (Koubi, 2019; Mach et al., 2019). Some studies have found that increases or decreases in temperature corresponded to increased conflict levels (i.e., incidence) (e.g., Zhang et al., 2006; Burke et al., 2009), while others reported mixed findings (e.g., Tol and Wagner, 2010) or no effect at all (e.g., Carleton et al., 2021). Similarly inconsistent findings have been reported with respect to the potential impact of rainfall variation on conflict levels (e.g., Theisen, 2012; Von Uexkull et al., 2016).

These contradictory findings are counter-intuitive. Environmental variables are clearly linked to economics, primarily through the impact of environmental variation on agricultural productivity and trade (Gornall et al., 2010). It seems that this should, in turn, affect the prevalence of violent conflicts between groups competing for access to increasingly scarce resources (e.g., Allen et al., 2016). If droughts, for instance, diminish agricultural productivity, then the resulting shortfall in the food supply and commodities might be expected to increase the odds that the negatively affected groups would attempt to compensate at times by taking the desired resources from others (e.g., Burke et al., 2009). Reluctance to hand over resources would then give rise to organised violent conflicts. Scholars of international relations and conflict and peace researchers have referred to this putative causal chain as a "scarcity mechanism' and it has intuitive appeal (e.g., Glowacki and Wrangham, 2013; Koubi, 2019; Schmidt et al., 2021). Even in cases where compensatory strategies were available (e.g., alternate foods, trade), these would not always work as hoped—trade agreements fail and alternate resources are not always sufficient. In addition, the scarcity mechanism would still produce higher levels of conflict given enough time or a large enough focal region. This is because the odds of conflict occurring would still be elevated, which ultimately means more conflicts on average. That recent research has so far failed to find evidence for a universal relationship between temperature and conflict levels is, therefore, surprising.

This situation has led some researchers to highlight the importance of longer-term records (e.g., Buhaug, 2015; Koubi, 2019). The suggestion makes sense because there are differences between records with different time horizons. Short-term records of conflict incidence, for instance, are likely to be highly erratic with respect to causation. Individual conflicts can happen for numerous reasons that vary among incidents. Additionally, there is a well-known pattern of autocorrelation in conflict data (Richardson, 1944; Houweling and Siccama, 1985; Brandt et al., 2000). Such autocorrelation means that a high level of conflict in one period can predict the level of conflict in subsequent periods. This pattern may occur simply because conflicts beget further conflicts as opponents retaliate for past aggression, which makes it difficult to attribute changes in conflict levels to external factors. Similar features are present in climatological data (Vasseur and Yodzis, 2004). Day-to-day variation in climatological observations cannot necessarily be attributed to changes in long-term patterns. At the same time, the temperature or precipitation in one interval is usually correlated with the temperature or precipitation in previous intervals—i.e., there tends to be autocorrelation in climatolological processes, too. These common features of conflict and climate processes create challenges for seeing meaningful persistent signals in short runs of observations because the records can be noisy and explained by previous observations alone. Consequently, it can be difficult to detect persistent and significant covariation between conflict records and climate change if only short intervals are considered.

Unfortunately, however, the inconsistency persists even when considering long-term conflict and climate records. To our knowledge, there are three major long-term historical case studies available for comparison. Each includes a conflict record spanning multiple centuries that has been analysed quantitatively. One is the epigraphic (monument inscriptions) record of Classic Maya conflict spanning more than 600 years (ca 250–900 CE) (Kennett et al., 2012); another involves more than 2000 years of Chinese conflict records (ca. 800 BCE–1911 CE) (Zhang et al., 2006); and the third involves nearly 1,000 years of conflict among central and western European societies (ca. 1,000–1980 CE) (Tol and Wagner, 2010). Recent studies involving the Classic Maya epigraphic data have found that increased temperatures corresponded to increased conflict while annual precipitation had no apparent effect (Carleton et al., 2017; Collard et al., 2021). Analyses of the Chinese historical data, on the other hand, found that decreasing temperature corresponded to increased conflict levels (Zhang et al., 2006). Lastly, studies involving the conflict data for second millennium CE Europe have found either weak evidence for an effect of climate change on conflict (Tol and Wagner, 2010) or no evidence at all (Carleton et al., 2021).

The last of these cases is particularly interesting. Europe was repeatedly afflicted by wars during the second millennium CE (Tallett and Trim, 2010). These include the Hundred Years War—a series of wars between Medieval England and France from 1,337 to 1453 CE (Green, 2014)—and the aforementioned Wars of the Roses from 1,455 to 1487 CE (Hicks, 2012). These Late Medieval clashes were then followed by the European Wars of Religion between the 1520s and 1640s CE, multiple wars with the Ottoman Empire, numerous revolutionary wars, the Napoleonic Wars, and of course the two world wars of the 20th century CE (Neiberg, 2003; Black, 2007; Tallett and Trim, 2010). The period was also punctuated by bouts of climate change. The beginning of the millennium witnessed a relatively warm period in much of Europe. Known today as the Medieval Warm Period (or Medieval Climate Anomaly), this lasted from about 950 to 1250 CE (Crowley and Lowery, 2000; Mann et al., 2009). Subsequently, around 1400 CE, the continent was plunged into the Little Ice Age, a deep cold that lingered into the early 19th century CE (Mann et al., 2009) with some parts of the Northern Hemisphere experiencing as much as a 4°C drop in average temperatures in a few decades (D'Andrea et al., 2011). The conflicts that occurred during these substantial swings in climatic conditions were in part fought over access to wealth and they required resources to initiate and sustain. It is, therefore, striking that the aforementioned studies found the association between climate change and conflict levels to be weak to non-existent.

There are several possible explanations for the failure of previous research to find a relationship between climate conditions and historical European conflict levels. One might involve biases in the conflict and/or climate records, for example. Another explanation might be that analyzing aggregated data for the whole of Western Europe obscured important local or regional differences in one or more variables, leading to a falsely negative signal about the climate-conflict relationship. A third explanation may be that the scarcity hypothesis is simply wrong, or points to an effect that is eclipsed by other factors like greed, prestige, and politics. Lastly, it could be that the statistical models used so far are too simplistic to identify the relationship between climate and conflict. As Carleton et al. (2021) point out, some of these explanations can be discounted by careful reasoning while others are harder to evaluate at present and should be the subject of future research.

In the present paper, we describe a study in which we explored an important avenue for future research identified by Carleton et al. (2021): the potentially unique impact of extreme climate conditions on conflict levels. Both Tol and Wagner (2010) and Carleton et al. (2021) employed regression models that assume the relationship between climate variation and conflict levels was constant for all levels of the climate variable, temperature being the key proxy for climate change in both cases. This assumption may have led to the analyses missing a threshold effect. It is possible that for moderate temperatures the European conflict process was dominated by non-climatic factors. These might have included retaliation or purely political motivations among those involved. But, during periods of extreme temperatures—say, the coldest intervals of the Little Ice Age—climate variation could plausibly have become much more important.

To explore this possibility, we revised the time-series model used in Carleton et al. (2021) so that it could identify threshold effects. As with the previous model, the new one is Bayesian and employs an autocorrelation term to reflect the "memory" present in the conflict record and allows for covariates to potentially explain any remaining variation in the record not better accounted for by autocorrelation. The new model, however, also employs a "broken-stick" regression framework for the covariates—the "broken stick" refers to connected regression lines that can have different slope values. The model creates the separate "sticks" by fitting two thresholds to the independent variable, one upper and one lower. These thresholds allow for three different ranges of covariate values. A separate regression coefficient (i.e., slope) can then be estimated for each of the three ranges (the three sticks). The separate regression functions make it possible for a given independent variable to have a different relationship to conflict over each of the ranges defined by the thresholds. Therefore, the relationship between conflict levels and a given covariate can be non-linear over the whole covariate range. Conflict levels, for example, could have a U-shaped relationship with temperature in the model, which would mean that conflicts were only significantly higher when temperatures were extreme and effectively random otherwise. Importantly, the model's parameters (including threshold locations and slopes) are all estimated simultaneously from the data. Thus, the estimated values reflect the combined likelihood of those parameter values given all of the data. After adjusting the model, we used it to compare a well-known time-series of European conflict levels (incidents per year) during the second millennium CE to four temperature time-series.

MATERIALS AND METHODS

The Data

The conflict record utilised in the present study was first analysed by Tol and Wagner (2010) in their influential investigation of climate-conflict dynamics. The record was recently reanalysed in the aforementioned paper by Carleton et al. (2021). The copy of the record we analysed was kindly provided by Richard Tol.

Tol and Wagner (2010) record contains an annual count of wars and battles between 1,000 and 2000 CE, with a conflict being counted in each year it was ongoing (**Figure 1**). Tol and Wagner (2010) compiled the record from entries in three databases: 1) Peter Brecke's catalogue of historical conflicts (https://brecke.inta.gatech.edu/research/conflict/); 2) the Uppsala Conflict Data Program (https://ucdp.uu.se/); and 3) the COSIMO database (hosted by Heidelberg Institute for International Conflict Research—HIIK) (https://hiik.de/). In total, the Tol and Wagner (2010) record includes 3,450 conflict-year events from 1,000 to 1999 CE—there are fewer uniquely named historical conflicts than conflict-years because a conflict is counted in every year in which it occurred. Like Tol and Wagner (2010) and Carleton et al. (2021), we limited the record to the period from 1,005 to 1980 in order to ensure complete temporal overlap with the available temperature reconstructions. The restriction reduced the counts by a small amount, from 3,450 to 3,367 conflict-year events.

It is worth highlighting that this dataset represents only one dimension of violent conflict. The record comprises conflicts counted in a given year, as explained. In such a dataset, a border skirmish involving two states and a hundred soldiers would count as much as a larger war involving tens of thousands of combatants and multiple states. Our study, therefore, is only looking at conflict from one angle, namely conflict incidence. Other dimensions of conflict include onset, duration, number of warring parties, number of battle deaths, and so on. One reason for focusing on incidence as we did, though, was to ensure our results would be comparable with those of previous studies. Another reason is that the historical record contains more information about conflict dates than it does about the variables needed to assess the other dimensions of conflict. Filtering the dataset to only those historical conflicts where we know the number of battle deaths, for instance, would reduce the number of observations so much that meaningful patterns could no longer

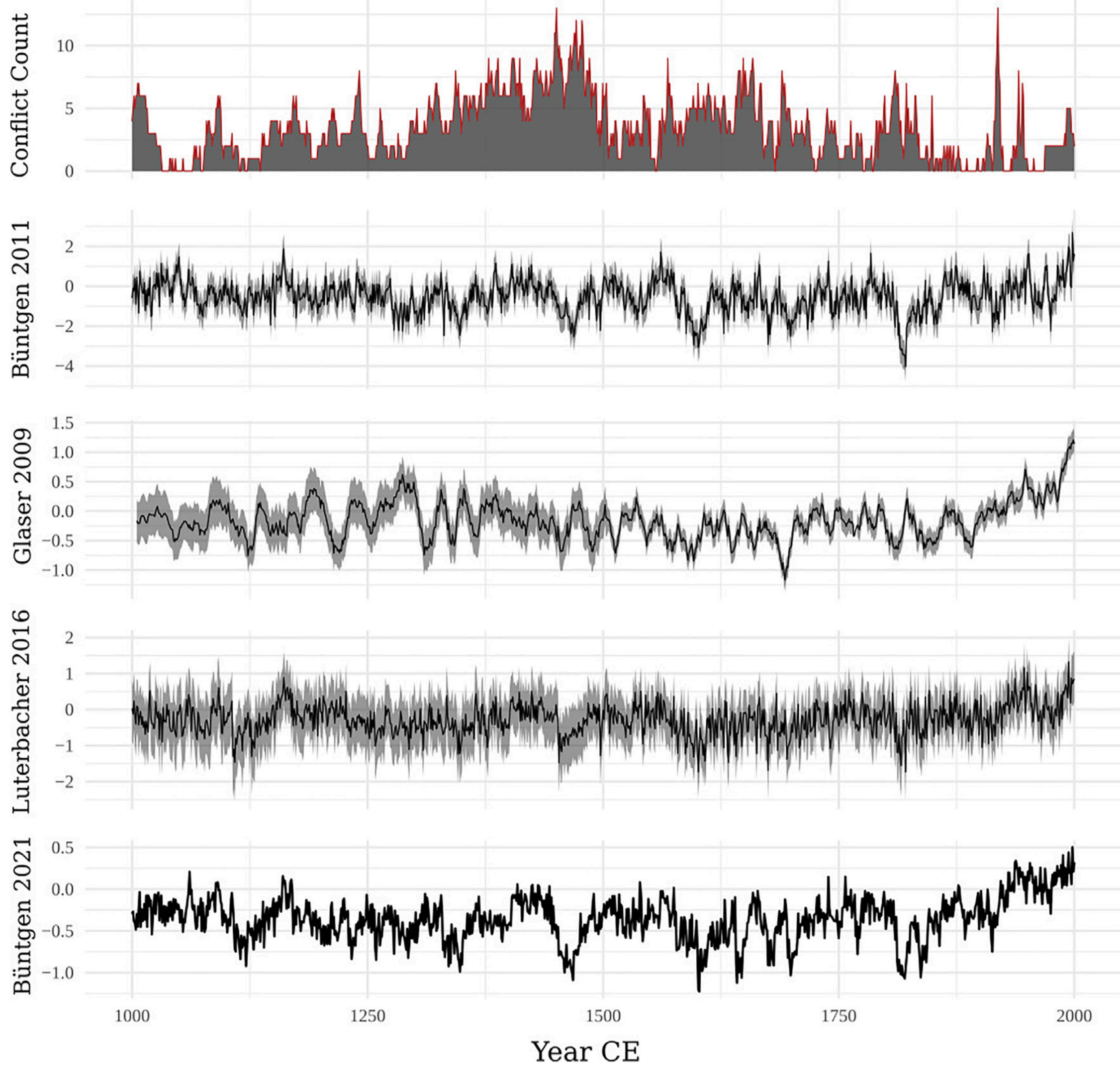

FIGURE 1 | Time series data used in this study. Where available, we include confidence intervals for the climate data **(middle three panels)** and those are represented by lighter grey ribbons.

be extracted. After all, it can be difficult to estimate battle deaths from modern and recent wars let alone historical and ancient ones. Lastly, our intention was to evaluate whether climatic extremes led to an increase in per-period conflict levels as would be expected if the scarcity mechanism was a principle cause of variation. Importantly, according to that hypothesis, we would expect conflicts to start when resources became scarce and to persist (or be reignited) as long as they remained scarce, all else being equal. Such a relationship would be obscured by looking only at conflict onset. Consider a simple time-series of onset counts compared to a climate record. In that comparison, the climate variable could have an extreme value when the count was one (conflict begins) and the same extreme value when conflict count was zero (no new conflicts, despite continued fighting), which would imply no relationship between the two variables. For this reason and others, incidence is frequently used in conflict studies intended to identify relationships between overall conflict levels and external forces (Gleditsch et al., 2002; Hsiang et al., 2013). Consequently, in our view, the Tol and Wagner (2010) record was suitable for the study.

We compared the Tol and Wagner (2010) conflict record to four annual temperature reconstructions, the first three of which pertain specifically to Western and Central Europe and they were used in Carleton et al. (2021) as well (**Figure 1**). One of the temperature records was developed by Glaser and Reimann (2009) based on European historical documents. These documents include a variety of annals and personal diaries from different regions within Europe, though concentrated in the central and northern portions. The corpus includes descriptions of weather conditions as well as statements about crop yields. Glaser and Reimann (2009) categorised the descriptions into an ordinal temperature index, spanning approximately 1,000–1,800 CE, which they then calibrated using a instrumental data from 1761 to 1970 CE. Glaser and Reimann's (Glaser and Riemann, 2009) index and the instrumental data are correlated with a Pearson's R coefficient of 0.88.

The second temperature reconstruction was developed by Büntgen et al. (2011) and is based on high resolution tree-ring-width data. The widths were measured from 1,089 stone pine and 457 larch trees scattered throughout Europe, although like the previous historical data the spatial distribution is uneven with clusters in the central regions of relatively higher elevation. The reconstruction spans approximately 400 BCE to 2000 CE. The authors report Pearson' R correlations in the range of 0.72–0.92 for the association between their reconstruction and instrumental data from 1864 to 2003.

The third temperature reconstruction was developed by Luterbacher et al. (2016) and is based on multiple lines of evidence. It is a product of the international PAGES 2k Consortium, a network of palaeoclimatologists who aim to create high-resolution climatic reconstructions (Turney et al., 2019). The source data include both tree-ring records and historical documents, some of which overlap with the data used for the previous two reconstructions. This composite reconstruction spans 138 BCE to 2003 CE. When the authors compared their reconstruction to instrumental data, they obtained Pearson R correlations on the order of 0.81–0.83. Luterbacher et al. (2016) produced two types of reconstruction and an average model. The average model is the one we used in the present study.

The fourth temperature time-series we included is a newly developed Northern Hemisphere tree-ring-based reconstruction (Büntgen et al., 2021). This time-series was constructed as part of a sizable community-based experiment in which the authors sought to determine how different methodological decisions affect tree-ring temperature reconstructions. The authors asked more than a dozen research groups to produce a reconstruction for the northern hemisphere and then compared the results. The reconstructions were based on tree-ring data from several sites around the Northern Hemisphere with a temporal ranges spanning the first two millennia CE. Ultimately, they determined that an ensemble mean most closely matched the instrumental record (with a Pearson R correlation of 0.79) and recommended using such ensemble means as a way of combating method-induced biases. In line with that recommendation, we decided to include the ensemble reconstruction in our analysis even though it likely registers hemispheric rather than European-specific temperature variation for the study period.

Defining Extremes

In order to explore the potential impact of "extreme" temperature values on conflict levels, we first needed to settle on a way of thinking about extremes in this context. Stewart et al. (this volume) conducted a large systematic survey of 200 journal articles in an effort to map out the ways in which extreme events in biological, societal, and Earth sciences have been studied. The review gave special attention to the quantitative and qualitative definitions used to operationalise extreme event research.

From their survey, Stewart et al. (this volume) determined that a common way of thinking about extremes involves deviations from reference ("normal") conditions. In particular, research on temperature extremes—e.g., heat waves—commonly employs thresholds like the 95% confidence interval for temperatures compared to a given reference period. This 95% threshold is defined by a distribution of values where the bulk closest to the mean are considered "normal". By way of contrast, extreme values deviate far from the mean, where "far" is defined by a threshold beyond which higher or lower values occur only 5% of the time or less in a random sample of measurements. Many studies also used a more effect-oriented way of thinking about extremes. Again, with respect to heatwaves for example, this effect-definition involved an established human biological heat tolerance threshold in degrees Celsius. The idea here is that, for biological reasons, temperatures in excess of this threshold lead to health problems and the relevant temperatures can, therefore, be considered "extreme".

We decided that neither of these approaches would be appropriate for the present study. We were reluctant to employ a particular probability threshold (e.g., 95%) because the choice of such a threshold is arbitrary—why not use 90% or 99%? The second approach would not have worked either because we have no information about the temperature threshold(s) that might exist in the conflict generating process, at least not in Europe. Thus, we opted for a composite approach, one that combined the notion of deviations with data-driven estimation for the threshold values. Specifically, we scaled and centred all the of the temperature series, such that the values would represent deviations from the study-period-wide averages. Extremes among these scaled deviations were not defined *a priori*. Instead, we designed the time-series model to include the values of the potential thresholds as parameters to be estimated from the data.

The Broken-Stick Model

The time-series model, adapted from Carleton et al. (2021), is based on the Poisson distribution. It treats the count of conflicts, y, at a given time t as a conditionally independent observation from a latent conflict generating process. Thus,

$$y_t \sim Pois(\lambda_t) \quad (1)$$

$$\lambda_t = e^{r_t+\mu_t}, \quad (2)$$

where λ refers to the mean of the Poisson distribution.

The r_t term represents the autocorrelation in the conflict record. It is defined as a function of the previous level of the autocorrelation term, r_{t-1}, multiplied by a coefficient, ρ. Importantly, the model is stochastic and flexible enough to represent strictly autoregressive processes where ρ is between −1 and 1, and explosive or collapsing processes where ρ is greater than 1 or less than −1, respectively. This process can be expressed as follows,

$$r_t \sim N(\mu_r, \sigma_r) \quad (3)$$

$$\mu_r = r_{t-1}\rho \quad (4)$$

$$\sigma_r \sim Exp(\cdot) \quad (5)$$

$$\rho \sim N(\cdot) \tag{6}$$
$$r_0 \sim N(\cdot). \tag{7}$$

As this block of equations shows, there are several components to the autocorrelation process. The "$(\cdot)$" notation is a placeholder for standard distribution parameters, while $N()$ and $Exp()$ refer to the Normal and Exponential distributions, respectively. The autocorrelation process has to have an initial level, denoted r_0, which is then fed into the equation for r_1. This term has a normal prior distribution with prior parameters for the mean and standard deviation, which we set to 0 and 2, respectively, and its most likely value is estimated from the data. Similarly, the autocorrelation coefficient, ρ, has a normal distribution with priors we set to 0 and 2 as well. The standard deviation of the autocorrelation process, σ_r, was given its own exponential prior distribution instead of using a fixed parameter value so that it could be estimated from the data. We opted for the exponential distribution because standard deviations must be positive by definition. This parameter controls the smoothness of the autocorrelation function. A large standard deviation would indicate a highly variable conflict generating process, which would make it very difficult to discern covariate impacts from intrinsic stochasticity. We assumed, therefore, that the background autocorrelation process is fairly smooth, which is reflected in our choice rate parameter (0.75) for the exponential prior.

The regression term in our model is represented by the μ_t parameter. Commonly in regression models, this parameter would be defined as follows,

$$\mu_t = x_t\beta \tag{8}$$
$$\beta \sim N(), \tag{9}$$

where x_t is a covariate measurement at time t and β is a regression coefficient with a normal distribution—of course, x and β could be vectors referring to multiple covariates as well.

However, for the purposes of the present study, we needed to include thresholds for delineating extreme covariate values—the broken-stick regression (Feder, 1975, regarding broken stick models). Two thresholds were used to account for upper and lower extreme effects. These thresholds can be thought of as creating a set of conditions such that β could take on one value if x_t is above the upper threshold, τ^+; another value if it is below the upper yet above the lower threshold, τ^-; and, a third value if x_t is below the lower threshold. The thresholds define the points of articulation between the "broken sticks" (linear regression functions). We can represent this logic with different cases for μ_t:

$$\mu_t = \begin{cases} x_t\beta^+, & \text{if} \quad x_t > \tau^+ \\ x_t\beta, & \text{if} \quad \tau^- \le x_t \le \tau^+ \\ x_t\beta^-, & \text{if} \quad x_t < \tau^-, \end{cases} \tag{10}$$

given that $\tau^+ > \tau^-$. Assigning indicator functions, $I()$, to the cases makes for simpler computer code and can condense the above equations into a single one—these indicators are simply functions that equal 1 when a condition is met and zero otherwise, like a switch. Let $I^+(x_t)$ be a function that returns 1 when $x_t > \tau^+$ and zero otherwise. Along similar lines, let $I^-(x_t)$ return 1 when $x_t < \tau^-$ and zero otherwise. Then,

$$\mu_t = x_t(\beta + (\beta^+ I^+(x_t) + \beta^- I^-(x_t))), \tag{11}$$

which means that the model can fit different regression coefficients to different levels of the covariate using the mid-level coefficient, β, as a baseline. The other levels—β^+ and β^-—are then offsets from the baseline effect and have to be interpreted that way. These β parameters define the slopes of the articulating "sticks".

The thresholds have to be given sensible priors and, in practice, need to be structured in such a way that they maintain their order so that the model remains identifiable. To that end, we defined the upper threshold first and then established the lower threshold by defining a differential parameter, d, that would be subtracted from the upper threshold. By then constraining d to be positive and non-zero we could ensure that the thresholds are properly estimated and always uniquely identifiable. Thus,

$$\tau^+ \sim U(\cdot) \tag{12}$$
$$d \sim U(\cdot) \tag{13}$$
$$\tau^- = \tau^+ - d. \tag{14}$$

In these equations, $U(\cdot)$ refers to the uniform distribution with minimum and maximum bounds. Those boundaries are priors in the model. For τ^+, we set the minimum boundary to 0 and the maximum to 5. We used these values because the covariates (i.e., temperature reconstructions) were mean-centred and scaled, as explained earlier. So, a value of 0 would refer to the study-period average against which extremes would be measured. We used a value of 5 for the maximum because none of the scaled temperature series exceeded $|4|$ (akin to 4 standard deviations if the data were from a stationary normal distribution). The most extreme positive deviation, then, would have been upwards of 4, which meant that using 5 allowed for the possibility that the best fitting model included no upper threshold in the range of the observed data. The model, in effect, could push the boundary out of consideration altogether if such a very high boundary value had a higher likelihood than a lower one located within the range of the observed data.

For the lower boundary—defined by d—we used a minimum of 1 and a maximum of 15 to define the prior. Remember that this value, which is between 1 and 15, would be subtracted from the upper threshold to produce the lower one. The minimum, therefore, had to be greater than zero in order to avoid the boundaries being equal, again because they need to be uniquely identifiable. Additionally, the maximum needed to be great enough that the resulting lower boundary, τ^-, could plausibly reach beyond the minimum observed deviation. Put another way, whatever the value was for τ^+, d had to be large enough to potentially exceed the lowest covariate value. As noted, the observed minimum was close to −4. So, a reasonable range of probable values for d would need to include at least twice the highest potential value for τ^+. That is, $\tau^+ - d$ must be able to reach at least < -5, which meant d had to plausibly be ≥ 10.

Including thresholds this way had an important advantage. It allowed us to remain agnostic about the threshold values. This is because those thresholds would be estimated from the data along with the regression coefficients and parameters of the autocorrelation process. The posterior distributions for the thresholds and other parameters all reflect the distributions of most likely values given the observed data.

The Analyses

Importantly, prior to running our main analyses we first tested the broken-stick model with simulated data (**Supplementary Material**). The simulated data were generated with one of the temperature reconstructions and predetermined values for the true regression coefficient and thresholds in order to determine that the model works as expected. We explored a variety of values for these settings and the model worked in each case. That we used a real temperature reconstruction in the simulation implies that the model would indeed be capable of identifying an effect (and correctly estimating model parameters) if there was a clear signal in our real data.

Subsequently, we ran four analyses to test whether temperature extremes affected conflict levels in Europe during the second millennium CE. For each analysis, we compared the conflict record to one of the temperature reconstructions using the model described above. We then examined the posterior distributions for the regression coefficients and threshold parameters estimated with a Markov Chain Monte Carlo (MCMC) simulation. There were three regression coefficient posterior distributions for each analysis: one for the mid-range of the given temperature series (β); one for the upper range defined by the upper threshold (β^+); and one for the lower range defined by the lower threshold (β^-). We reasoned that if extreme temperature values had an impact on conflict levels, one or more of these posteriors should be non-zero at the 95% level in at least one analysis. That is, the 95% credible interval of the posterior distribution for at least one of the regression coefficients pertaining to at least one of the temperature series should exclude zero.

It should be noted that, in theory, estimates for the threshold parameters can potentially cause the model to "collapse" into a standard regression with only one informative regression coefficient. This would occur in the event that the most likely upper and lower thresholds were above and below the observed maximum and minimum deviations in a given temperature series. Effectively, this would imply that one regression coefficient adequately describes the relationship between a given temperature series and the conflict record over the whole range of observed temperatures—i.e., no threshold effects. Consequently, the MCMC would return posterior distributions that reflect the priors for the upper and lower regression coefficients: normal distributions with means of 0 and standard deviations of 100.

All the analyses were conducted using R (R Core Team, 2021). We used an MCMC simulation to estimate the posterior distributions for the model's parameters. The MCMC was performed with the Nimble package (de Valpine et al., 2021). Each MCMC simulation was run for at least 2,000,000 iterations. Convergence of the resulting MCMC parameter chains was determined by a combination of visual inspection and standard Geweke diagnostics (Geweke, 1992). The MCMC diagnostics, exploration of priors, and simulation test are all presented in the Supplementary Information associated with this manuscript. We also made use of the "ggplot2" (Wickham, 2016) and "ggpubr" (Kassambara, 2020) packages for plotting. R code and data are also available on Github (https://github.com/wccarleton/extreme-conflict) and have been archived with Zenodo (DOI TBD).

RESULTS

The model performed well with the simulated dataset. It was able to accurately estimate the regression parameters and threshold positions that we used to create the simulated count data (**Supplementary Material**). With this in mind, we are confident that the approach could identify a relationship between the climate records and the real conflict record, including adequate estimates for the thresholds, under the assumptions of model.

According to all four analyses, temperature variation had no significant effect on conflict levels. The coefficients for the three main regression parameters in each analysis—referred to above as β, β^+, and β^-—were all indistinguishable from zero (**Figure 2**). These results align with those of Carleton et al. (Carleton et al., 2021) regarding the impact of temperature variation more generally on second millennium European conflict levels.

Importantly for the present study, the results indicate specifically that extreme temperatures had no discernible impact on conflict levels. The posterior distributions for the upper and lower extreme value regression coefficients were estimated to be zero on average, as noted above. They also had variances that reflected the relevant priors (**Figure 2**). This means that there was insufficient information in the data to update those prior distributions. The reason for this, computationally, was that the highest likelihood thresholds were outside the range of observed temperature deviations (**Figure 3**). The upper threshold was estimated to be higher than the highest observed temperature deviation in each reconstruction (~ 3–5). Similarly, the lower threshold was estimated to be lower than the lowest observed temperature deviations (d~6–15). Thus, the MCMC determined that the most likely parameter values effectively excluded thresholds—it pushed those thresholds beyond the observed data. This meant that no threshold effects (β^+ and β^-) could be estimated. Instead, the optimal solution was one in which temperature deviations had no effect on conflict over the whole range of observed temperature values.

DISCUSSION AND CONCLUSION

In HBO's TV adaptation of the first novel in George R.R. Martin's *A Song of Ice and Fire* series, King Robert says to his friend and advisor Ned Stark, "(t)here's a war coming, Ned. I don't know when, I don't know who we'll be fighting; but it's coming." These lines convey something about the nature of warfare: it appears to inevitably arise from some inexorable process that is difficult to predict. For at least

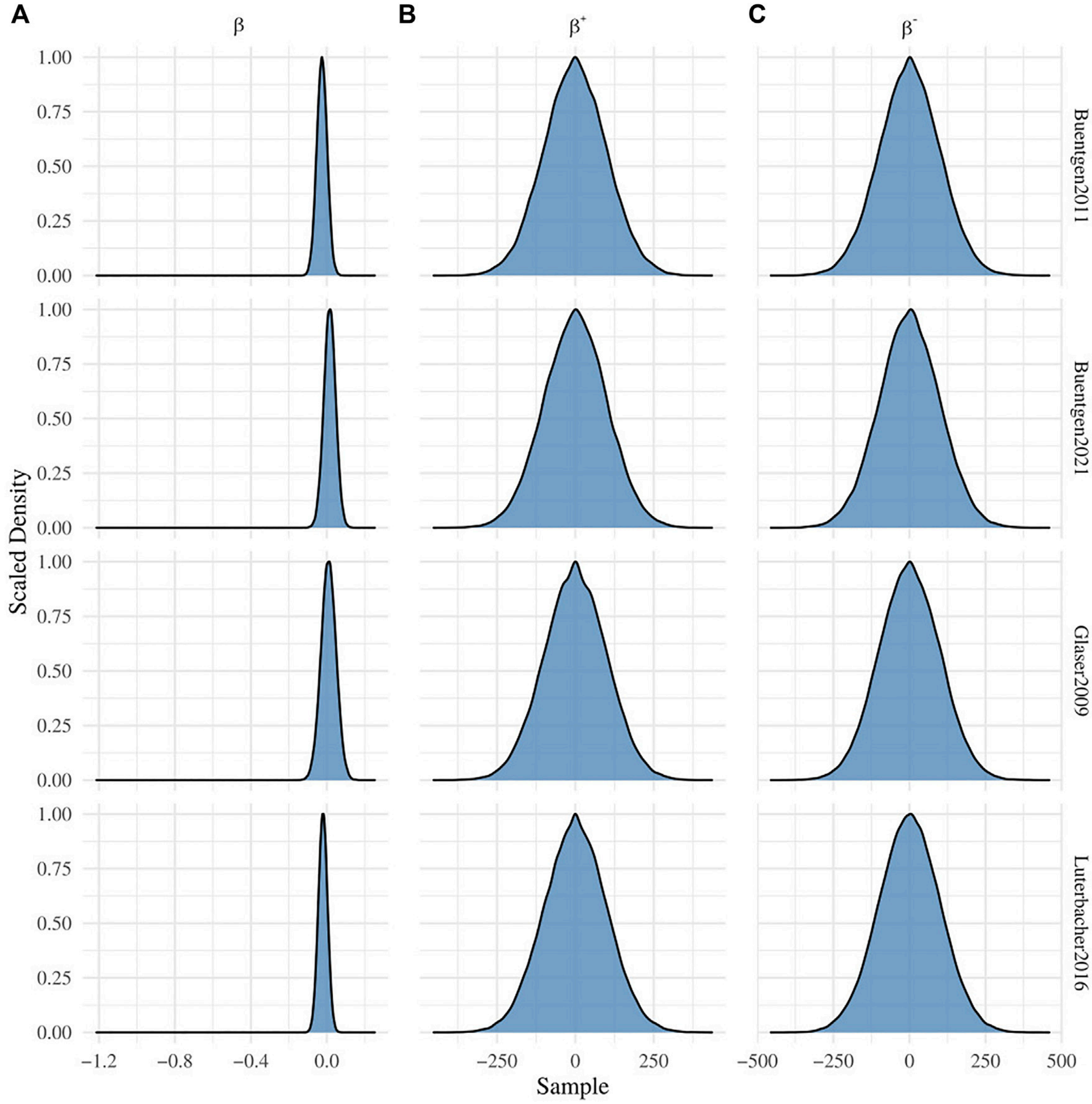

FIGURE 2 | Posterior densities for the key regression model parameters. Each row contains the posterior densities for the model involving the temperature reconstruction indicated by the labels on the right of the plots. All densities have been scaled to a maximum of one. The **(A)** column contains the posterior densities for the baseline regression coefficient; the **(B)** column contains the posterior densities for the regression coefficient when the given temperature record is above the most likely upper threshold; and the **(C)** column contains the posterior densities for the regression coefficient when the given temperature record is below the most likely lower threshold. Note that the x-axis appears large in the left column only because the MCMC sampled and retained some low values for that parameter. While the densities in that column are largely normal and centred on zero, we nevertheless include the low values for the sake of transparency and reporting accuracy.

60 years, social scientists have tried to understand that process by identifying the correlates of warfare, motivated largely by a desire to predict and ideally prevent the process from giving rise to violence in the future (Suzuki et al., 1998). Recently, climate change has taken a central position in the literature on this topic, with many scholars declaring that climatic changes can be expected to increase the risk of violent conflict (e.g., Burke et al., 2009, 2015; Hsiang et al., 2013; Schmidt et al., 2021).

The results of the present study are not consistent with this claim. They indicate that even extreme climate conditions (as indicated by temperature reconstructions) did not affect conflict levels in Europe during the second millennium CE. This finding is perhaps surprising. Not only were there substantial climatic fluctuations in Europe during the second millennium CE, but also for much of the time period in question European societies were substantially less technologically developed than present-day European societies and were also more reliant on local agriculture. Less complex technology and greater dependence on local resources, one would think, should have made European societies susceptible to environmental shocks, especially large ones. But that does not seem to be the case. There is no evidence that the Little Ice Age or any of the other environmental shocks that impacted Europe during the second millennium CE affected conflict levels on average.

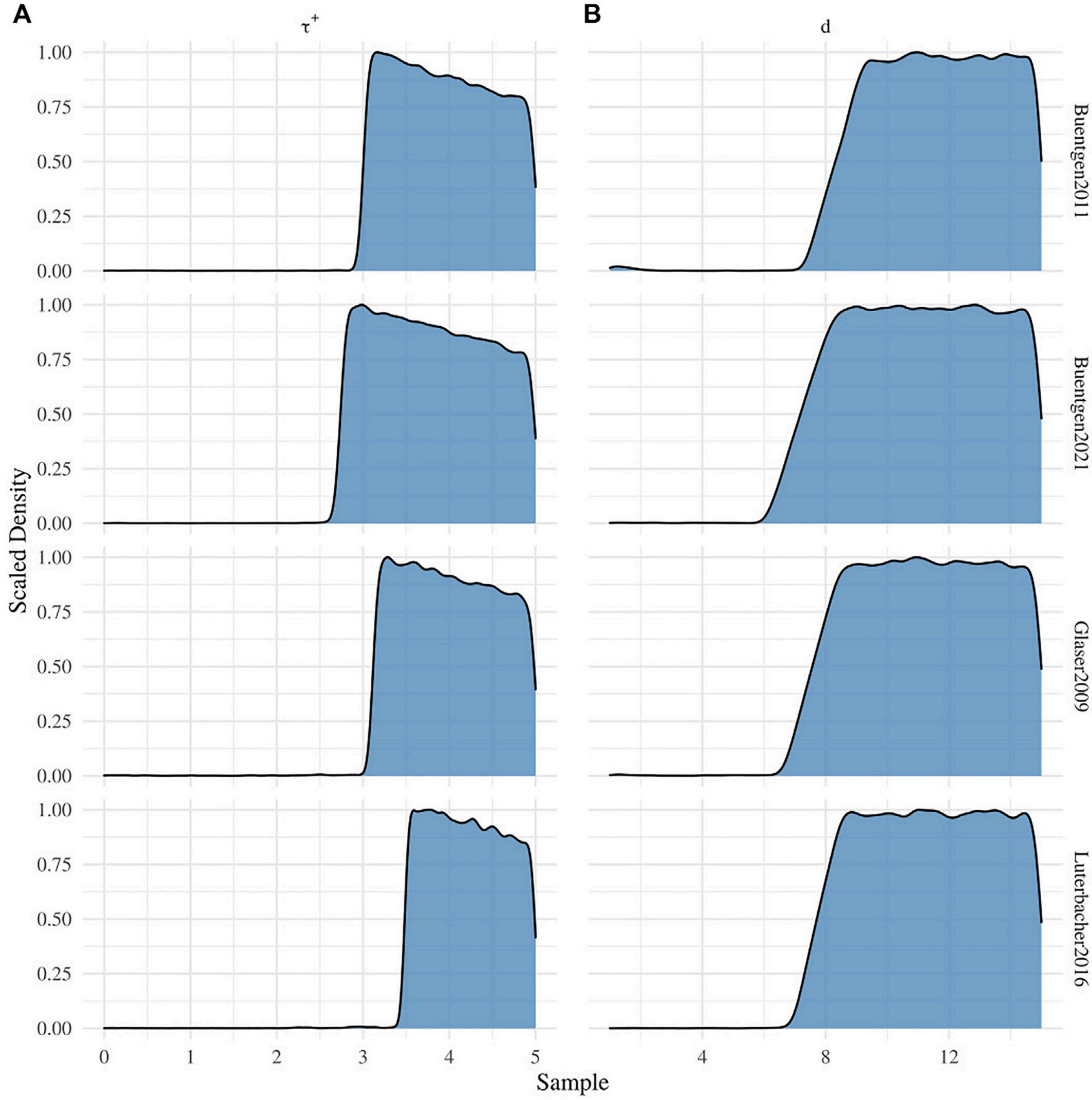

FIGURE 3 | Posterior densities for the estimated temperature threshold values. Each row contains the posterior densities for the model involving the temperature reconstruction indicated by the labels on the right of the plots. All densities have been scaled to a maximum of one. The **(A)** column contains the posterior density estimates for the upper threshold value, and the **(B)** column contains the estimates for the difference between the upper and lower threshold.

Why did our analysis fail to identify an impact of extreme climatic events on conflict levels in Europe during the second millennium CE? There are at least six explanations that are worth considering, some of which we alluded to earlier. The first three we think can be discounted by careful reasoning. The last three, however, are harder to eliminate at present and suggest avenues for future research.

The first explanation—one we think can be discounted—involves sampling biases in the conflict record. As explained earlier, the conflict data we analysed were compiled from authoritative conflict databases. But, since no historical database is likely to be complete, it is possible that the record we analysed is missing conflict events for several reasons. Not all conflicts that actually occurred were necessarily recorded, for example, and more recent periods are likely to be better represented because of document survival biases or other period-specific differences in reporting. Spatial gaps may be present in the data as well. Some sub-regions in western Europe may have been more important to historians and chroniclers, such as regions that were economically and politically important to ruling elites. In addition, the density of surviving historical documents varies spatially within Europe, with early historical coverage concentrated around major urban centers and in the south, particularly France and Italy. Thus, we should expect the Tol and Wanger (2010) conflict record to be incomplete and biased. However, there is reason to believe that regional-scale trends in second millennium conflict levels are likely captured by the Tol and Wagner (2010) record. Most major conflicts involved Europe's largest, most literate societies. So, the most significant conflicts were probably recorded in a sufficient number of archives that knowledge of them survived to the present. This means that trends in economically and politically important conflicts are likely reflected in the record we analysed. There is also no obvious trend(s) in the record that might indicate a persistent document survival bias (**Figure 1**). Moreover, geographic unevenness would not be a significant problem for our analysis. If conflict levels were substantially affected by temperature variation in general, then we would expect the conflict records of any sizable sub-region within Europe to respond in the roughly same way to region-wide temperature changes.

Another potential explanation that we think can be discounted involves biases in the four temperature time-series. The temperature proxies we analysed are based on historical documents, tree-ring widths, or a combination of the two. Neither primary source is evenly distributed in space or time within Europe and, therefore, they undoubtedly contain biases. These biases will be acute for short term temperature fluctuations and sub-regions within western Europe. Recent research has also demonstrated that methodological and analytical choices involved in the production of tree-ring-based temperature reconstructions affect the patterns present in those reconstructions (Büntgen et al., 2021). Variability with respect to analytical choices of researchers—all of which may be justifiable—can lead to biases in and differences among individual reconstructions even when they are based on overlapping source data (some of the same trees or trees from the same regions). Despite these known biases, however, the reconstructions all appear to contain the same long-term, large-scale signal. They have each been shown to correlate positively with temperature variations during instrumental periods with Pearson's R values ranging from 0.7 to 0.8. One of the reconstructions in particular—the one created by Büntgen et al. (2021)—averages out methodological differences and correlates very well (0.79, $p < 0.001$) with instrumental observations at different scales. It also has autocorrelation properties that match those of instrumental observations, and it has considerable predictive power for 20th and 21st century temperatures in the Northern Hemisphere. Taken together, the diagnostics performed by the scientists who produced the reconstructions appear to reflect their target reasonably well. Thus, despite their imperfections, the temperature time-series very likely capture regional trends and variations during the Common Era—this is especially true for the newest ensemble reconstruction produced by Büntgen et al. (2021). It is unlikely, then, that at the scale and resolution of our analysis, biases present in the temperature reconstructions account for our findings.

A third potential explanation, and the last we find unconvincing, is that we looked at the wrong type of climate data. The main agriculture staple in Europe throughout most of the second millennium was cereal grain (e.g., wheat, barley, rye, and oats) (Alfani and Ó Gráda, 2018; Ljungqvist et al., 2021). Yields for the main grain crops are affected by climate conditions, especially significant deviations from optimal conditions (Zscheischler et al., 2017). But, sensitivity to temperature specifically varies with crop type and region (Ljungqvist et al., 2021). Wheat, for example, is known to be quite tolerant of temperature deviations within the range of variation indicated by the reconstructions, even during much of the Little Ice Age (Porter and Gawith, 1999). In contrast, precipitation and, crucially, the timing of precipitation is very important for determining wheat yields (Brooks et al., 2018; Alfani, 2010). Thus, temperature may simply be the wrong covariate for investigating climate-conflict dynamics in Europe given that different crops react differently to temperature deviations. On its own, though, this explanation is wanting. Temperature variation is often used as a general climate indicator. The reason for this is that average temperatures (average over large areas and long spans of time) are associated with certain weather patterns and, so, major deviations in average temperatures are likely to entail changes in those patterns (Arnell et al., 2019). Extreme temperature deviations, therefore, could be expected to lead to significant changes in precipitation amounts and annual distributions of precipitation. Because both precipitation extremes—flooding on the one hand, and drought on the other—would have been bad for any cereal grain production, the temperature proxies we looked at should still be relevant. Essentially, the reconstructions we used can be thought of as general climate indicators and extreme values would likely have meant local, short-term disruptions to "normal" weather patterns. Crucially, the specific direction of that disruption with respect to precipitation—more rainfall or less—is not as important as the fact that a major disruption occurred. Substantial perturbations in either direction would likely have affected grain yields even though temperature may not have been the proximate cause (Zscheischler et al., 2017).

The fourth potential explanation—the first that we think is plausible—is that spatial aggregation of the data masked the true climate-conflict dynamics. This could occur in at least two ways. A change in temperature can lead to different effects in different locations (Mahlstein et al., 2013). A change in average European temperature may have produced different localised responses. Some areas might have been negatively affected while others were not. In fact, some research has indicated that northern and southern Europe will likely experience dramatically different outcomes as a result of continued global warming, with water shortages expected in the south and an increase in agricultural land in the north (e.g., Bindi and Olesen, 2011). A similar pattern of regional differentiation may have occurred in the past, meaning that northern and southern European societies may have experienced very different agro-economic effects from changes in average temperature (Alfani, 2010; Alfani and Ó Gráda, 2018). Consequently, spatially heterogeneous climate-conflict relationships may be obscured by the spatially aggregated data. Some areas may have experienced a higher level of conflict while others did not for a given change in regional average temperatures. In a related way, spatial aggregation of the conflict record may have masked the impact of climate on conflict levels. Prior to the First World War, conflicts often only involved two main groups. Potentially, combining these events into a single series makes it harder to adequately model the conflict generating process because not all groups included in the aggregate dataset were equally likely to engage in conflict with the other groups represented in the dataset. For example, France would have been less likely to go to war with Poland, in part because they share no borders. In aggregate, then, differences between the likelihood of conflicts between pairs of combatants could average out the impacts of climate, which were also spatially aggregated in our analysis. Essentially, the likelihood that any given pair—or "dyad"—would have actually engaged in violent conflict cannot be controlled for. A dyad approach has, for this reason, become common in research on modern international conflict and politics (Croco and Teo, 2005; Gleditsch et al., 2014; Schmidt et al., 2021). In a dyad study, the unit of analysis is conflict in a given time interval between specified pairs of potential combatants. That way, locally-specific climate effects can be compared to conflicts between groups where at least one of the groups is certainly affected by the given climate variable and the groups in question formed a plausible dyad in the first place.

The fifth potential explanation is that the model we used is too simplistic to account for climate–conflict dynamics. Climate-change driven resource shortages may be involved in conflict levels in more complex ways than can be evaluated with linear or even broken-stick models. Resource shortages, for example, could be both a cause and consequence of conflict. A crop shortfall could put additional pressure on a leader, affecting their decision-making vis-a-vis engaging in conflict. But at the same time, launching and sustaining conflicts consumes resources. In the Late Medieval period, it would not have been uncommon for bands of soldiers to extract resources from the area they happened to be moving through or positioned in (Howard, 2009; Alfani, 2010). With enough troops or a long enough campaign, the draw on local resources would have been significant. Even without bad weather, then, local shortages could arise as a consequence of conflict. Additionally, war often would have disrupted trade, which would remove a key resource buffer—local shortfalls could not be compensated by buying goods from elsewhere (Howard, 2009). In more recent periods, conflict still drained resources, but supplies were centrally coordinated rather than having soldiers simply pillage what they needed from locals. Nevertheless, conflict is costly and can draw down a society's resources, increasing the risk of critical shortages with or without additional shocks from bad weather. This dynamic creates a feedback that could be hard to detect empirically even at an annual resolution and may require more complex statistical models. Along similar lines, it may be necessary to take into account additional mediating variables—e.g., population size, carrying capacity, political history—before the impact of climate change on conflict levels can be detected (Schmidt et al., 2021). Climate change including extreme events like the Little Ice Age may only impact conflict levels when a society is near its effective carrying capacity, which is a function of technology, population size, and the ability of socioeconomic institutions to buffer shortages (Alfani, 2010; Alfani and Ó Gráda, 2018). Without including interactions between these potential mediators and the climate covariate, the impact of climate change on conflict levels may be obscured by all of the other factors driving variation in the latter.

The final plausible possibility we have identified is that the scarcity mechanism may simply be insufficient for explaining long-term variations in conflict levels. This could be true irrespective of whether the scarcity is driven by average or extreme environmental conditions. Humans often fight for social, political, and economic reasons having little to do directly with resource shortages. The aforementioned Wars of the Roses are a prime example. The wars are generally thought to have erupted out of contentions over rival claims to the English throne (Hicks, 2012). Resources undoubtedly played a role, of course. In a sense, the throne is the ultimate resource (access to power, influence, and wealth) and resources were required to take it. But, the elite houses who wanted it had sufficient wealth that scarcity was unlikely to be a proximate motivating factor. If anything, engaging in the conflict over the crown created opportunity costs and resulted in financial losses, not to mention incurring the risk of imprisonment and death—"When you play the game of thrones, you win or die", declared Cersei Lannister (Martin, 1996). Thus, while the crown was a prized, scarce resource, desire for it was not needs-based. Instead, actors fought for this resource out of greed, and it was largely insensitive to the weather—a drought or flood would not have changed the crown's availability. A simple scarcity mechanism might, therefore, be insufficient to explain the conflicts, at least where "scarcity" refers only to crop yields or abstractly to economic resources.

We are left, then, with the puzzle we started with: How is it that significant climate changes apparently had no impact on second millennium CE European conflict incidence? The short answer, we think, may be that conflict happened mostly for other reasons, as we just explained. But, the other explanations we discussed above suggest a few avenues for future research. One of these is to examine the impact of other climate variables, such as rainfall. Another possibility is to look at additional mediating variables such as population size and political histories. A third avenue is to disaggregate the climate and conflict data into regional datasets. Lastly, future research could potentially involve more complex statistical models designed to include feedback between resources and conflict levels; computer simulations and purely mathematical models may be useful in this regard.

Even if climate change did have no impact on conflict incidence, it is worth highlighting that other dimensions of conflict may have been affected. The frequency of warfare is only one dimension of conflict within and between human groups. Others include conflict onset, duration, category, and magnitude. Each of these dimensions will be harder to evaluate than simple incidence. Onset and duration are probably the easiest to explore if precise start and end dates are available for each conflict. Evaluating different categories of conflict, say rebellion versus inter-state warfare, would involve more detailed historical research, but it may be possible to achieve a high level of confidence about the categorizations. Magnitude, unfortunately, would be much harder to measure for historical conflicts since any appropriate metric, like number of battle deaths, will probably be hard to estimate for pre-modern periods. Despite these potential challenges, though, research into the impact of climate change on these other dimensions of conflict over the long-term would be informative and important. If a relationship between climate change and one of these other dimensions was found, the fact that incidence appears to be unaffected would be less puzzling—such a finding would mean that intuitively appealing explanations like the scarcity mechanism may hold, just not in the most obvious way.

Despite not answering the question that motivated our study, our results have implications for our understanding of the impact of extreme events on society. Climatological extremes may have impacted societies in particular ways without those impacts reverberating to every potential domain. There is evidence, for instance, that the cold of the Little Ice Age was recognised as intense and anomalous by people who experienced it firsthand. The historical record contains references to water bodies freezing unexpectedly along with frequent mentions of crop failures, famines, and farms being deserted during this period (e.g., Holopainen and Helama, 2009; Alfani, 2010; Lockwood et al., 2017; Alfani and Ó Gráda, 2018; Athimon and Maanan, 2018). So, it seems safe to assume there were impacts. And yet our study has revealed that extreme temperature deviations had no clear impact on regional conflict levels. We can, therefore, infer that while extreme climate events likely did have some impact on European societies during the second millennium, the effects were circumscribed and contingent. An implication of this is that context matters in the analysis of the impact of extreme climatic events, possibly as much as the extreme nature of the events themselves. What makes a climatic event extreme for human societies may have more to do with its ultimate effects than its intrinsic character.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

WC, MC, MS, and HG collectively conceived of the research and study design. WC and MS gathered the required data. WC developed the R code and ran the analyses. WC, MC, MS, and HG collectively interpreted the results. WC led the writing of this manuscript with contributions from MC, MS, and HG.

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The Stalagmite Record of Southern Arabia: Climatic Extremes, Human Evolution and Societal Development

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The fluctuating climatic conditions of the Saharo-Arabian deserts are increasingly linked to human evolutionary events and societal developments. On orbital timescales, the African and Indian Summer Monsoons were displaced northward and increased precipitation to the Arabian Peninsula which led to favorable periods for human occupation in the now arid interior. At least four periods of climatic optima occurred within the last 130,000 years, related to Marine Isotope Stages (MIS) 5e (128–121 ka BP), 5c (104–97 ka BP), 5a (81–74 ka BP) and 1 (10.5–6.2 ka BP), and potentially early MIS 3 (60–50 ka BP). Stalagmites from Southern Arabia have been key to understanding climatic fluctuations and human-environmental interactions; their precise and high-resolution chronologies can be linked to evidence for changes in human distribution and climate/environment induced societal developments. Here, we review the most recent advances in the Southern Arabian Late Pleistocene and Early Holocene stalagmite records. We compare and contrast MIS 5e and Early Holocene climates to understand how these differed, benchmark the extremes of climatic variability and summarize the impacts on human societal development. We suggest that, while the extreme of MIS 5e was important for *H. sapeins* dispersal, subsequent, less intense, wet phases mitigate against a simplistic narrative. We highlight that while climate can be a limiting and important factor, there is also the potential of human adaptability and resilience. Further studies will be needed to understand spatio-temporal difference in human-environment interactions in a climatically variable region.

Keywords: Arabia, monsoon, dispersal, *Homo sapiens*, stalagmite, isotope, climate

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INTRODUCTION

The fluctuating palaeoclimate conditions of Southern Arabia are frequently related to broad changes in hominin distribution as well as regional societal developments. Intensifications and expansions of the monsoon domain increased precipitation across Southern Arabia during periods of increased solar insolation, following orbitally-paced cycles (Burns et al., 1998; Burns et al., 2001; Fleitmann et al., 2003b; Fleitmann et al., 2011; Parton et al., 2015b; Jennings et al., 2015; Nicholson et al., 2020). During the last 130 kyrs, at least four prolonged periods of increased precipitation have been identified and dated to MIS 5e (128–121 ka BP), MIS 5c (104–97 ka BP), MIS 5a (81–74 ka BP) and the Early Holocene (10.5–6.2 ka BP), and perhaps early MIS 3 (60–50 ka BP), each lasting for a few millennia (Burns et al., 2001; Fleitmann et al., 2011; Parton et al., 2013; Nicholson et al., 2020). These extreme increases in rainfall permitted the formation of large, deep and perennial lakes and other

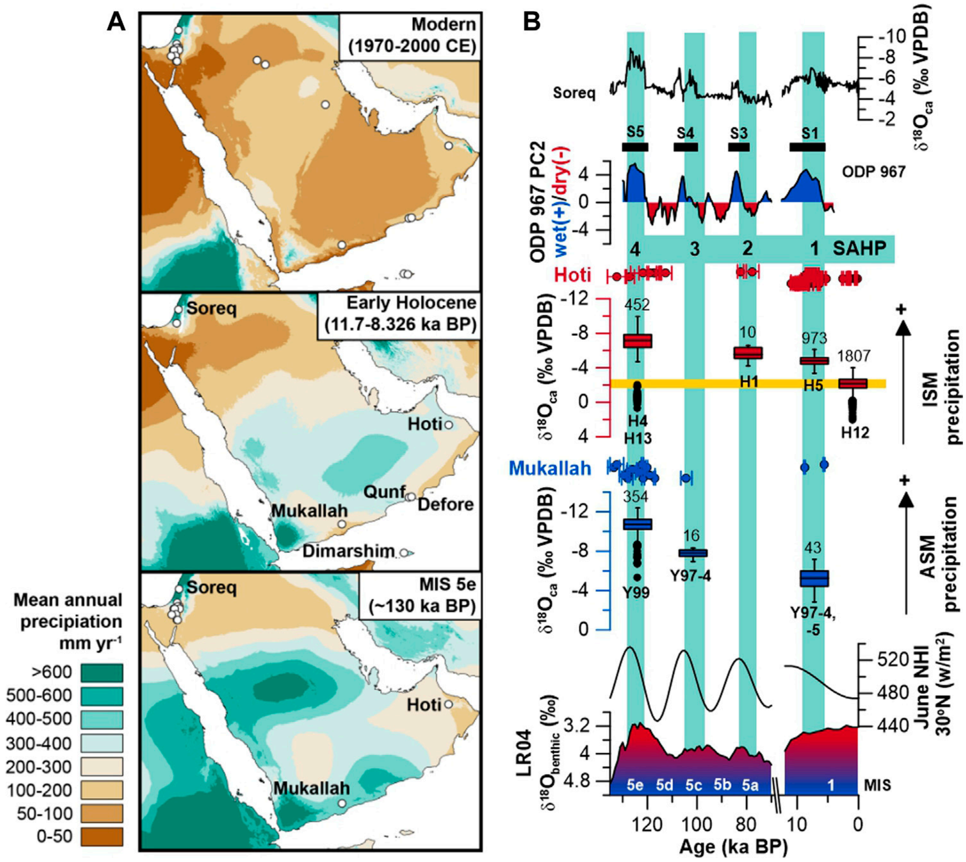

FIGURE 1 | (A) simulated mean annual precipitation maps of the Arabian Peninsula for modern (Fick and Hijmans, 2017), Early Holocene (Fick and Hijmans, 2017; Fordham et al., 2017; Brown et al., 2018) and MIS 5e (Otto-Bliesner, 2006; World Clim, 2015) periods. Speleothem cave sites (white circles) show distribution of fossil stalagmites (modern) and their respective growth periods (Early Holocene and MIS 5e). **(B)** box-whisker plots of stalagmite $\delta^{18}O_{ca}$ values from Hoti (red) and Mukallah (blue) caves vs. the Soreq Cave $\delta^{18}O_{ca}$ curve (Bar-Matthews et al., 2003; Grant et al., 2012; Grant et al., 2016), ODP 967 PC2 wet/dry index and sapropel layers (Grant et al., 2017), low-latitude (30°N; Berger and Loutre, 1991) and global ice-volume ($\delta^{18}O_{benthic}$; Lisiecki and Raymo, 2005). Black circles denote statistically extreme values. Sample counts and stalagmite specimens are given above and below boxes, respectively. See **Supplementary Material** for results of ANOVA and Wilcoxon rank sum test. The yellow bar denotes the range of modern stalagmite $\delta^{18}O_{ca}$ values from Hoti Cave (Fleitmann et al., 2003a; Fleitmann et al., 2011). ^{230}Th ages and age uncertainties (2σ) for Mukallah (blue) and Hoti (red) cave speleothems are given above their respective boxplots (Fleitmann et al., 2011; Nicholson et al., 2020). Relevant Marine Isotope Stages are provided using the taxonomy of Railsback et al. (2015).

waterbodies in the now arid interiors (Rosenberg et al., 2011; Rosenberg et al., 2012; Petraglia et al., 2012; Rosenberg et al., 2013; Parton et al., 2013; Parton et al., 2015a). As well as increased surface water availability and refilling of aquifers, increased rainfall led to "greening" events of Arabia, in which grassland environments expanded into the now arid desert interiors and supported the spread of large mammals and human settlement (Rose et al., 2011; Petraglia et al., 2012; Groucutt et al., 2015; Stimpson et al., 2016; Groucutt et al., 2018; Stewart et al., 2020a; Stewart et al., 020b; Groucutt et al., 2021; Scerri et al., 2021).

Speleothems (stalagmites, stalactites and flowstones) have been key sources of terrestrial palaeoclimatic information in Southern Arabia. Unlike other terrestrial archives (e.g., lacustrine and alluvial records), their subterranean location protects them from desert weathering conditions (Burns et al., 1998; Vaks et al., 2010; El-Shenawy et al., 2018; Burstyn et al., 2019; Henselowsky et al., 2021). Additionally, speleothem growth requires a positive precipitation-evaporation balance, and can thus inform the timing of prolonged soil humidity above the cave. Stalagmites are particularly useful for palaeoclimate reconstructions; their laminated growth permits the development of precise climatic records through U-Th dating and analyses of calcite oxygen ($\delta^{18}O_{ca}$) and carbon ($\delta^{13}C_{ca}$) stable-isotopes, which can be linked to archaeological (and historical) records. Since 1998, a series of publications have provided a unique insight into the palaeoclimate of Southern Arabia using stalagmites collected from Hoti (23.08° N, 57.35° E), Mukallah (14.91° N, 48.59° E), and Qunf (17.16° N, 54.3° E) caves (**Figure 1A**). Specific site descriptions of the caves are available elsewhere (Burns et al., 1998; Neff et al., 2001; Fleitmann et al., 2003b; Fleitmann et al., 2003a; Fleitmann et al., 2007; Fleitmann et al., 2011). Here, we summarize these works and provide a comparison between two of these climatically extreme periods: MIS 5e and the Early-Mid Holocene.

TIMING OF INCREASED RAINFALL DURING THE LAST 130 KYRS

At least four South Arabian Humid Periods (SAHPs) occurred during the Late Pleistocene and Early Holocene. At Mukallah Cave, stalagmite deposition was recorded during MIS 5e (~128–121 ka BP; SAHP 4), 5c (~104–97 ka BP; SAHP 3), and the Early Holocene (~10–6 ka BP; SAHP 1). At Hoti cave, stalagmite deposition occurred during MIS 5e, 5a (~85–74 ka BP; SAHP 2) and the Holocene (10–5.2 ka BP and 2.6 ka BP to present) (Fleitmann et al., 2007). Stalagmite growth is also recorded at Qunf Cave (Q5), Defore Cave (S3, S4, S6, S9) and Dimarshim (D1). An almost continuous climatic record (~10.6–0.3 ka BP) is provided by Q5, whereas S3 and S4 are only active before and after SAHP 1 and D1 grows from ~4.2 to 0 ka BP. Determination of stalagmite fluid inclusion water $\delta^{18}O$ and δD values from Mukallah and Hoti caves have shown that increased precipitation during MIS 5e and the Early-Mid Holocene were delivered by the African Summer Monsoon (ASM) and the Indian Summer Monsoon (ISM) (Fleitmann et al., 2003b; Nicholson et al., 2020). This is in good coherence with other records of ASM and ISM intensity, particularly sapropel layers S5 (128.3–121.5 ka), S4 (107.8–101.8 ka), S3 (85.8–80.8 ka) and S1 (10.5–6.1 ka) from Mediterranean Sea core ODP 967 (Rohling et al., 2015; Grant et al., 2017).

Stalagmite distribution, size and shape can reveal changes in precipitation amounts in arid environments. An estimated annual precipitation >300 mm yr^{-1} for SAHPs was established using the distribution of active stalagmite growth in the Negev desert (Vaks et al., 2006; Vaks et al., 2010; Vaks et al., 2013), suggesting palaeo-precipitation doubled current amounts at Mukallah and Hoti Caves (Fleitmann et al., 2011; Nicholson et al., 2020; **Figure 1A**). MIS 5e stalagmites (Y99 and H13) are large (width >30 cm; and height >1 m), suggesting annual rainfall was considerably higher than 300 mm yr^{-1}. This is supported by deposition of a large MIS 5e flowstone at Hoti Cave, which indicates flowing water on the cave floor, deposition fluvio-lacustrine sediments in Northern Arabia (Rosenberg et al., 2013; Parton et al., 2018) and Southern Arabia (Rosenberg et al., 2011; Rosenberg et al., 2012; Matter et al., 2015; Parton et al., 2015a), the deposition of sapropel S5 caused by ~8 times higher Nile outflow (Amies et al., 2019) and modeled rainfall amounts of 300–600 mm yr^{-1} during MIS 5e (Otto-Bliesner, 2006; Jennings et al., 2015; **Figure 1B**). Stalagmites from later growth periods, such as Y97-4 and Y97-5, are comparatively smaller (Fleitmann et al., 2011), suggesting that annual rainfall was less than during SAHP 4. This is consistent with modeled Early Holocene rainfall of 200–300 mm yr^{-1} over Mukallah Cave (Fordham et al., 2017; Brown et al., 2018).

Differing rainfall amounts between SAHPs are confirmed by stalagmite $\delta^{18}O_{ca}$ values, which are influenced by the intensity of ASM (Mukallah) and ISM (Hoti) rainfall (Fleitmann et al., 2011; Nicholson et al., 2020). SAHP 4 (MIS 5e) has the most negative $\delta^{18}O_{ca}$ values (increased rainfall), whereas SAHP 1 (Holocene) has the most positive $\delta^{18}O_{ca}$ values (drier conditions) (Nicholson et al., 2020). The competing effects of high-latitude glacial-boundary conditions and low-latitude insolation are both considered to control the expansion, contraction and intensity of the monsoon domain (Burns et al., 2003; Cheng et al., 2009a; Beck et al., 2018) and are key differentiating factors of SAHPs (Nicholson et al., 2020). While precipitation intensities of SAHP 4, 3 and 2 follow the declining intensity of glacial-boundary minima, SAHP 1 contradicts this trend, as positive $\delta^{18}O_{ca}$ occurred during an interglacial maximum. Instead, SAHP $\delta^{18}O_{ca}$ values consistently follow the pattern of declining low-latitude summer Northern Hemisphere Insolation (NHI) maxima, which are regulated on orbital eccentricity (100 kyr) and precession (21 kyr) cycles (**Figure 1B**). Low-latitude insolation is a key control on the interhemispheric pressure gradient, whereby greater solar heating of the Tibetan Plateau and northern Indian Ocean results in enhanced low pressure and intensification of northern hemisphere cyclones (Burns et al.,

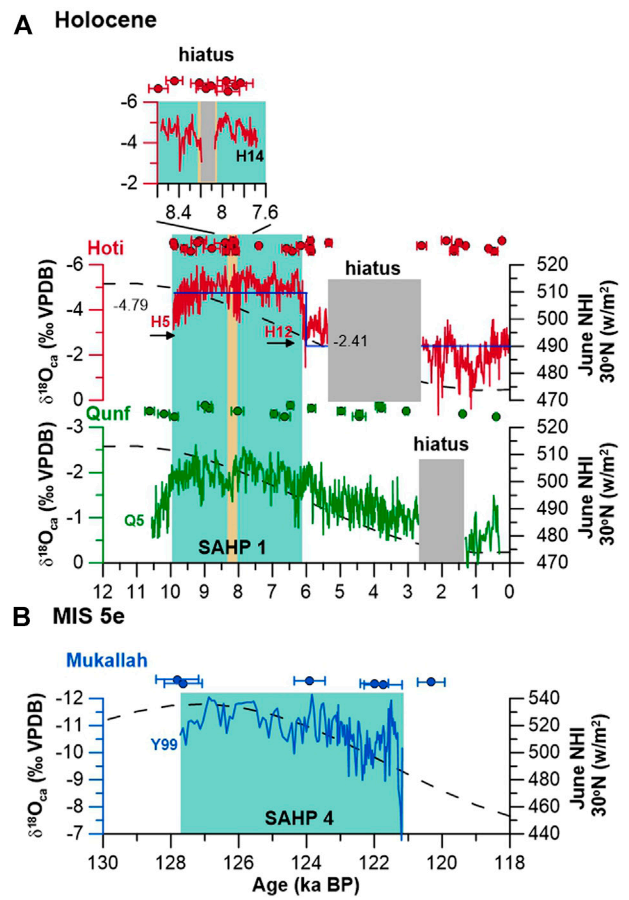

FIGURE 2 | (A) High-resolution $\delta^{18}O_{ca}$ stalagmite values for the Holocene (H5, H12, H14 and Q5). Blue lines for H5 and H12 represent means before and after the change-point at ~6.2 ka BP. The change-point was identified using the changepoint package for R (Killick et al., 2016). ^{230}Th ages (cricles) and uncertainty (2σ) bars are given above their respective curves. **(B)** High-resolution $\delta^{18}O_{ca}$ stalagmite values for MIS 5e (Y99). ^{230}Th ages and uncertainties (2σ) from Nicholson et al. (2020) (circles) used to create the StalAge (Scholz and Hoffmann, 2011) age-depth model (Nicholson et al., 2021a).

2003; Fleitmann et al., 2007; Parton et al., 2015b; Beck et al., 2018). Thus, comparatively low insolation values during SAHP 1 are matched by a weaker response of monsoon intensity compared to preceding SAHPs. Importantly, SAHPs had differing climatic conditions and likely brought unique environmental responses and challenges for human populations.

RAINFALL TRENDS DURING MIS 5E AND THE HOLOCENE

MIS 5e

Precise ^{230}Th ages of stalagmites combined with $\delta^{18}O_{ca}$ values have provided records of MIS 5e and Holocene climatic variability. The Y99 (Mukallah) $\delta^{18}O_{ca}$ and $\delta^{13}C_{ca}$ records cover SAHP 4 in Yemen, with onset and termination of stalagmite growth at 127.8 and 121.1 ka BP (Nicholson et al., 2020; Nicholson et al., 2021a). There are four distinct features of the Y99 $\delta^{18}O_{ca}$ curve: 1) onset of enhanced rainfall is characterized by negative $\delta^{18}O_{ca}$ values, suggesting this was abrupt, perhaps within <500 years as suggested by other ASM records (e.g., Bar-Matthews et al., 2003). 2) There is a clear relationship to the July 30°N isolation curve, demonstrating rainfall intensity was modulated by low-latitude insolation (**Figures 1B**, **2B**). 3) While there is considerable variability, $\delta^{18}O_{ca}$ values are consistently more negative (wetter conditions) than succeeding wet phases. 4) There is an abrupt increase in $\delta^{18}O_{ca}$ and $\delta^{13}C_{ca}$ (drier conditions) at the termination of the wet period as the tropical rain-belt retreated southwards and annual rainfall fell below the threshold for large stalagmite formation (Nicholson et al., 2020). Additionally, sub-annually resolved H13 (Hoti) $\delta^{18}O_{ca}$ and $\delta^{13}C_{ca}$ records shows MIS 5e was characterised by increased seasonality (wetter summers and drier winters) dominated by a monsoon-driven precipitation regime (Nicholson et al., 2020). This was likely echoed by a seasonal vegetation response, as indicated by the presence of C4 plants (Bretzke et al., 2013; Nicholson et al., 2020), with potentially significant implications for animals and human hunter-gatherers.

Early-Mid Holocene

The Early-Mid Holocene is characterized by another period of increased rainfall in Arabia, known as the Holocene Humid Period (HHP), or SAHP 1 in Southern Arabia (Burns et al., 1998; Burns et al., 2001; Fleitmann et al., 2003a, Fleitmann et al., 2007; Fleitmann and Matter, 2009; Lézine, 2009; Rosenberg et al., 2011; Engel et al., 2012; Rosenberg et al., 2013). Stalagmite records from Hoti (H5 and H12), Qunf (Q5) and Defore (S3 and S4) caves provide information of rainfall variability throughout the Holocene. While at Hoti Cave $\delta^{18}O_{ca}$ values show shifting dominances of winter (derived from the Mediterranean Sea) vs. summer (derived from the Indian Ocean) precipitation, Qunf Cave $\delta^{18}O_{ca}$ values record ISM precipitation intensity. Whereas Hoti Cave $\delta^{18}O_{ca}$ values indicate that winter precipitation has been dominant over the last ~6 kyrs, the Early Holocene is marked by more negative $\delta^{18}O_{ca}$ values reflecting increased summer precipitation (Neff et al., 2001; Burns et al., 2003; Fleitmann et al., 2007; Shakun et al., 2007). This is coeval to more negative $\delta^{18}O_{ca}$ values at Qunf Cave which indicate an intensification of the ISM. At both caves $\delta^{18}O_{ca}$ values show:

1) Intensification of summer precipitation between 10.6 and 9.4 ka BP, which slightly lags low-latitude insolation due to comparatively high glacial-boundary forcing (Fleitmann et al., 2007). 2) Considerable multi-decadal variability within both H5 and Q5, displaying clear relationships with GRIP, NGRIP and DYE-3 ice-core $\delta^{18}O$ records (Johnsen et al., 2001; Neff et al., 2001; Fleitmann et al., 2003a; Fleitmann et al., 2007; Fleitmann and Matter, 2009). More negative ice-core $\delta^{18}O$ (colder northern-hemisphere conditions) were reflected by more positive (drier conditions) stalagmite $\delta^{18}O_{ca}$ values. 3) A distinct increase of $\delta^{18}O_{ca}$ values (drier conditions) is observed between ~8.2–8.0 ka BP and is related to the so-called "8.2-kyr event"; a global climatic event caused by the collapse of Atlantic Overturning Meridional Circulation (AMOC) due to draining of Hudson Bay glacial lakes and freshwater influx into the Atlantic (Barber et al., 1999; Kobashi et al., 2007). $\delta^{18}O_{ca}$ values of H14 and H5 (Hoti Cave) show this period was characterised by a weakening of rainfall and led to a hiatus of H14 growth (Cheng et al., 2009b). 4) Summer precipitation declines at ~6.2 ka BP. At Qunf Cave, this decline is gradual and closely follows the 30°N isolation-curve (for an extended discussion, see Fleitmann et al., 2007). At Hoti Cave, this precipitation decline is more abrupt (identifiable by change point analysis; **Figure 2A**) and related to winter rainfall becoming the dominant source of precipitation in northern Oman (Fleitmann et al., 2007). As Hoti Cave provides solid timing on the shifting dominance of winter vs. summer precipitation, the H5 record has been used to define the duration of SAHP 1 and is consistent with the ^{230}Th ages of Holocene stalagmites from Mukallah Cave (Fleitmann et al., 2011; Nicholson et al., 2020). Whereas the Y99 record indicates SAHP 4 (during MIS 5e) persisted for ~6.5 kyrs, the Hoti Cave composite record indicates SAHP 1 lasted for a shorter period of ~4 kyrs.

These patterns follow established conditions during SAHP 1, which in Southern Arabia are also evidenced by vegetation expansion (Fuchs and Buerkert, 2008), vegetation that requires adequate precipitation (Parker et al., 2004), and palaeolake and river formation (Farraj and Harvey, 2004; Preston, 2011; Berger et al., 2012). Across Arabia, these changes are asynchronous (Preston and Parker, 2013; Preston et al., 2015), with northern Arabia experiencing a truncated period of increased rainfall compared to the south.

DISCUSSION

MIS 5e

What do the varied conditions between SAHPs mean for discussions of human populations and climatic extremes? There is a growing body of evidence which relates Pleistocene human movements between Arabia and Africa to periods of enhanced precipitation. Archaeological remains at Jebel Faya were dated to MIS 5e and may evidence the earliest instance of *H. sapiens* in the region (Armitage et al., 2011). Outside of

Arabia, MIS 5 *H. sapiens* fossils uncovered at Skhul, Qafzeh (Israel, Millard, 2008) and Fuyan Cave (≥80 ka BP, China; Liu et al., 2015) represent some of the earliest instances of Late Pleistocene humans outside of Africa. MIS 5e saw the most intense enhancement of precipitation, highlighting that this period may have been particularly favorable for hominin occupation and dispersal across the Saharo-Arabian deserts (Larrasoaña et al., 2013; Nicholson et al., 2021b). Such a large increase of precipitation was likely echoed by a greater vegetation response than later SAHPs, as evidenced by Mukallah Cave $\delta^{13}C_{ca}$ values (Nicholson et al., 2020) and the Jebel Faya phytolith record (Bretzke et al., 2013). It is thus likely that the carrying capacity of the Arabian Peninsula was greater during SAHP 4 compared to subsequent SAHPs, meaning population expansions and/or dispersals could have been rapid (Nicholson et al., 2021b). Additionally, the longer duration of SAHP 4 indicates that "green" environments were longer-lived than in SAHP 1, offering potentially longer-term occupation of the now arid interior. In this sense, climatic conditions during MIS 5e were at one extreme of Southern Arabia climatic variability and should not be understated as an optimal period for human dispersal.

However, it must be noted that archaeological finds are also dated to MIS 5c, 5a and 3 (Petraglia et al., 2011; Rose et al., 2011; Delagnes et al., 2012; Groucutt et al., 2018). While MIS 5e may therefore be the most extreme period of increased rainfall, other periods were still able to support human populations despite being "less favorable". Do these climatic differences suggest that strategies of survival differed between SAHPs (e.g., Bretzke and Conard, 2017)? Were subsequent dispersals more limited in terms of numbers of people and other animals? What do statistically significant differences in $\delta^{18}O_{ca}$ values translate to in terms of annual rainfall differences, as well as spatio-temporal variance on long (e.g., millennial) and short (e.g., annual) timescales? Or were the additional benefits of SAHP 4 compared to other SAHPs simply not that important for human occupation (i.e., humans could make do with less)? Additionally, the presence of *H. sapiens* in Arabia within MIS 3 suggests either occupation throughout the MIS 4 glacial or re-entry despite a "drier" climate (Armitage et al., 2011; Delagnes et al., 2012). While these are questions for future research, one message we may take from this is resilience/adaptation despite climatic differences, and that - while the stalagmite record provides useful information on the timing of major climate changes and major *H. sapiens* biogeographic shifts - providing a climatic "bench-mark" for Late Pleistocene occupations from the stalagmite record is too deterministic and overlooks taphonomical biases and dating uncertainties within the archaeological record.

One thing that is perhaps clearer is that the termination of these wet periods saw a substantial change in environmental conditions. The termination of SAHP 4 likely meant annual rainfall declined to <300 mm yr^{-1} and was echoed by a decline in vegetation resources. In terms of the "lived" experiences of humans, such a decline would have likely required a shift in survival strategies (Nicholson et al., 2021b). This may have included increased home-range foraging size and mobility patterns, retraction to high-resource retaining areas (such as the Yemeni Highlands; Delagnes et al., 2012; Delagnes et al., 2013) or in some cases dispersal out of Arabia (Nicholson et al., 2021b). Such responses to declining precipitation were also likely variable and not simplistic. Recent archaeological finds in Northern Arabia hint at techno-cultural continuity between Mid-Pleistocene wetter phases (Scerri et al., 2021), perhaps suggesting human resilience to increasingly unfavorable climatic conditions.

Early-Mid Holocene

The key precipitation changes during the HHP/SAHP 1 of gradual intensification of summer precipitation (~10.6–9.4 ka BP) that only declines following ~6.2 ka BP, and temporarily during the 9.2-kyr and 8.2-kyr events (Fleitmann et al., 2008), influenced humans and communities living in Arabia (for full summaries, see Parker et al., 2006; Goudie and Parker, 2010; Groucutt et al., 2020; Petraglia et al., 2020).

When compared to MIS 5e however, precipitation increases and associated vegetation response were less intense (Fleitmann et al., 2011; Bretzke et al., 2013; Nicholson et al., 2020). Despite this, and similar to MIS 5c, 5a and 3 (see above), there remains archaeological evidence for human occupation. Mustatils appear in northern Arabia from 9.2 ka BP (Kennedy, 2017; Guagnin et al., 2020; Thomas et al., 2021), and desert kites are evidenced in Jordan from 10 ka BP (Al Khasawneh et al., 2019). In southern Arabia, occupation of Jebel Qara took place ~10.5–9.5 ka BP (Cremaschi et al., 2015), pastoralism is evidenced by 8.0 ka BP (Drechsler, 2007; Drechsler, 2009; Martin et al., 2009), graves are attested 7.2–6.0 ka BP (Kiesewetter, 2006) and monumental stone platforms are evidenced 6.4 ka BP (McCorriston et al., 2012; Magee, 2014).

Reduced rainfall following ~6.2 ka BP led to a temporary end of Neolithic herding in the desert interiors, shrinking population numbers, and migration to areas with greater ecological diversity, perhaps suggesting a minimum amount of precipitation is required for human occupation in these marginal environments (Uerpmann, 1992; Vogt, 1994; Uerpmann, 2002; Potts et al., 2003; Goudie and Parker, 2010). However, human communities returned to the interior of Southern Arabia from ~5.2 ka BP without amelioration of climate, which even aridified further; varied occupation continues until the modern day (Magee, 2014; Petraglia et al., 2020). Therefore, it seems likely that drier climates create challenges for human populations, but these can be overcome by technological (e.g., mustatils, pottery, water management; camels domestication) and strategic (e.g., mobility, pastoralism) adaptations (Petraglia et al., 2020).

Finally, stability and variance of precipitation (which can be hard to detect in palaeoclimate records) may have been more influential to humans than long-term changes in amounts (Thornton et al., 2014). A temporary transition to herding practices occurred in some parts of Arabia during the 8.2 ka event (Drechsler, 2009; Crassard and Drechsler, 2013), whilst more positive $\delta^{18}O_{ca}$ values (drier conditions) are observed at Hoti cave (**Figure 2A**). Conversely, Cremaschi et al. (2015) suggested that—although increasing precipitation ~10.5–9.5 ka

BP facilitated occupation—overly “wet” landscapes at Jebel Qara after 9.5 ka BP led to site abandonment and a preference for coastal settings, hinting at the varied human responses to fluctuating climatic conditions.

CONCLUSION

Overall, when compared to other periods, stalagmite climate records indicate that the African and Indian Summer Monsoons were most intense during MIS 5e, which was one extreme of climatic variability in the last 130 kyrs. This was likely an important period for the dispersal of *H. sapiens* from Africa, as well as occupation in the now desert interiors of Arabia, and the subsequent decline back to more arid conditions likely impacted survival strategies in Southern Arabia. A comparably weaker intensification of precipitation (yet long-term trends are comparable) occurred during the Early Holocene. The expansion of human populations into the now arid interior was similar to MIS 5e but the responses to climatic variability and subsequent aridification differed. We emphasize that evidence for human occupation during all periods of insolation maxima, and the varying climates of these drier periods, highlights human resilience/adaptation despite climatic differences and mitigates against a simplistic narrative. Future research will benefit from the addition of climate/environmental proxies (trace-element and perhaps aDNA), increased surveys to advance the spatial-temporal coverage of the speleothem record and development of continuous climate records for SAHP 3 and 2. Understanding the shifting survival strategies in the context of declining rainfall and aridification, as Arabia transitioned from one extreme to another, will be of key importance to future debates of *H. sapiens* biogeography, behavioral flexibility, and both past and future climate-induced socio-political change.

AUTHOR CONTRIBUTIONS

SLN acted as primary author for the article, conceptualizing the manuscript, producing the initial draft and figures and ongoing editing of the manuscript. MJ acted as secondary author, assisting with the initial draft, and editing of the manuscript. RH and DF supervised and edited the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.749488/full#supplementary-material

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Microhabitat Variability in Human Evolution

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Climate variability and hominin evolution are inextricably linked. Yet, hypotheses examining the impact of large-scale climate shifts on hominin landscape ecology are often constrained by proxy data coming from off-site lake and ocean cores and temporal offsets between paleoenvironmental and archaeological records. Additionally, landscape response data (most commonly, records of vegetation change), are often used as a climate proxy. This is problematic as it assumes that vegetation change signifies global or regional climate shifts without accounting for the known non-linear behavior of ecological systems and the often-significant spatial heterogeneity in habitat structure and response. The exploitation of diverse, rapidly changing habitats by *Homo* by at least two million years ago highlights that the ability to adapt to landscapes in flux had emerged by the time of our genus' African origin. To understand ecosystem response to climate variability, and hominin adaptations to environmental complexity and ecological diversity, we need cross-disciplinary datasets in direct association with stratified archaeological and fossil assemblages at a variety of temporal and spatial scales. In this article, we propose a microhabitat variability framework for understanding *Homo*'s adaptability to fluctuating climates, environments, and resource bases. We argue that the exploitation of microhabitats, or unique ecologically and geographically defined areas within larger habitats and ecoregions, was a key skill that allowed *Homo* to adapt to multiple climates zones and ecoregions within and beyond Africa throughout the Pleistocene.

Keywords: microhabitat variability, human evolution, climate change, paleoecology, africa

INTRODUCTION

Climatic and environmental variability are often presented as major influencers on human evolution (Vrba, 1995b; Potts, 1998a; Trauth et al., 2010; Cerling et al., 2011; deMenocal, 2011), including the origins and diversification of *Homo* or the development of specific stone tool technologies (Potts et al., 2020; Lupien et al., 2021; Schaebitz et al., 2021). Variable Pliocene-Pleistocene climate for example, may have required hominins to effectively respond to the extreme selection pressures imposed by dynamic climatic systems, leading to genetic and morphological change and technological innovation (e.g., Committee on the Earth System Context for Hominin Evolution, 2010). It is even argued that changes in African climate and hominin extinction, speciation, and behavioral events were inextricably linked over the past 6 million years (deMenocal, 2011). The last appearance of *Australopithecus afarensis* around 2.9 Ma (Campisano and Feibel, 2008; Alemseged et al., 2020), the appearance of the genus *Homo* at 2.8 Ma (Villmoare et al., 2015), the emergence of *Paranthropus* after 2.7 Ma (Coppens, 1968; Harrison, 2002), and the earliest evidence for Oldowan stone tools at 2.6 Ma (Semaw et al., 1997; Braun et al., 2019) appear to overlap with Northern Hemisphere glacial intensification, faunal changes, aridification, and grassland expansion in Africa (Bobe and Eck, 2001; Semaw, 2003; Evolution, 2010; deMenocal, 2011). Moreover, the emergence of *Homo erectus* and subsequent migrations out of Africa seemingly occurred when subtropical temperatures cooled around 1.9 Ma (Ravelo et al., 2004), while the appearance of the Acheulean at ~1.75 Ma has been suggested to coincide with increases in African wind-borne dust and aridification near 1.8 Ma (deMenocal, 2004; Lupien et al., 2018).

Yet, linking hominin landscape ecology and climate variability to technological, morphological, or behavioral changes remains challenging as clear cause-and-effect relationships between specific climatic events and major evolutionary occurrences are difficult to establish. This is often due to temporal and spatial gaps in paleoclimatic, paleoenvironmental, and archaeological records (Marean et al., 2015; Faith et al., 2019; Faith et al., 2021). Additionally, recent discoveries of the earliest stone tools (i.e., the Lomekwian) from Kenya dating to 3.3 Ma (Harmand et al., 2015), the earlier appearance of *H. erectus* in southern Africa at 2.0 Ma (Herries et al., 2020), and the likelihood that Acheulean biface shaping emerged gradually out of bifacial core reduction during the Oldowan (Duke et al., 2021) are not evidently linked with major climate and environmental events. Furthermore, Northern Hemisphere Glaciation was a gradual process, and a consistent stepwise transition toward greater aridity in Africa at ~2.8 Ma does not exist, with regional, often asynchronous, changes being observed in different parts of the continent (Trauth et al., 2021). Mammalian evolution is also not always directly linked to major climate shifts in a one-to-one manner as species adopt a variety of strategies, including mobility/migration, dietary, morphological, or cultural change, and the ongoing utilization of small microhabitats within a wider changing regional environmental context (Boutin and Lane, 2014; McCain and King, 2014; Figueirido et al., 2019; Stewart et al., 2021).

Indeed, particular caution must be adopted when studying paleoclimate and paleoecology within a human evolutionary framework, as hominin habitat-types are not always synchronous with changes in regional or global climate (Blumenthal et al., 2017; Groucutt, 2020; Faith et al., 2021; Trauth et al., 2021). That is, landscape response data (most commonly, records of vegetation change), are often used as a climate proxy even though it is well established that ecosystems do not necessarily exhibit a linear response to global or regional climate drivers (Holling, 1973; Bennett et al., 2021). Although difficult to identify archaeologically, we must also consider hominin agency, specifically the genus *Homo* in comparison to other hominins and primates, for its capacity to survive and adapt to resource limited conditions and manipulate their environments. We know, for instance, that by least ~1.8 Ma (Gabunia et al., 2000; Zhu et al., 2008; Garcia et al., 2010; Ferring et al., 2011) and possibly ~2.1 Ma (Zhu et al., 2018), *Homo* had adapted to multiple climate zones and ecoregions within and beyond Africa, selected specific habitats within larger biomes, and was able to tolerate extreme climatological and ecological events without the need of sophisticated technology. In addition, Middle Pleistocene hominins modified their ecosystems, such as through fire use, which influenced local and regional ecologies, thus adding another dimension to vegetation change that is not entirely climate mediated (Gowlett, 2016; Petraglia, 2017; Thompson et al., 2021).

Until relatively recently, cross-disciplinary datasets in direct association with stratified archaeological and fossil assemblages were not specifically targeted when reconstructing hominin landscape environments or ecologies. "Off-site" (i.e., distal) lake and ocean cores have produced well-integrated, high-resolution reconstructions of the broad environmental context in which the genus *Homo* and its closest hominin relatives evolved, adapted, and experimented with novel technologies (Feakins et al., 2005; Feakins et al., 2007; Castañeda et al., 2009; Magill et al., 2013a; b; Uno KT. et al., 2016; Tierney et al., 2017; Caley et al., 2018; Colcord et al., 2018; Lupien et al., 2018; Lupien et al., 2019; Lupien et al., 2020; Lupien et al., 2021). These data, however, are often derived from sources distal to hominin activity. Although we have long-term records that demonstrate changes in plant landscape composition (Feakins et al., 2005; Feakins et al., 2007; Feakins et al., 2013; Uno K. T. et al., 2016), they do not necessarily show the ecological subtleties and complexity that on-site (i.e., proximal) records can provide. Increasingly, however, phytolith and pollen records (Bonnefille, 1995; Barboni et al., 1999; Albert et al., 2006; Bamford et al., 2006; Bamford et al., 2008; Albert et al., 2009; Barboni et al., 2010; Rossouw and Scott, 2011; Albert and Bamford, 2012; Barboni, 2014; Albert et al., 2018; Itambu, 2019; Mercader et al., 2021; Stollhofen et al., 2021), as well as paleontological and stable isotope analyses (WoldeGabriel et al., 1994; Cerling et al., 1997; Pickford and Senut, 2001; Wynn, 2001; White et al., 2009b; WoldeGabriel et al., 2009; Prassack, 2010; Cerling et al., 2011; Kovarovic et al., 2013; Magill et al., 2013a; b; Quinn et al., 2013; Bibi and Kiessling, 2015; Bibi et al., 2018; Colcord et al., 2018; Pante and de la Torre, 2018; Prassack et al., 2018; Faith et al., 2019; Roberts et al., 2020; Sanders, 2020), have sought to track changes in landscapes occupied by Pleistocene hominins. The pursuit of more detailed data relating to hominin population resource use and microhabitat availability across space and time is beginning to provide more nuanced insights into the relationship between hominin morphologies and technologies and local-to-regional scale environmental change (Barboni et al., 2010; Blumenschine et al., 2012; Magill et al., 2015; Itambu, 2019; Patalano, 2019; Martin et al., 2021; Mercader et al., 2021).

This article reviews the potential role of microhabitat variability in human evolution by examining archaeological and paleoecological datasets that have revealed hominin morphological and technological adaptations to changing

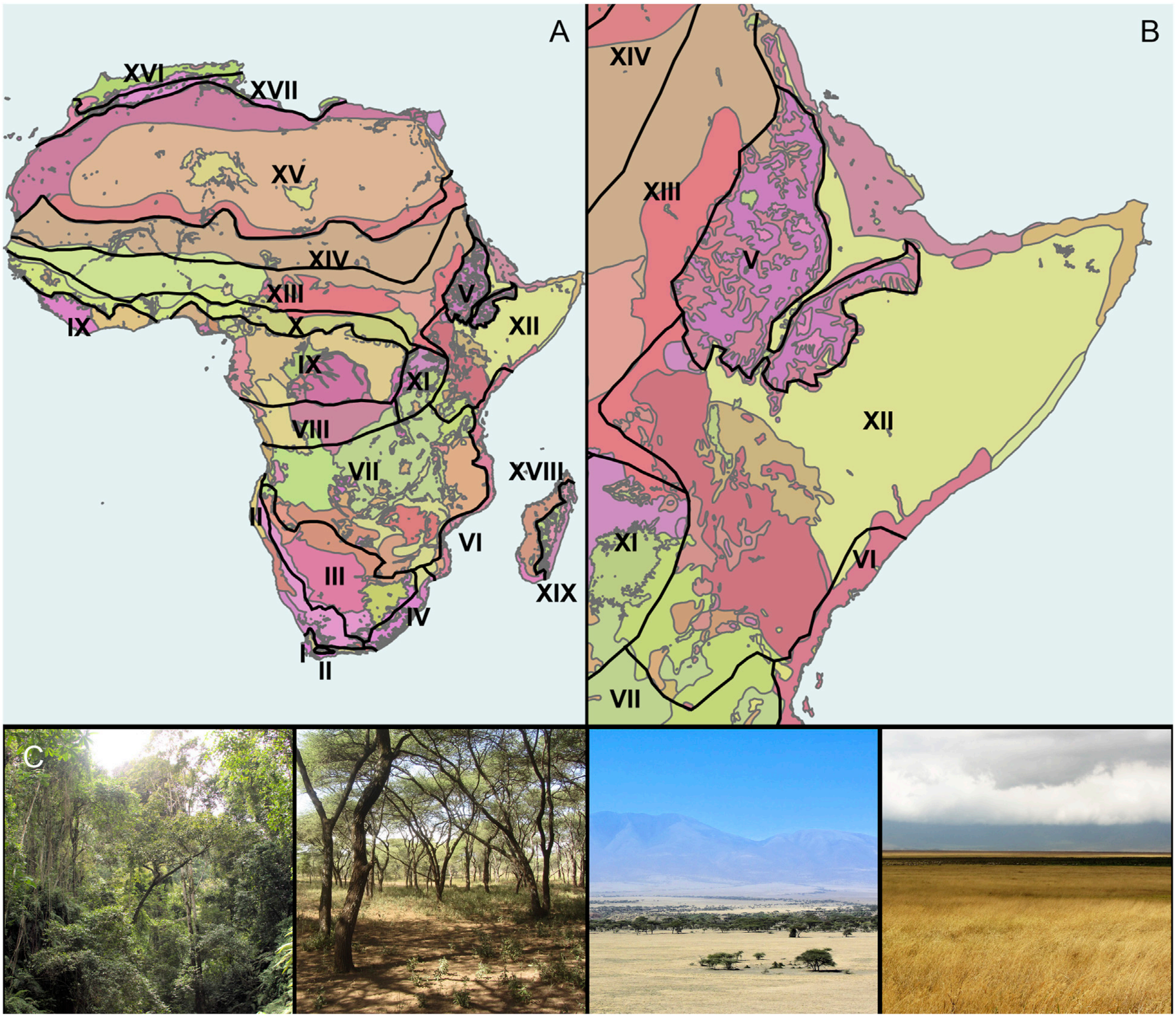

FIGURE 1 | Different scales of plant landscape variability. **(A)** Biomes as defined by White's (1983) African phytochoria (supplementary information for classifications) overlain on African ecoregions as delineated by the World Wildlife Federation (WWF) (Olson et al., 2001); **(B)** Eastern African biomes and ecoregions with focus on White's Somalia-Maasai Regional Center of Endemism (XII). Note the numerous and diverse ecoregions within the larger phytogeographic biomes. **(C)** Different habitat types that can be found throughout the Somalia-Maasai Regional Center of Endemism. From left to right: forest, woodland, wooded grassland, and grassland. **Table 1** for a synopsis of main habitat types.

environments over time and space. We begin by defining microhabitat variability, and the differences between biomes, ecoregions, and habitats. We then present field and analytical research methods designed to identify microhabitat variability in the Pleistocene. This is followed by a review of the key prevailing climate and environmental hypotheses for human evolution, as well as issues related to landscape response data like the inherently non-linear attributes of some ecosystems. This is followed by case studies using three examples of microhabitat variability from Oldupai Gorge (formerly Olduvai) in Tanzania and the adaptability of *Homo* to distinct environmental settings. Finally, we propose a framework for utilizing diverse datasets compiled from multiple environmental proxy records as an analytical tool for evaluating hominin adaptability across ecologically diverse landscapes and consider how to best factor a microhabitat variability framework into existing paleoclimatic, paleoenvironmental, and evolutionary models.

MICROHABITAT VARIABILITY

High spatial resolution and multi-proxy archaeological and paleoecological datasets are crucial for locally reconstructing climate drivers and biome- and intrabiome-scale ecological change. Such analyses are a necessary starting point for underpinning how climate-ecosystem feedbacks have influenced hominin evolution. We classify "microhabitats" as unique ecologically and geographically defined areas within larger

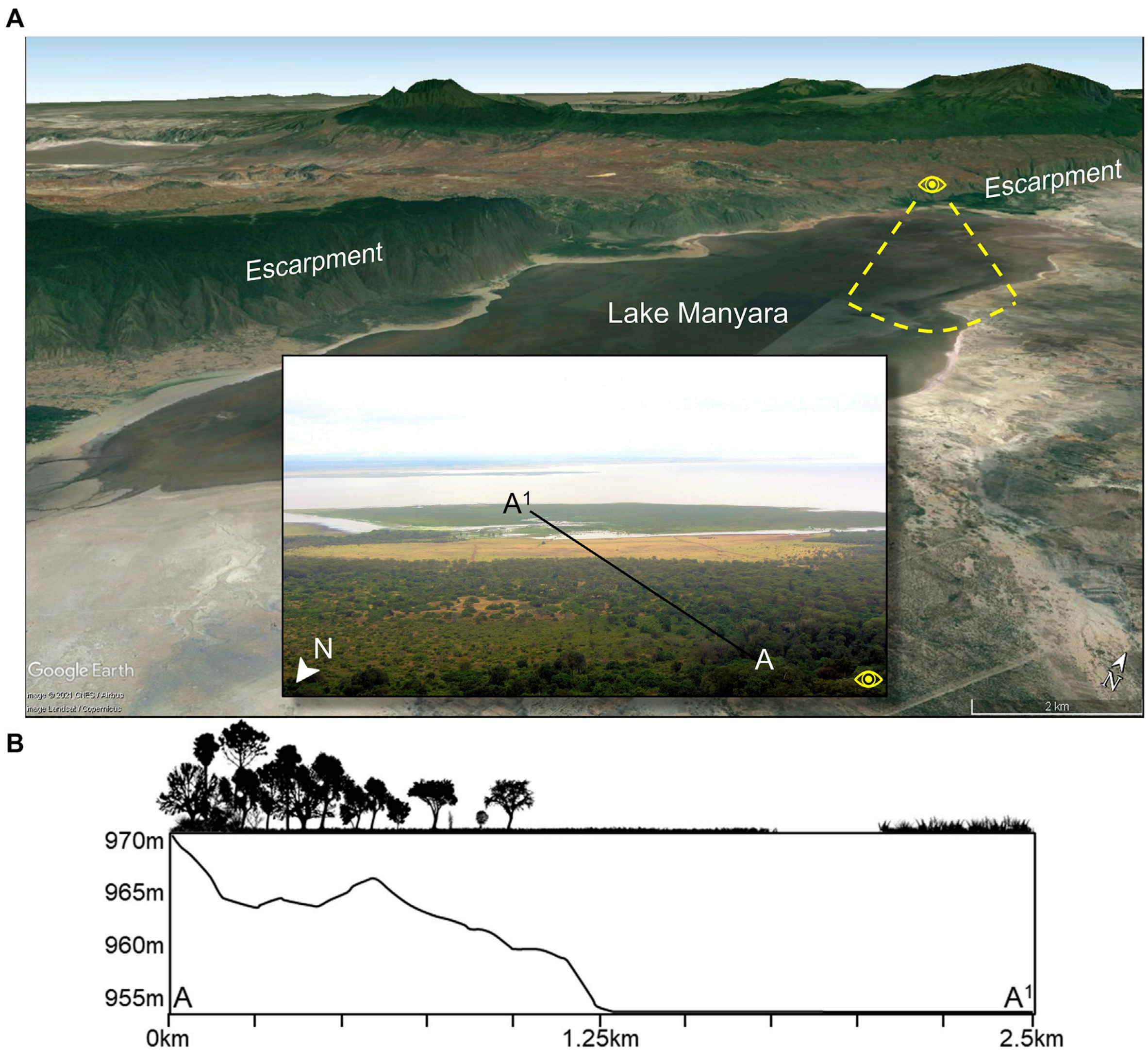

FIGURE 2 | (A) Google Earth image showing Lake Manyara in the Tanzanian Rift Valley and forests on the northern and western shores that are fed by groundwater discharged from the escarpment. Insert photo shows the view from atop the northern escarpment. **(B)** An ecological and elevation profile of segment A-A[1] showing variability at a small scale. In the ecological profile, true forest is found from 0 to 0.25 km, and then gradually transitions to woodland until ~0.6 km before opening into wooded grassland until 1.0 km. After 1.0 km, the wooded grassland transitions to an open grassland, which terminates at the water's edge at 1.75 km. After 2.1 km, emergent halophytic vegetation (saline and brackish swamp adapted species) flourish on an exposed surface.

habitats (**Figure 1**, **Figure 2**). At the largest scale are "biomes," which we identify using White's (1983) description of extant African phytochoria, termed *Regional Centers of Endemism* (White, 1979). Nested within the biomes are various "ecoregions," or relatively large areas of land containing a distinct assemblage of natural communities and species that share climatic and environmental conditions (Olson et al., 2001). The porosity and chemistry of soils, topography, groundwater sources, and edaphic conditions influence vegetation structure and floristic patterns to create distinct habitat and microhabitat assemblages inside each ecoregion (Sept, 2013). "Habitats" are areas covered by relatively uniform vegetation types within each ecoregion (**Table 1**), that represent major biotic zones and correlate with various climatic indices such as rainfall seasonality, summer aridity, and minimum winter temperatures (Van Wyk and Smith, 2001). A "microhabitat" on the other hand, is a smaller but highly distinctive area that differs from encompassing habitat types in that it exhibits unique floristic conditions that can change at meter scales (**Figure 2**). While, on a spatial scale, these ecosystems might seem relatively unimportant, biotically they can be home to a variety of diverse flora and fauna, often exerting specific pressures on the evolution of morphology, feeding behaviors, and migratory patterns (Fjeldså and Lovett, 1997; Stewart et al., 2010; Sintayehu, 2018).

Microhabitat variability is exemplified best by mosaics, or where local geological, tectonic, microclimatic, and hydrological conditions and both natural and anthropogenic

TABLE 1 | Synopsis of main habitat types mentioned in the text. Adopted from White, 1983.

	–
Forest	A continuous strand of trees at least 10 m tall with a closed, multistory, overlapping canopy. Woody plants dominate the biomass, and a shrub layer is normally present. The ground layer is usually sparse but may contain bryophytes, epiphytes, orchids, or mosses depending on moister availability
Woodland	Open stands of trees that are at least 8 m high, but no more than 20 m, with woody plants accounting for ~40% of the biomass over a field layer of grasses. Woodland canopies do not overlap extensively, but occasionally, stands of woodland have a closed canopy and thus a poorly developed grass layer
Bushland and thicket	Open stands of bushes, defined as woody, multi-stemmed plants usually 3–7 m tall with a main stem 10 cm or more in diameter, that cover >40% or more of the land. Bushes often flourish in rocky or stony substrates that are unfavorable to grasses. Thicket is a closed stand of bushes that are so densely interlocked that they form a nearly impenetrable obstacle that hinders movement
Shrubland	Stands of shrubs that vary in height from 0.1 to 2 m. Usually open or closed stands of shrubs occur where taller bushes and trees cannot grow because of low rainfall, extended drought periods, low temperatures, high rates of evapotranspiration, and oligotrophic or nutrient-poor soils
Grassland	Stretches of grasses and other herbs that develop when woody plant cover is <10%. African grasslands are structurally simple with woody species only occurring in specialized microhabitats that are dependent on the availability of moisture. Forbs also form an important component of grasslands and may contribute more in terms of biome species richness than do grass species
Wooded Grassland	Stretches of grasses and other herbs, with woody plant cover ranging from 10 to 40%. Woody plants are always scattered, but often grade into grassland or woodland

disturbances create well-defined patches of distinct plant communities that may offer unique food resources (Mucina and Rutherford, 2006). Gallery forests for example, are a key element within the Somalia-Maasai Regional Center of Endemism of eastern Africa (White, 1983), which consists of *Acacia-Commiphora* deciduous bushland and thicket, wooded grassland, edaphic grasslands, and other habitat types. Dense, fire-exclusionary gallery forests can grow proximal to abundant or permanent freshwater sources, including near rivers or groundwater aquifers. Thus, a particular combination of eco-hydrological conditions can permit the formation of highly diverse landscape mosaics over relatively small geographic distances (Mucina and Rutherford, 2006). Contributing to microhabitat variability is ecological diversity, which includes both alpha (α-diversity) and beta (β-diversity) diversity (Whittaker, 1960). Alpha diversity reflects that within a localized microhabitat, while β-diversity reflects that between different microhabitat types. Both α-diversity and β-diversity are determined by climatic conditions as well as the frequency of fires and other disturbances and a combination of slopes, aspect, soil depth and nutrients, moisture availability, age, and evolutionary history of the landscape (Geldenhuys, 1992; Mucina and Rutherford, 2006). The well-drained alluvial fans on the northwestern and western shores of Lake Manyara, Tanzania for example, support a "drought resilient" groundwater-fed evergreen forest that would otherwise not develop under the existing rainfall regime of 650 mm per year (Copeland, 2007; Barboni, 2014) (**Figure 2**). This forest is atypical of the Somalia-Maasai *Acacia-Commiphora* deciduous bushland and thicket and volcanic grasslands that abound in this region of Tanzania. Crucially, this forest supports key edible taxa that are relied upon by a range of fauna (such as chimpanzees in western Tanzania) like the Cape Mahogany (*Trichilia emetica*) and the Sycamore Fig (*Ficus sycomorus*) (Copeland, 2007 and references within).

Identifying Microhabitat Variability

Reconstructing microhabitat variability through archaeological or paleoecological proxies is, of course, difficult given the delimited nature of excavations or core retrieval and taphonomic limitations. Recent studies, however, have shown that it is possible to track microhabitat changes at spatial scales (Magill et al., 2015; Arráiz et al., 2017; Itambu, 2019; Patalano, 2019). Many archaeological and paleoanthropological sites permit well-defined, high-resolution temporal analyses, though few have had adjacent geological exposures that allow for analyses to be conducted at a high spatial resolution targeted as well. Oldupai Gorge in northern Tanzania, the Ain Béni Mathar-Guefaït basin in eastern Morocco, and even the Nihewan Basin in northern China are such examples where exposed sedimentary deposits allow for radiometric or magnetostratigraphic dating of fluvio-lacustrine sequences so that both temporal and spatial paleo-reconstructions are possible (**Figure 3**). The application of sequence stratigraphic methods to geologic exposures provides a time-layered framework that enables correlations between sedimentary units across facies boundaries (Uribelarrea et al., 2017; Stanistreet et al., 2018). This also allows for the horizontal sampling of terrestrial sediments at and beyond archaeological sites, as well as across exposed sedimentary units along meter-, and when possible, kilometer-scale transects (**Figure 3**). The analyses of specific paleo-proxies (**Table 2**) collected in paleosol horizons can then help document spatial distributions in vegetation and provide an ecological context of such things as hominin foraging behavior or raw material procurement (**Section 5**).

Nevertheless, investigations into hominin resource use and microhabitat variability have largely been limited to Oldupai Gorge due to its number of documented archaeological sites, geographic extent, and well-defined stratigraphy (Barboni et al., 2010; Blumenschine et al., 2012; Magill et al., 2015; Itambu, 2019; Patalano, 2019; Mercader et al., 2021). Sampling at other paleoanthropological locations on the other hand, has mostly

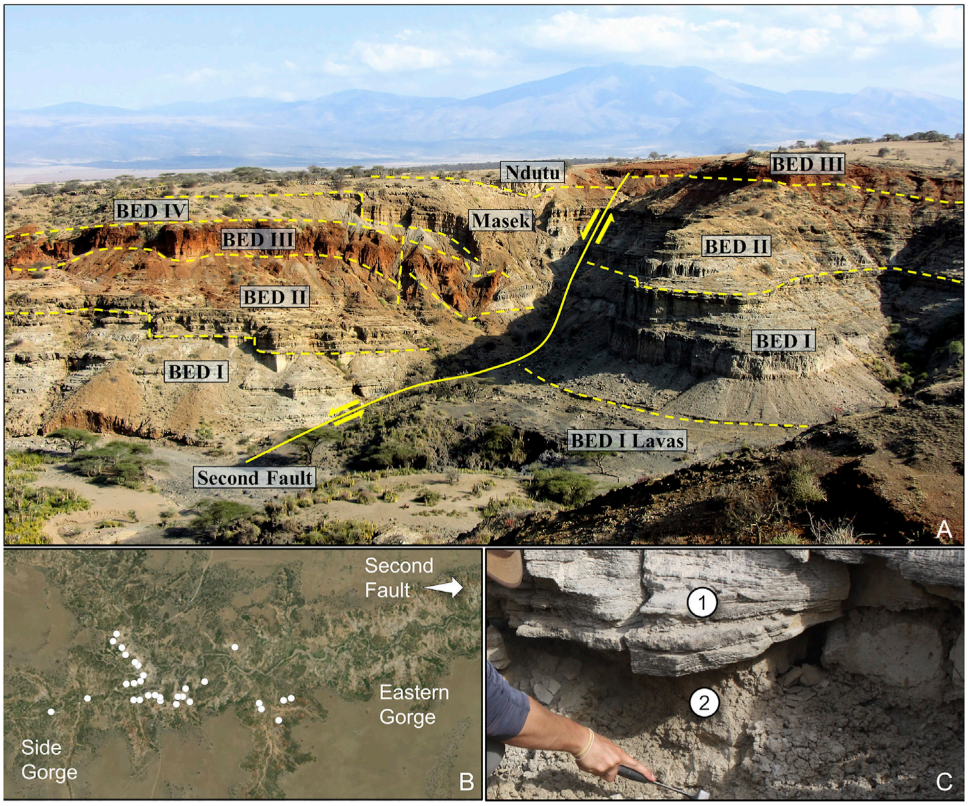

FIGURE 3 | Stratigraphic overview of Oldupai Gorge and landscape sampling for spatial habitat variability. **(A)** View of the Second Fault in the eastern part of the gorge and the displacement of the stratigraphic Beds. On the left (hanging wall), all beds except for Naisiusiu are exposed, while on the right (foot wall), only the Bed I Lavas and Beds I-III are visible. Exposure taken from the northern rim of the gorge facing south and encompasses ~600 m east to west. Photo by Robert Patalano. **(B)** Locations (white dots) around the main confluence of the gorge where clays in contact below Tuff IF were sampled for plant wax biomarkers and phytoliths (Itambu, 2019; Patalano, 2019). **(C)** Example in which both Tuff IF (1) and the clays in contact below the tuff (2) are exposed. Photo by Laura Tucker.

TABLE 2 | Main paleoecological proxies that can be used to study microhabitat variability.

	Pollen	Phytoliths	Plant waxes	Faunal isotopes
Benefits	Compositionally rich record of vegetation change Highest taxonomic resolution	Often abundant in paleosols Can track boundary between woodland and grassland	Ubiquitous in terrestrial and aquatic sediments Track photosynthetic pathway and changes in hydroclimate	Ratios track dietary preference Provide landscape-scale environmental signals
Drawbacks	Preservation contingent on anoxic conditions, usually in aquatic depositional settings Transport distance differs between taxa	Cannot reliably identify photosynthetic pathway or plant taxonomy, specifically at the species level	Production varies by taxonomic group Preservation depends on initial burial dynamics and diagenesis	Biased to feeding behavior Not diagnostic of hominin habitat preference

focused on proxy records collected in lake basin or ocean cores that track long-term climatic trends and regional environmental signals (Faith et al., 2021). Classifying paleo-microhabitats is also contingent on the taphonomy of environmental proxies (**Table 2**). Diverse faunal assemblages can suggest the juxtaposition of distinct microhabitats (Kovarovic et al., 2013), but can be skewed by niche exploitation of specific species by hominins or the disproportional preservation and dominance of some species [e.g., very large mammals (≥180 kg)] in fauna collections over other [e.g., small mammals (<1,000 g)] (Faith et al., 2019). Biogenic silica, pollen, and plant wax biomarkers (Godwin, 1934; Faegri and Iversen, 1989; Piperno, 2006; Sachse et al., 2012; Diefendorf and Freimuth, 2017; Cabanes, 2020; Patalano et al., 2021), are three additional proxies most often applied for plant landscape reconstructions (**Table 2**), and when used effectively, have the potential to produce a clear ecological context into which hominin behavior can be interpreted (e.g., Mercader et al., 2021). By taking a multi-proxy approach to studying non-analog ecosystems and microhabitat variability, it is possible to overcome some of the problems inherent with

TABLE 3 | Synthesis of selected environmental hypotheses for human evolution.

Hypothesis	Type	Environmental setting	Evolutionary outcome	Drawback	References
Savanna	Habitat specific	Transition from closed forest to open grassland	Bipedalism, tool use, encephalization, etc.	Hominin landscapes were ecologically diverse with multiple habitat types	Dart (1925); Washburn (1960); Wilson (1979); Wolpoff (1980)
East side story	Habitat specific	Wet, forested west/central Africa vs. dry, open eastern Africa	Split between *Pan* and *Homo* from last common ancestor	Based on the assumption that hominin evolution only occurred in eastern Africa	Coppens (1994)
Turnover pulse	Climate variability	Rapid phases of aridity and limited resources	Extinction and speciation	No solid evidence for rapid ecological and evolutionary changes in the eastern African fossil record	Vrba (1985); Vrba (1995a); Vrba (1995b); Vrba (2007)
Variability selection	Climate variability	Trends toward drier and more variable climate resulting in unpredictable resource base	Heritable traits that enhance adaptive versatility favored over those that thrive in stable environments	Assumes linear driver-response between climate change and hominin ecosystem change	Potts (1996); Potts (1998b); Potts (2013)
Pulsed climate variability	Climate variability	Short periods of extreme climate variability and rapid landscape reorganization	Hominin speciation, encephalization, and dispersals out of Africa	Does not account for hominin localities or habitats beyond the East African Rift Valley	Maslin et al. (2014)
Red queen	Productive stability	Stable, predictable, resource rich environments	Competition amongst species leading to fitness optimum and evolution	Ignores importance of abiotic factors and may only operate at the population level	Van Valen, (1973)
Chase red queen	Productive stability	Stable, predictable, resource rich environments	Cladogenesis (typically amongst populations)	Has been difficult to show in extinct taxa	Strotz et al. (2018)
Microhabitat variability	Ecological variability	Diverse and varied with ample resource opportunities	Successful adaptability of *Homo* to environmentally complex landscapes	Few paleoanthropological localities allow for testing spatial variability	—

undertaking regional climate-ecosystem comparisons for human origins studies (Faith et al., 2019; Faith et al., 2021).

ENVIRONMENTAL AND CLIMATE VARIABILITY AND HUMAN EVOLUTION

The evolutionary significance of climatic and environmental variability has been reviewed elsewhere within the context of human origins (Vrba et al., 1989; Potts, 1996; 1998a; b; Vrba, 2007; Maslin and Trauth, 2009; Potts, 2013; Maslin et al., 2015; Faith et al., 2021). Early explanations of human evolution focused on intrinsic stimuli whereby a simple transition from one habitat type to another (forest to grassland, for example) set the stage for speciation or specific hominin characteristics like bipedalism and tool use (Dart, 1925; Washburn, 1960; Wilson, 1979; Wolpoff, 1980; Coppens, 1994). While these *Habitat Specific Hypotheses* have, for the most part, been replaced, their assumptions often persist in evolutionary discourse (**Table 3**). Generally, these hypotheses stipulate that the transition from closed woodlands to open grasslands underpinned the development of meat-eating, hunting, brain enlargement, fire use, food distribution, complex sociality, and even language (review in Potts, 2013).

Laporte and Zihlman (1983) were early proponents for the impact of environmental change on driving African mammalian evolution (including hominins) by proposing that adaptive changes were a response to changing environments caused by global cooling or orogeny, or as hominins migrated into new habitats. This has since resulted in multiple climate variability hypotheses that link changes in climate to environmental reorganization and subsequent speciation and extinction events, species' adaptive versatility, and the selection of behavioral and morphological mechanisms that enhance adaptive fitness (**Table 3**). For instance, the appearance of *Homo* and *Paranthropus* around 2.5 Ma was proposed to have followed climate pulses caused by Northern Hemisphere glacial intensification and the closing of the Isthmus of Panama (Vrba et al., 1989; Vrba, 1995a; b). We now know, however, that there is even earlier evidence of *Homo* around 2.8 Ma (Villmoare et al., 2015), and possibly as early as 3.3 Ma, (Püschel et al., 2021), and there was no pulse towards greater aridity in Africa at the time (Trauth et al., 2021). On the other hand, increased ecological resource variability (Potts et al., 2020) is considered a major factor in a species' adaptive versatility specifically in unstable, unpredictable, or unfamiliar environments, and there is now more compelling evidence for hominin evolutionary events during periods of highly variable eastern African climate shifting from very-dry and very-wet conditions between 5.0 and 0.2 Ma (Trauth et al., 2005; Maslin et al., 2013; Maslin et al., 2014; Potts et al., 2020; Lupien et al., 2021).

In contrast to these hypotheses centered on upheaval and change, some treatises have argued that climatic stability may have been important for driving hominin evolution as species must adapt and evolve in competition with other evolving species (Van Valen, 1973; Strotz et al., 2018). In these (**Table 3**), highly productive and stable environments lead to competition among species resulting in directional selection as they move toward fitness optimum when striving to gain a competitive advantage over others (Brockhurst et al., 2014). As cladogenesis can lead to populations deviating from their species and the possibility of a descendant evolving while its ancestor persists, there is thus a link between microevolutionary processes and macroevolutionary patterns (Strotz et al., 2018). *P. boisei*, *H. erectus*, *H. habilis* and *H. rudolfensis* were all present at Koobi Fora during the maximum extent of Paleo-Lake Lorenyang (1.9–1.8 Ma), when resource availability would have been highest, resulting in these hominins co-evolving in competition with each other (Maslin et al., 2015). Additionally, *Au. sediba*, *P. robustus*, and *H. erectus* were contemporaneous in South Africa between 2.04 and 1.95 Ma (Berger et al., 2008; Herries et al., 2020), coinciding with substantial changes in South African ecosystems that may have placed selective pressures on *Australopithecus*, leading to divergent *Homo* and *Paranthropus* lineages (Ledogar et al., 2016; Joannes-Boyau et al., 2019).

ECOSYSTEM RESILIENCE IN FACE OF CLIMATE CHANGE

Disentangling the influence of climate changes on plant landscapes and impacts on resource availability is a fundamental, yet often overlooked, stepping-stone for linking climate drivers to human behavioral change, evolution, and migration patterns. This is an essential element for validation of the variability hypotheses given that they all mandate a degree of environmental determinism (e.g., Faith et al., 2021). Yet historically, paleoecological and paleoclimatic records have often been conflated (e.g., Morrison and Hamilton, 1974), an approach often necessitated by cost, access, and methodological constraints. While linear driver-response assumptions may be viable for climatically sensitive habitats such as tropical montane settings, they may overlook the inherently non-linear attributes of ecosystems (Holling, 1973; Hirota et al., 2011; Willis et al., 2013; Seddon, 2021). Thus, an interpretation of a stable climate exclusively drawing on paleoecological data extracted from a climatically resilient ecosystem would be entirely misconstrued (Hamilton et al., 2020). Equally problematic is an assumption of extreme climate change from ecological data showing a catastrophic ecological state shift in response to a relatively minor, potentially non-climatic disturbance (Hirota et al., 2011). This emphasizes the importance of producing independent records of climatic and non-climatic stressors and landscape response data prior to making interpretations of hominin behavior from the archaeological record.

From a climate perspective, the progressive formation of the East African Rift System (EARS) after 12 Ma increased aridity in eastern Africa as wind patterns became less zonal, reducing available moisture particularly on the leeward sides of uplifted regions (Sepulchre et al., 2006; Hardt et al., 2015). Tectonic activity also helped create distinctive and topographically complex landscapes and geographical barriers that hominins had to successfully navigate (King and Bailey, 2006). Evidence from soil carbonates (Wynn, 2001; Levin et al., 2004; Wynn, 2004; Levin et al., 2011; Quade and Levin, 2013) and pollen and plant wax biomarkers (Feakins et al., 2005; Feakins et al., 2007; Feakins et al., 2013) illustrate a progressive proliferation of C_4 plants beginning at approximately 10 Ma, presumably in response to increased aridity following rifting (deMenocal, 2004). Grass pollen and plant wax biomarkers from marine cores in the Gulf of Aden (Feakins et al., 2013) and the Somali Basin (Uno K. T. et al., 2016) show that C_3 grasslands had actually expanded in eastern Africa by 12 Ma but from 10 Ma onwards, were steadily replaced by C_4 plants (Feakins et al., 2007; Uno K. T. et al., 2016), though this was not a gradual process (Magill et al., 2013a; b; Colcord et al., 2018; Lupien et al., 2019).

Changes in northeastern African flora have also been attributed to variability in orbital precession (Feakins et al., 2005; Feakins et al., 2007; Maslin and Trauth, 2009; Magill et al., 2013b; Feakins et al., 2013; Uno KT. et al., 2016; Lupien et al., 2018). Precession, with an average periodicity of ~23,000 years, may have influenced human evolution and adaptability by controlling local water availability, biome diversification, and key speciation and dispersal events (Maslin and Trauth, 2009; Potts, 2013). Environmental variability may have also increased the adaptive versatility of hominins and their capacity to adjust to new habitats (Potts, 2013). The timing and nature of changes in hydrology and vegetation cover and the relationship to hominin species turnover (Feakins et al., 2007; Lupien et al., 2018), the appearance of new stone tool technologies (Lupien et al., 2020), the ability to control fire (Collins et al., 2017; Brittingham et al., 2019), and hominin dispersals out of Africa (Castañeda et al., 2009; Tierney et al., 2017) have all been viewed in light of orbital forcing and environmental variability. In southeastern Africa, rapidly fluctuating wet-dry cycles between approximately 2.2 Ma to 2.0 Ma likely contributed to the local extinction of *Australopithecus* and *Paranthropus* due to habitat marginalization (Caley et al., 2018), at a time when the genus *Homo* was emerging prominently in Africa (Antón, 2003; Plummer et al., 2009; Herries et al., 2020).

On shorter timescales, the Intertropical Convergence Zone (ITCZ) dictates the position of African and Indian Ocean Monsoons and controls the seasonal distribution of precipitation across Africa (Nicholson, 1996). Driven by solar insolation, the ITCZ produces singular rainy seasons in many parts of the continent, but it is difficult to simply attribute African precipitation cycles directly to incoming solar radiation (Yang et al., 2015), as African hydroclimate is modulated by influences from both the West African and Indian Ocean monsoons, the Walker Circulation, topography, and anomalies of ocean sea-surface temperatures, all of which can cause unimodal to trimodal distributions of rainfall across of the continent (Nicholson, 1993, 1996; Williams et al., 2012; Yang et al., 2015; Parhi et al., 2016; Ummenhofer et al., 2018; Schaebitz et al., 2021). In eastern Africa for example, the region's aridity has been attributed to the Turkana low-level jet (Nicholson, 2016) and orography (Christensen and Kanikicharla, 2013) even though there is a bimodal annual cycle of precipitation. Continental rainfall distribution is also sensitive to changes in the El Niño Southern Oscillation (ENSO) (Nicholson and Selato, 2000; Pausata et al., 2017), originating from Pacific sea surface temperature anomalies (Kaboth-Bahr et al., 2021). Changes in ENSO influence east-west and equatorial-southern moisture gradients across Africa (Nicholson and Selato, 2000; Nash et al., 2016; de Oliveira et al., 2018), such that when humid condition prevail in eastern or equatorial Africa, arid conditions persist in western or southern Africa (Nicholson, 1996; Kaboth-Bahr et al., 2021).

African plant landscapes, and forests in particular, are unique in that they recover faster after disturbances and appear to be more resistant to drought compared to other tropical habitats, such as those in South America or Southeast Asia (Willis et al., 2013; Cole et al., 2014; Bennett et al., 2021). This drought-resistance may be due to the relatively dry contemporary conditions across the continent (Malhi et al., 2004) as well as the biogeographic history and diversification of drought-adapted species (Parmentier et al., 2007). As African climate has oscillated between wetter and drier conditions, modern plant biomes may have developed drought-tolerance over time due to the loss of mesic-adapted species (Pennington et al., 2009). If, for example, humid lowland tropical African forests are more resistant to short-term extreme climate anomalies today, it is possible that moisture availability across Africa (e.g., paleo-ENSO effects) may not have had a large role in governing the distribution of vegetation communities or plant landscape structure at shorter timescales during the Pleistocene (Bennett et al., 2021). There is also non-linearity in both the spatial and temporal response of African vegetation to specific climatic drivers. Understanding these differences is important for determining spatial patterns of resilience and the sustainability of ecosystems in relation to climate changes (Willis et al., 2013).

Alternatively, hominin ecosystem engineering, especially intentional fire manipulation by *H. sapiens*, is an aspect of vegetation change that is not entirely climate mediated but may have had a significant influence on plant community composition and structure (Gowlett, 2016; Petraglia, 2017; Thompson et al., 2021). Controlled fire use is apparent in the archaeological record prior to the Middle Stone Age (Glikson, 2013; Gowlett, 2016), and both archaeological and ethnographic evidence indicate deliberate landscape modification through controlled burning to maintain mosaic landscapes and as a subsistence-related strategy (White, 2013; Scherjon et al., 2015; Petraglia, 2017; Bliege Bird et al., 2020; Thompson et al., 2021). This also suggests that controlled and manipulated fire may have had a pronounced effect on Pleistocene environments (Archibald et al., 2012), with Middle Pleistocene hominins burning landscapes to create resource-rich microhabitats that provided populations with abundant gatherable plants and ecological settings appealing to animal prey species (Haws, 2012; Thompson et al., 2021). Reconstructing paleoenvironments through a microhabitat variability framework can therefore help to understand the impact of hominin ecosystem modification on plant landscapes, especially when non-linearity and spatial patterns of resilience and climate drivers are also considered.

MICROHABITAT VARIABILITY AND HUMAN EVOLUTION

By two million years ago, there is an apparent increase in the body mass of *Homo* (Pontzer, 2012; Antón et al., 2014), which in turn is related to its wider geographic distribution compared to other hominins (Antón, 2003) and an increase in energy expenditure (Aiello and Key, 2002; Aiello and Wells, 2002). Additionally, there was a shift in the archaeological record from assemblages of low-density artifact scatters in narrower depositional contexts to denser concentrations of archaeological material in a broader array of habitat settings (Plummer and Finestone, 2018). Although earlier hominins had access to a wide array of habitat types (**Figure 4**), *Homo* excelled in the successful exploitation of resources from greater ecological contexts. In eastern Africa for example, greater tool use possibly allowed hominins to adapt to microhabitat variability and ecological instability, as evident in the occupation of a broad spectrum of habitats ranging from open grasslands to riparian forests. At Kanjera South, on the Homa Peninsula in Kenya, hominins exhibited comparatively complex land use and toolmaking behaviors as raw materials were transported from over 10 km (Braun et al., 2008a; Braun et al., 2008b; Braun et al., 2009a; Braun et al., 2009b; Braun and Plummer, 2013). Tools were employed to process a diverse range of resources including animal tissue and underground storage organs and woody and herbaceous plants (Ferraro et al., 2013; Lemorini et al., 2014; Lemorini et al., 2019).

Microhabitat Variability at Oldupai Gorge: A Case Study

As an "archaeosphere" representing the paleoanthropological record of broader eastern Africa, Oldupai Gorge (formerly Olduvai Gorge) presents an interesting opportunity to explore microhabitat variability across both temporal and spatial scales using multiple paleoecological proxies collected in archaeological and geological horizons (**Figure 3**, **Supplementary Figure S1**). Spatial geomorphological, sedimentological, stratigraphic, and geometric analyses are made possible by Oldupai's well-defined Beds: I-IV (2.038 ± 0.005–0.6 Ma), Masek (600,000–400,000), Ndutu (400,000–32,000), and Naisiusiu (17,550 ± 1,000–10,400 ± 600 BP) (Leakey, 1971; Hay, 1976; Deino, 2012; Domínguez-Rodrigo et al., 2013; Diez-Martín et al., 2015). In fact, these beds and marker tuffs, which are exposed for ~25 km throughout the eastern and western gorges, have made it possible to correlate paleoecological and archaeological datasets across time and space, highlighting the evolution of *Homo* within a diverse, variable landscape (Cavallo and Blumenschine, 1989; Sikes, 1994; Blumenschine et al., 2012; Uribelarrea et al., 2014; Uribelarrea et al., 2017; Stanistreet et al., 2018).

At the Ewass Oldupa site, where the earliest evidence of the Oldowan is found at Oldupai Gorge (Mercader et al., 2021), hominins used a homogenous toolset within emerging landscapes and volcanically-disturbed habitats multiple times over 235,000 years. The Oldowan assemblage consists of some raw material sourced from up to ~12 km away and shows technological adaptation to major geomorphic and ecological transitions, whereby stone tool use permitted provisioning across ecologically diverse and complex environments over time and space. Tool use allowed for a more generalist strategy in acquiring plant food resources within a rapidly changing plant landscape that ranged from fern meadows to woodland mosaics, naturally burned landscapes, lakeside woodland/palm

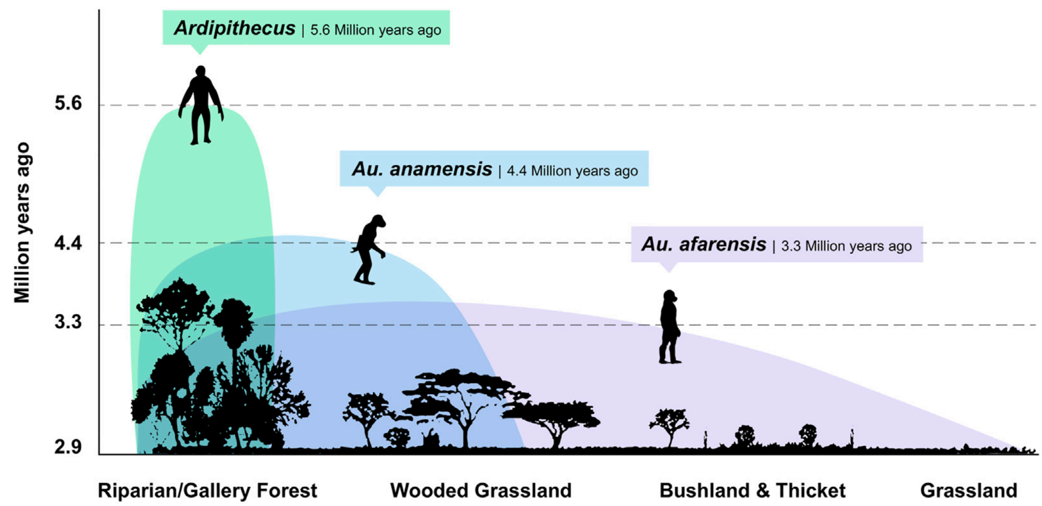

FIGURE 4 | Eastern African hominin paleoecology. The paleoenvironmental record from early hominin bearing sites shows ecologically diversified landscapes. The Mio-Pliocene environments of *Ardipithecus* have been reconstructed as lakeside, mosaic ecosystems that included permanent wetlands, dense woodlands or gallery forests, wooded grasslands, and grasslands, all of which indicate a degree of spatial variability in the proportion of plant type composition and coverage (WoldeGabriel et al., 1994; WoldeGabriel et al., 2001; Levin et al., 2008; White et al., 2009a; White et al., 2009b; Lovejoy et al., 2009; WoldeGabriel et al., 2009; Cerling et al., 2010). *Australopithecus anamensis* also frequented C_3 dominated, closed canopy riparian or gallery forests within an otherwise dry, open acacia woodland catchment (Leakey et al., 1995; Saylor et al., 2019), while *Au. afarensis* accessed open grasslands, dry bushlands, and riparian woodlands and forests (Johanson et al., 1982; Andrews, 1989). In southern Africa (not shown), *Au. africanus* likely had access to forests, ecotones, wooded grasslands, and grasslands (Rayner et al., 1993; Sloggett, 2016), and *Au. sediba* made use of C_3-dominated microhabitats within a regional environment of abundant C_4 grasses ~2.0 Ma (Bamford et al., 2010; Henry et al., 2012).

groves, and hyper-xeric steppes. This generalist strategy and ability to use emerging landscapes, a finding that is unique for *Homo* ~ 2.0 Ma, depicts complex behavior among early Pleistocene hominins. Early evidence of this environmental response suggests that fundamental aspects of human adaptability was not solely connected to our species' origin (Potts et al., 2020), but rather by the time of our genus' origin and likely played a major role in *Homo*'s ability to expand within and beyond Africa.

Perhaps the most well-known locality at Oldupai is the Frida Leakey Korongo (FLK) site, as it was here at "Level 22" (better known as FLK *Zinj*) that Mary Leakey discovered *P. boisei* in 1959 (Leakey, 1959). This level, situated between Tuffs IB and IC (**Supplementary Figure S1**), was interpreted as an occupation or living floor (Leakey, 1959; Leakey, 1971), where hominins made stone tools to butcher mammals from nearby habitats (Bunn and Kroll, 1986; Blumenschine, 1995). Situated in uppermost Bed I and only ~100 m north of FLK *Zinj* is FLK North, one of the richest Pleistocene archaeological deposits known (Leakey, 1971; Domínguez-Rodrigo et al., 2010). FLK N is a 3.0 m, 15,000-years sequence in Upper Bed I subdivided into nine archaeological units dated between 1.803 Ma and 1.818 Ma (Deino, 2012). The marker tuffs that cap each site, and the organic rich silty-waxy clays directly in contact below the tuffs, are observable in exposures for more than 2 km throughout the main confluence of the gorge (**Figure 3**). These organic-rich clays were deposited on the alluvial fans and floodplains surrounding paleo-Lake Oldupai and have been the focus of recent paleoecological, microhabitat variability studies.

There is evidence from plant wax biomarkers (Magill et al., 2015; Patalano, 2019) and phytoliths (Barboni et al., 2010; Blumenschine et al., 2012; Arráiz et al., 2017; Itambu, 2019), collected from organic rich clays directly in contact with both Tuff IC and Tuff IF, for ecologically diverse hominin microhabitats throughout the Oldupai depositional basin (**Figure 3**, **Figure 5**). A combination of plant wax biomarkers and their stable carbon isotopes, phenol derivatives of lignin which distinguishes woody from herbaceous plants, fern and sedge biomarkers that demarcate wetlands, and phytoliths revealed the geographic distribution of different microhabitats across the FLK *Zinj* paleo-landscape (Magill et al., 2015; Arráiz et al., 2017). Abrupt changes from wetland vegetation, to dense C_3 woody coverage, to open C_4 grassland were identified at meter-level scales, showing that FLK *Zinj* was a forest microhabitat adjacent to a wetland situated within a greater grassland catchment (Magill et al., 2015). Compounded with the phytolith results, which are dominated by woody morphotypes and supported by grass, sedge, and palm types (Arráiz et al., 2017), both datasets indicate relatively wet and wooded microhabitats across the FLK *Zinj* landscape, situated within a catchment dominated by arid-adapted C_4 species. Additionally, plant wax carbon and hydrogen isotopes and biogenic silica also show that C_3 plants dominated the archaeological assemblage at FLK N (Itambu, 2019; Patalano, 2019). Phytolith and plant wax data from the clays directly below Tuff IF indicate that at the top of Bed I, Oldupai's landscape was variable mosaic with areas of dense vegetation and abundant fresh water (e.g., FLK N), *Typha* dominated wetlands, open grassland, and ecotones (**Figure 5**).

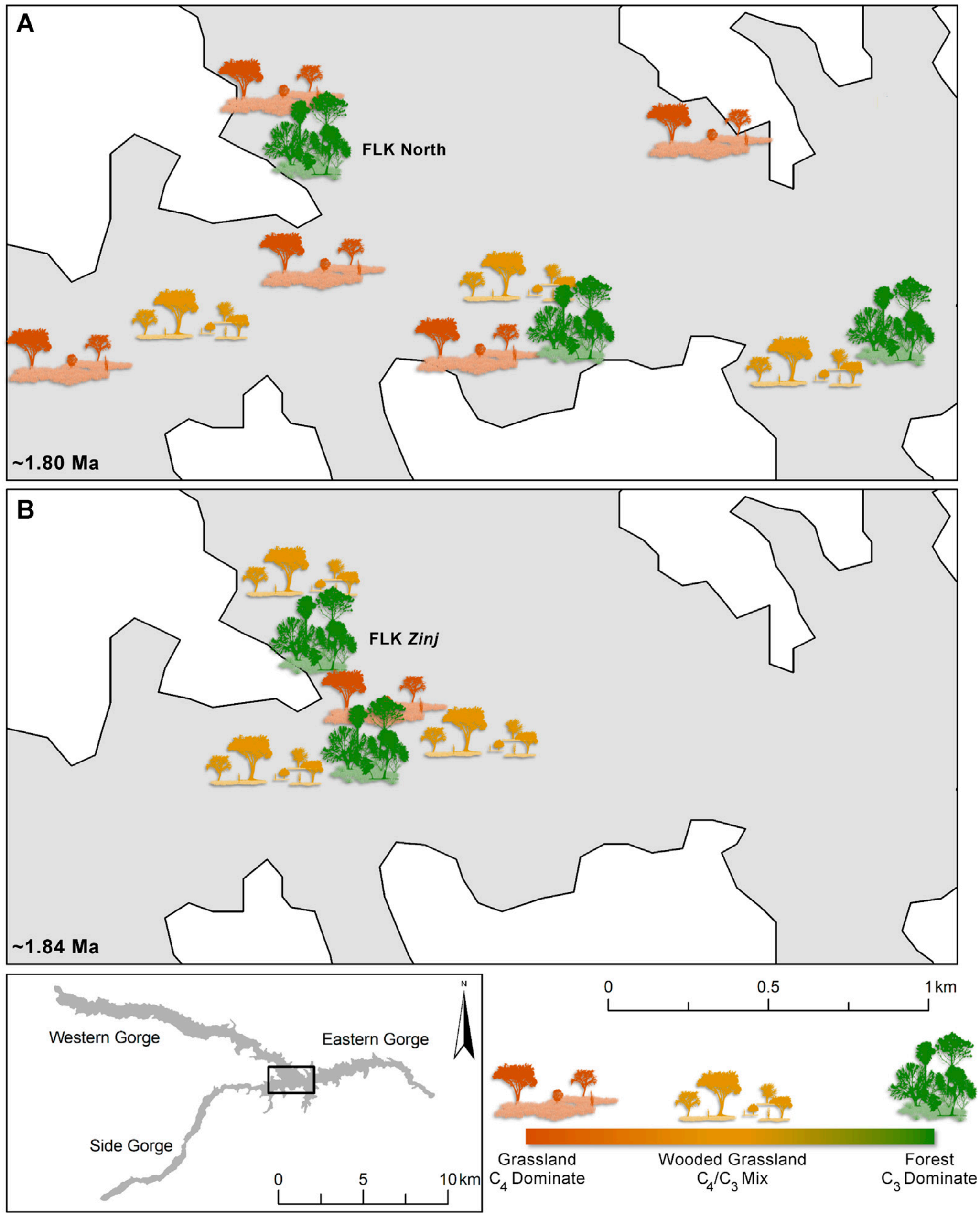

FIGURE 5 | Microhabitat Variability at Oldupai Gorge at ~1.8 and ~1.84 Ma reconstructed from plant wax biomarker and phytolith analyses. **(A)** Data from the clays directly below ~1.8 Ma Tuff IF (Itambu, 2019; Patalano, 2019). **(B)** Data from the ~1.84 FLK *Zinj* horizon (Magill et al., 2015; Arráiz et al., 2017). Microhabitat icons are not to scale but rather represent the reconstructed plant landscape structure at given sampling locations based on plant proxies.

Interpreted as a woodland or even a true forest, the reconstructed C_3 environment at FLK N suggests that it may have been similar to the dense evergreen forest that now flourishes near freshwater springs percolating out of the rift escarpment on the northwestern and western shores of Lake Manyara.

The archaeology and paleontology of each site indicate that hominins butchered animals at FLK *Zinj* (Leakey, 1971; Blumenschine, 1995; Dominguez Rodrigo, 1997; Domínguez-Rodrigo and Barba, 2007; Domínguez-Rodrigo et al., 2014), but processed hard-shelled nuts and fruits at FLK N (Domínguez-Rodrigo et al., 2007a; Diez-Martín et al., 2010; Domínguez-Rodrigo et al., 2010). Apart from the FLK *Zinj* Level 22 and David's Site (DS) (Domínguez-Rodrigo et al., 2017a), no other Bed I site provides evidence for access and the direct consumption of animals by hominins (Domínguez-Rodrigo et al., 2007b; Domínguez-Rodrigo et al., 2017b). That is, all other sites seemingly involved the use of Oldowan tools for plant processing (cf. Blumenschine, 1995). Woody vegetation patches may have been the incentive that enticed hominins to use FLK *Zinj* and FLK N as focal points on the landscape to process both plant and animal foodstuffs acquired within the microhabitats that developed across Oldupai's basin.

EXPANDING THE MICROHABITAT VARIABILITY FRAMEWORK

Over the past two decades, spatial paleoecological analyses have allowed us to better understand the ways in which hominins adapted to microhabitat variability across space and time. Others have brought attention to the role microhabitat variability played in creating potentially resource-rich habitat types and opportunities for niche diversification and specialization amongst hominins (Stern, 1993; Foley, 1995; Cachel and Harris, 1998; King and Bailey, 2006; Reynolds et al., 2015). Higher spatial resolution environmental proxy data and more-precise dating techniques (Herries et al., 2020; Martin et al., 2021), even demonstrate the influence of microhabitat variability in shaping hominin evolutionary biology and anatomy. Although the focus has been on early *Homo* from around 2.0 Ma and at Oldupai Gorge, morphological differences between *P. robustus* from Drimolen and Swartkrans in South Africa, which are only ~6 km apart, represent highly resolved evidence for microevolutionary change associated with ecological variability across a short time frame and restricted geography (Martin et al., 2021). Differences in mandibular morphology between specimens from each location developed as a dietary adaptation to a marginal ecological setting. That is, the slightly younger but more robust Swartkrans *P. robustus* exhibit a more efficient bite force, likely representing a microevolutionary change within this population due to a dietary shift toward foods that were mechanically challenging to process (Sponheimer et al., 2006). This coincided with a reduction in ecological productivity following increased aridity and small-scale microhabitat reorganizations (Caley et al., 2018).

The Oldupai case study highlights how global and regional climate, tectonic and sudden geomorphological activity, and hydrogeography all contribute to spatially variable, often ecologically diverse and environmentally complex biomes, ecoregions, habitats, and microhabitats. Based on the available evidence, the ability of the genus *Homo* to adapt and thrive across regions of both high and low ecological diversity, as well as within ecosystems that change drastically, was in place by at least 2.0 Ma and likely assisted in technological developments and dispersals within and beyond Africa later in time. For instance, *H. sapiens*' successful ability to innovate under decreased resource predictability was cultivated by an evolutionary history of navigating complex and diverse ecological transitions. In the Olorgesailie basin of Kenya, the onset of the eastern African Middle Stone Age (MSA) is tied to *H. sapiens* behavioral and technological adaptation to habitat and resource variability (Potts et al., 2020). Between 400 and 320 Ka, dynamic landscape change through space and time (triggered by geologic, climatic, and ecological factors) likely led to lower resource reliability and may have necessitated that *H. sapiens* adopt MSA types of stone tool technology as a hunting innovation (Potts et al., 2020), specifically as distinct ecological zones developed over a distance of less than 20 km following increases in Middle-to Late-Pleistocene aridification and environmental variability (Owen et al., 2018).

By filling a "generalist specialist" niche, *Homo* and especially *H. sapiens,* excelled at adapting to environmental extremes and exploiting microhabitat variability across deserts, at high altitudes and latitudes, and within tropical rainforests, was able to successfully innovate under periods of decreased resource predictability (e.g., Potts et al., 2020), and construct their own environments (e.g., Thompson et al., 2021). As this ability to adapt and thrive in dynamic environments was already well-established in *Homo,* the addition of unique behavior like complex ecological knowledge and plant landscape modification and construction, eventually allowed *H. sapiens* to occupy of a wide diversity of ecological settings across the majority of the Earth's continents (review in Roberts and Stewart, 2018).

The microhabitat variability framework suggests that as African landscapes were impacted spatially by tectonic activity and hydrogeology, and temporally by orbital forcing and rainfall seasonality, the flexibility of *Homo* was likely beneficial in unstable, unpredictable, or unfamiliar environments. As tool innovation and use, specifically after 2.0 Ma, allowed for a more generalist strategy in acquiring plant and animal food resources across diverse and rapidly changing landscapes, the adaptive versatility of *Homo* and the capacity to adjust to new habitat types may have helped to withstand periods of extreme climate variability throughout the Pleistocene. There are numerous hypotheses regarding climatic variability driving hominin evolution and the eventual appearance and dispersal of our species (**Table 3**). However, there has been less consideration of ecological variability across space, largely due to sampling and methodological issues (also Faith et al., 2021). With new, transdisciplinary approaches toward reconstructing hominin environments directly on-site and across archaeological and geological horizons, we can address and test the following research questions:

- Did Pliocene and Pleistocene hominins rely on oases of woodland/forest habitats within wider grassland ecoregions? If so, to what extent and for what purpose (e.g., protection, food)?
- Did dispersals of hominins simply occur when larger ecoregions expanded (e.g., "savannah" corridors (Dennell and Roebroeks, 2005))?
- On the other hand, did geographic ecological variability always play a role in hominin dispersals first across Africa and then beyond?
- How can we better factor the microhabitat variability framework into paleoclimatic, paleoenvironmental, and evolutionary models? That is, can we go beyond the natural selection and speciation models that use distal proxy records to compare climate windows to biome and ecoregion changes and the ensuing influence on genetic variability and human evolution?

To tackle these questions, future research designs should consider correlating and sampling terrestrial sediments from archaeological and geological horizons to collect and analyze such environmental proxies as outlined in **Table 2**. This would involve identifying geologic strata and their geographic extent, collecting sediments from correlated deposits, testing organic preservation, and then paleoenvironmental reconstruction through proxy analyses. By understanding the spatial variability of environments and locations of concentrated archaeological assemblages, we can then better interpret hominin land-use patterns and activity within a regional and global climatic context to discern the ways in which *Homo* adapted to microhabitat variability over time and space.

CONCLUSION

Microhabitat variability provides a framework within which to understand the adaptability of hominins across spatially and temporally changing, sometimes rapidly, plant landscapes. Because members of the genus *Homo* were already adept at exploiting diverse food-types from multiple habitats including disturbed and emerging environments by 2.0 Ma, they successfully navigated ecosystem reorganization during pulses of climate instability throughout the Pleistocene. By incorporating paleoecological analyses for studying microhabitat variability in future paleoanthropological research, we can better interpret the evolutionary importance of climatic and non-climatic stressors and plant landscape responses to then validate or refute the habitat specific or variability hypotheses.

A microhabitat variability approach incorporates evidence for adaptations involving tool use, demonstrated by Oldowan hominins from Oldupai, high-resolution environmental proxy evidence for meter-scale changes in hominin landscape ecology, and field and laboratory methodologies for identifying patches of distinct plant communities that may have offered unique food resources and shelter. With research designs that focus on exploring and understanding hominin microhabitat variability, we can uncover further information relating to major adaptive morphological, technological, and cultural features that have not been fully addressed by human evolution environmental hypotheses. This approach, therefore, has the potential to significantly contribute to current interpretations of hominin evolutionary processes within an ecological framework by uncovering additional evidence for *Homo*'s successful exploitation of resources under wide-ranging climate zones and ecoregions within and then beyond Africa.

AUTHOR CONTRIBUTIONS

RP, EF, RH, and PR conceived the concepts presented throughout; all authors wrote and revised the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.787669/full#supplementary-material

Supplementary Figure S1 | Stratigraphic subsections of Bed I. The expanded profile is of the FLK-N Oldowan site. Ewass Oldupa is located stratigraphically below Tuff IA and dates to 2.038 ± 0.005 Ma (Mercader et al., 2021). Stratigraphic and archeological units are not to scale except for the 3 m FLK-N profile. Dates and stratigraphy adapted from Ashley et al., 2010; Deino, 2012; Diez-Martín et al., 2015; Domínguez-Rodrigo et al., 2007; Hay, 1976; McHenry and Stanistreet, 2018; Stanistreet, 2012.

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REVIEW
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Evidence of the Storegga Tsunami 8200 BP? An Archaeological Review of Impact After a Large-Scale Marine Event in Mesolithic Northern Europe

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Around 8,200 years ago, the Storegga tsunami hit the coasts of the Norwegian and North Seas. This event is well known from wide ranging geological and palaeobotanical work undertaken over the last 30 years. Outside of attempts at palaeodemographic models, however, exploration of the social impact of the wave on Mesolithic hunter-gatherer societies living on the coasts of west Norway, the north and east British Isles, and around the southern North Sea basin have been less common. It has been widely assumed that the tsunami was a disaster–but what constituted a disaster for the Mesolithic peoples who lived through this event? What can we learn about life after natural hazards by considering the archaeological material from regions with distinct Mesolithic histories? This paper presents a review of evidence of the Storegga tsunami at Mesolithic sites from western Norway, the Northeast UK, and elsewhere around the southern North Sea basin. We consider the ways in which the social impact of the Storegga tsunami has been studied up till now and suggest an alternative way forward.

Keywords: Storegga tsunami, mesolithic, Norway, Scotland, Doggerland, disaster, archaeology

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INTRODUCTION

"*After the tidal wave, the Indians told of tree tops filled with limbs and trash and of finding strange canues* [sic] *in the woods. The Indians said the big flood and tidal wave tore up the land and changed the rivers. Nobody knows how many Indians died*" (Beverly Ward, recounting stories told to her around 1930 by Susan Ned, born in 1842, Ludwin et al., 2005, 142).

Although recalling events that occurred generations prior (17th Century), the opening quote still indicates the impact a tsunami can have. It describes a force of nature which physically transformed the landscape, bringing carnage and untold loss of life, and conjuring an image of a terrifying and traumatic event. Around 8,200 years ago, a massive multi-phase submarine landslide (the Storegga Slide) off the continental shelf of Central Norway caused a tsunami to hit the coastlines of west Norway, Scotland, and around the southern North Sea basin. This was seemingly the largest tsunami event to hit this area since at least the beginning of the Holocene. It is well known thanks to geological and palaeobotanical investigations undertaken over the last 30 years (e.g., Svendsen 1985; Dawson et al., 1988; Dawson et al., 1990; Bondevik et al., 1997; Dawson and Smith 2000; Bondevik et al., 2003; Bondevik et al., 2012; Løvholt et al., 2017). Evidence has been found as far away as Greenland (Wagner et al., 2006) and the event is well documented from many locations on or near the Norwegian and northern UK shorelines (**Figure 1**).

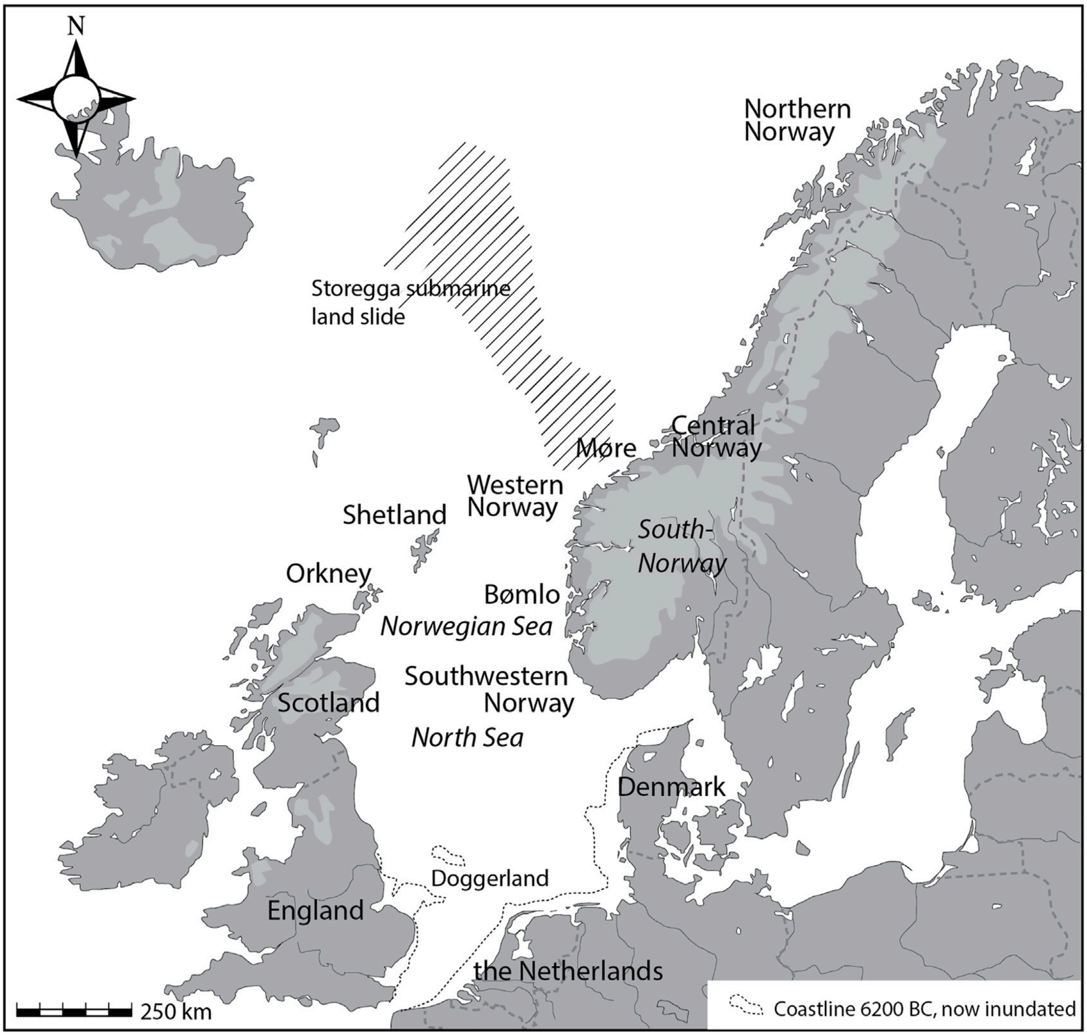
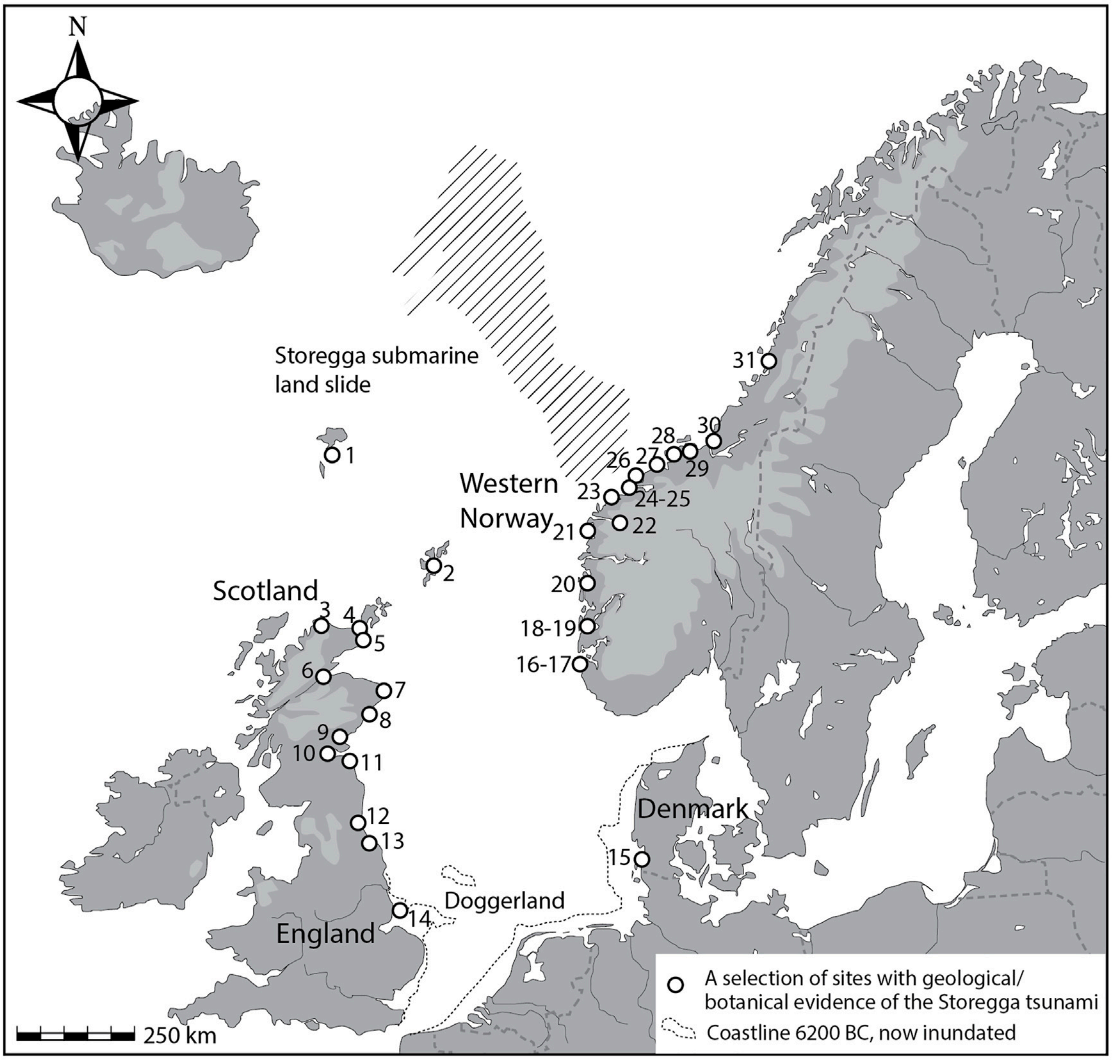


FIGURE 1 | Map with names on regions and places mentioned in the text (Illustration: A.J. Nyland).

The size of the Storegga tsunami has led to it being commonly assumed as having been a disaster for the hunter-gatherer-fisher (Mesolithic) societies living on shores of Norway and the North Sea basin (e.g., Edwards 2004; Bjerck 2008; Waddington 2014; Waddington and Wicks 2017). While the tsunami itself has been well evidenced, the effects it had upon coastal Mesolithic communities have been less systematically explored. To add to the challenge, the tsunami appears to have struck at the coldest period of a climatic downturn associated with this stage of the Holocene, the 8.2 ka climatic downturn (Bondevik et al., 2012), making it challenging to differentiate the impact of these two events. To date, most assessments have had to infer cultural effects from primarily environmental data, or utilise large-scale palaeodemographic modelling to summarise trends that amalgamate rather than differentiate the 8.2 and Storegga events (Wicks and Mithen 2014; Waddington and Wicks 2017; Mithen and Wicks 2021). In this paper, we attempt to give a broad overview of the cultural data to hand, presenting a regional assessment of the Mesolithic record broadly contemporaneous with Storegga tsunami from western Norway, Northeast UK, and the southern North Sea basin. The period in question spans between 7,500–5,000 BC, with the tsunami placed at around 6200 BC (8,150 cal BP). Based on recorded sites, we know that Mesolithic people in Norway, Scotland, and northern UK, were coastal dwellers, living on shores of islands and headlands, or along resource-rich tidal currents, but what archaeological material is there to indicate how people were affected by the tsunami?

Climate change, tsunami-disasters, and other natural hazards leading to societal disruption and devastation have increasingly come into focus the last 25 years in anthropology (e.g., Oliver-Smith 1996; Oliver-Smith and Hoffman 1999; Barrios 2016; 2017), and archaeology (e.g., Grattan and Torrence 2002; Riede 2014; Egan and Sheets 2018; Riede and Sheets, 2020). Increasingly, it has also been acknowledged that "*Hazards [. . .], can no longer be thought to have a purely "natural" ontology; rather, the human and social now reside within them*" (Barrios



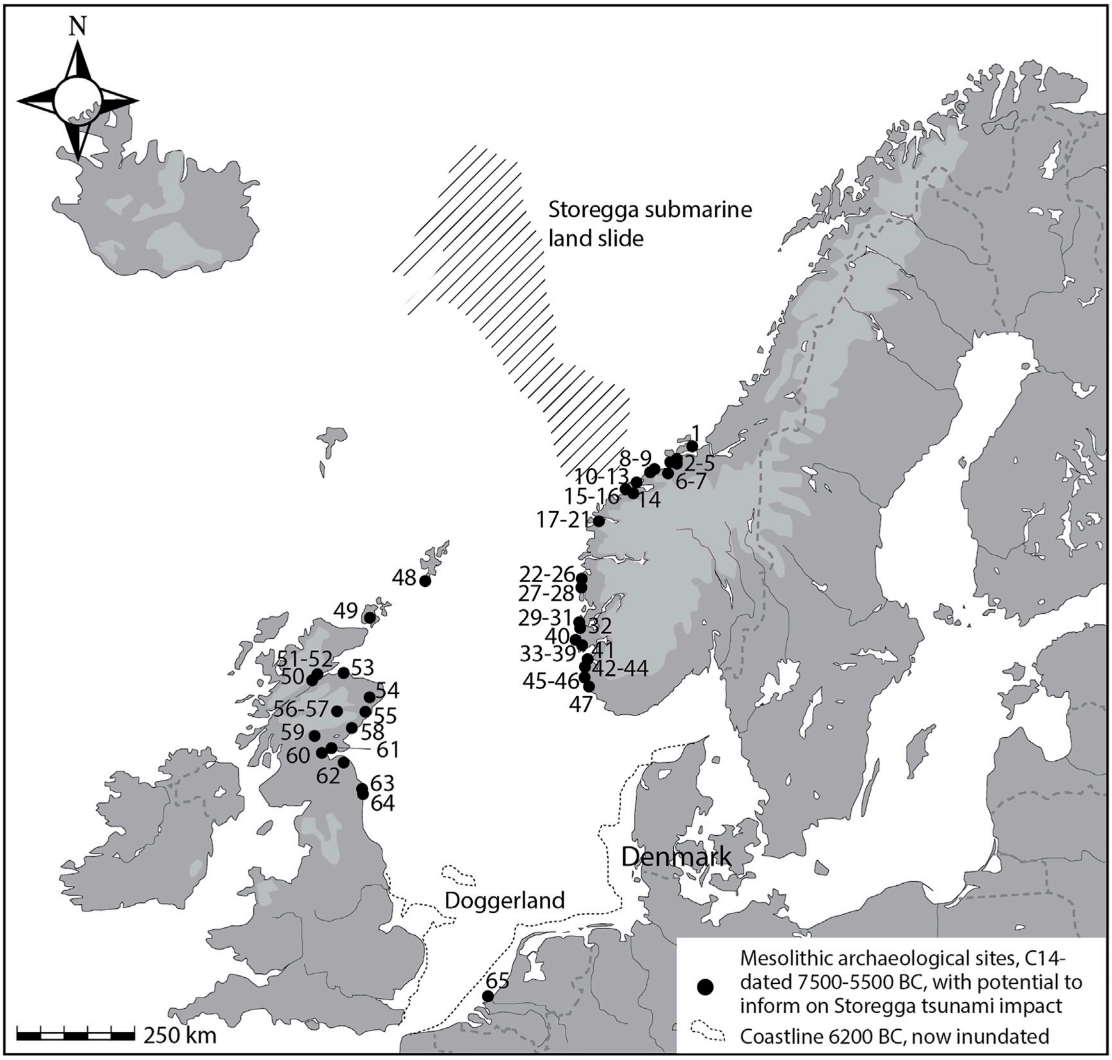
1 Suderøy; 2 Unst; 3 Loch Eriboll/ Lochan Harvurn; 4 Sutherland/Caithness; 5 Dornoch Firth; 6 Inner Moray Firth; 7 North East Scotland ; 8 Tayside; 9 Near St. Andrews (Silver Moss, Craigie); 10 Firth of Forth; 11 Near Dunbar (East Lothian); 12 Broomhouse Farm; 13 Howick; 14 ELF 001A; 15 Rømø; 16-17 Hålandsvannet & Sola; 18-19 Løvegapet & Bømlo; 20 Austrheim; 21 Florø; 22 Nordfjord; 23 Bergsøy/Leinøy; 24-25 Longva & Dysvikja; 26 Harøy; 27 Lok.30 Nyhamna; 28 Leira; 29 Litjvatnet; 30 Bjugn; 31 Hommelstø

FIGURE 2 | Map with sites where Storegga tsunami deposits have been geologically and botanically identified. Information is compiled from published papers, book chapters and reports, as well as unpublished (archival) excavation reports].

2017, 156). Nevertheless, our review demonstrates how the identification of the Storegga tsunami impact has primarily been reliant upon natural markers and top-down analyses of cumulative-data, and because of this, there are gaps in our knowledge. We still don't understand the tsunami's social impact, even at a local level, for the Mesolithic coastal communities who lived through it. However, as our review will show, the material that can enable such studies is growing. How do we investigate prehistoric impact if we cannot find direct evidence of "squashed Mesolithic people" (Wickham-Jones 2002)? Perhaps a better approach would be to use the Storegga tsunami as a point of departure from which to discuss the ways in which prehistoric communities may have withstood or recovered from a catastrophic event.

EVIDENCE OF THE STOREGGA TSUNAMI; A REGIONAL OVERVIEW

Evidence of the Storegga tsunami was first recognized in the 1980s, and in the years that have followed, a number of research papers have identified deposits relating to the tsunami (e.g., Svendsen and Mangerud 1987; Dawson et al., 1988; Bondevik et al., 1997; Bondevik et al., 1998; S. Dawson and Smith 2000;



1 Fillan trafo; 2-3 Kalveheiane 2 & 3; 4 Myrset; 5 Leira; 6-7 Meisingset 1-2; 8 Lok.11 Hestvikholmane; 9 Henda; 10-13 Lok. 29, 30, 50 Nyhamna, Lok. 62 Grunnvika; 14 Lok.1 Sætergården; 15-16 Lok. 65 Longva & Dysvikja; 17-21 Lok. 17 (Phase 1), 19 & 154 Havnen, Lok. 30 Nygård (Phase 1), Lok. 6 Haukedal (Phase 1); 22 Botnaneset VIII/1&2; 23-26 Kotedalen Phase 2-4; 27-28 Lok. 6. Revarvika & Lok.17 Budalen; 29 Lok.111 Djupedalen; 30 Grunnavåg; 31 Svortland; 32 Løvegapet; 33 Breiviksklubben; 34-38 Botten 1, Helleren lok.2; Lindøy lok. 4 & 1b, Fosnaneset lok.1b; 39 Nedre kvinnesland; 40 Fiskåvatnet; 41 Vistehola; 42-44 Ølberg, Sola Sentrum, Sunde 34; 45-46 Lego I -II; 47 Hå Old Vic; 48 West Voe; 49 Longhowe; 50 Tarradale; 51 Muirtown; 52 Castle street; 53 Lesmurdie Rd.; 54 Warren Fields; 55 Garthdee; 56-57 Chest of Dee : 58 Broughty Ferry; 59 Edramucky Burn; 60 Chapelfield; 61 Castlandhill; 62 Fallago Rig; 63 Howick; 64 Low Hauxley; 65 Yangtze Harbour

FIGURE 3 | Overview of sites that have the potential to demonstrate impact of the Storegga tsunami on a regional level. The list is not exhaustive, but it gives an overview of primarily coastal Mesolithic sites that are C14 dated to around the period that the tsunami hit. Information is compiled from published papers, book chapters and reports, as well as unpublished (archival) excavation reports listed in **Supplementary Table S1, S2**.

Selvik, 2001; Bondevik et al., 2005; Prøsch-Danielsen 2006) (**Figure 2**). These works bear testament to the magnitude of the tsunami, on the coasts of western Norway and the northern UK. During the 1990s, awareness of this event slowly became apparent in the archaeological literature too. For example, a potential tsunami deposit at the Mesolithic site of Castle Street, Inverness, had been reported, but due to the timing of the discovery, had not initially been connected to the Storegga event (Wordsworth et al., 1986; Dawson, Smith et al., 1990). This was later reinterpreted as a tsunami deposit by geographers who were already familiar with the phenomenon (Dawson et al., 1990). In Norway, the tsunami was also starting to be discussed as a potential depositional agent in site reports in the 1990s (e.g., the site Leira, see Johansen and Sandvik 1995; Lok1 Sætergården, see Simpson 1998).

The Norwegian coastline presents a "topographic, bathymetric, and environmental mosaic", to quote Blankholm (2018), and the complexity of this mosaic only increases when expanded to include the surrounding of the North Sea basin for consideration. This complexity, alongside differences in national research traditions, as well as, of course, genuine archaeological variability, affects the number, preservation, and location of archaeological sites across different regions. Hence, West Norway, the UK, and the Mesolithic southern North Sea perimeter, hold different 'archives' and archive potential for studying the impact of the tsunami.

Western Norway

In western Norway, the Middle (ca. 8,000–6000 BC) and Late Mesolithic (ca. 6000–4000 BC) population had a pronouncedly coastal orientation, living at the shores, exploiting islands, islets, headlands, bays, and along tidal currents (e.g., A.B. Olsen 1992; Bergsvik 1994; Nærøy 1994; Bergsvik 2002a; Bjerck 2008; Bjerck et al., 2008; Skjelstad 2011; Bergsvik et al., 2020). As acidic soils have broken down most organic materials, dating of sites is often aided by sea-level variation, a method that has long been integrated in Norwegian Stone Age archaeology (Fægri 1944; Kleppe 1985). Lately, sea-level curve adjusted site heights and C14 dates have begun being compiled (e.g., Bjerck et al., 2008), as recent development led archaeological excavations have increased the number of radiocarbon dated sites before/after the tsunami. Moreover, the increase in number of well excavated and dated sites gives new possibilities to investigate variation or continuity in mobility patterns, settlements, lithic technology, etc. (**Figure 3**, **Supplementary Table S2**).

With some regional exceptions, most recorded Mesolithic sites in Norway are currently on dry land, their location range in general somewhere between 7–20 m. a.s.l. However, due to a period of marine transgression in the second half of the Middle Mesolithic, sites became covered by beach deposits (see Nyland 2020 for examples of varying sea level curves). This *Tapes-transgression* reached its maximum during the Late Mesolithic (Fjeldskår and Bondevik 2020). Depending on the exposure to, and level of wave energy, the preservation status of sites and material found below transgressed beach sediments varies (e.g. Bjerck et al., 2008; Skjelstad 2011; Åstveit, 2016). Finds can be severely water rolled, enmeshed in clay or gravel, or, if the transgression was sheltered and slow, pristine and sealed. Nevertheless, the covering and potential disturbance of Middle Mesolithic sites are elements that needs to be considered when how representative the sample of sites from the time around the Storegga tsunami is. Still, the Tapes-transgression notwithstanding, there is a good number of Middle/Late Mesolithic sites that enable studies of life before and after the Storegga tsunami. Thus, we will mention some key sites in three distinct areas along the west coast and representing the kind of sites one can study along the Norwegian sites (but see **Figure 3** and **Supplementary Table S1** for an overview of radiocarbon dated sites from before and after the tsunami).

As stated, there are sites that are clearly transgressed and disturbed after occupation by the tapes transgression. For example, at the Fosen peninsula at Karmøy, Rogaland County, five sites were dated to the Middle and Late Mesolithic (Skjelstad 2011). One of these sites, Botten 1, one layer was dated to the Middle Mesolithic, 6,830–6,650 cal BC (7,900 ± 40 uncal BP, Beta-1973313); under a layer of gravel and sand, there was a clay layer with pristine finds. The finds were intact, perhaps because the site had been located in a sheltered bay, still, its site distribution and cultural layers were disturbed (Olsen 2011). There was charcoal dated to 6,370–6,230 cal BC in the layer too (7,420 ± 50 uncal BP, Beta-198763), that is, from a time the site was already transgressed. Hence, the situation indicates a disturbance, but whether it was caused by the Storegga tsunami, remains up for debate.

Other sites, such as one on, and under a raised beach at Løvegapet, Bømlo in Hordaland, are also clearly disturbed by the transgression as seen in water-rolled lithics (Åstveit, 2016). However, here, the gravel and sand also sealed layers which give opportunities for dating continual phases of activity at one and the same site (*ibid.*). Moreover, in the immediate vicinity of the Mesolithic activity, the raised beach has also sealed a 20 cm thick sandy layer which is interpreted as a Storegga deposit (Åstveit, 2016). Another site with persistent habitation is Kotedalen, located further north, on the side of a strong tidal current in Hordaland. The site was excavated in the late 1980s (Olsen 1992) and extensive zoo-osteological, botanical macro- and micro-fossil analyses were undertaken (Hjelle, 1992). A cultural layer with a total of 16 Stone Age phases was identified, where Phases 2–6 date from 6,560 to 5,580 cal BC (approx. 7610–6800 uncal BP), i.e., immediately spanning the Storegga event (Olsen 1992, 266) (see also **Supplementary Table S2**). Other sites with cultural layers dating to before and after the event include Nyhamna, Aukra, Møre og Romsdal. In 2003-2004, a total number of 28 sites located in immediate proximity to each other were excavated (Bjerck et al., 2008). Compared to Kotedalen, less organic material was preserved, but thick cultural layers provided the possibilities for extensive radiocarbon dating, as well as botanical analyses of macro fossils and pollen. From the project as a whole, there are 287 radiocarbon dates, including AMS and conventional dates (Bjerck et al., 2008, 79). At least four sites of varying size, content, organization and in different condition are dated to the period before and after the tsunami event (see **Supplementary Table S2**). In a trench through a wetland area, a sediment trap between two of the sites (Sites 29 and 30) dated to the Middle and Late Mesolithic, a layer consisting of unsorted material, sand, gravel, stones was dated and interpreted based on two dates: 6,380–6,220 cal BC and 6,375–6,220 cal BC, and heterogeneous composition as a tsunami deposit (Bjerck et al., 2008, 126–127). The same layer was not documented on top of the cultural layers at Sites 29 and 30, which again opens the question as to how to directly identify the impact of the Storegga event archaeologically.

In general, pertaining the Norwegian evidence, despite the comparatively large scale of recent archaeological investigations, there are not many sites where impacts of the Storegga tsunami have been directly documented, beyond layers in nearby wetland areas. Nevertheless, the recent extensive development led archaeological excavations of Mesolithic sites has greatly improved the number of sites where one can investigate persisting traditions in settlement and lithics production. There are more, and better radiocarbon dated sites and layers. The thick cultural layers at some sites indicate a tradition for reoccupation of the same place over time, of persistence of maritime traditions or site location preferences throughout the Mesolithic. The mentioned examples are from different parts of the west coast of South Norway, which the tsunami hit with varying force. We must thus assume that the impact, as well as experience would have led to varying responses. There is material to discuss, but the challenge is perhaps to securely relate it to tsunami impact.

Eastern Scotland and Northeast England

The potential human impacts of the Storegga tsunami in Eastern Scotland have been identified through a small number of claimed associations between archaeological deposits and tsunami deposits and overall models of changing activity (**Figure 3**, **Supplementary Table S1**). The Mesolithic of Eastern Scotland is poorly resolved chronologically, and the tsunami falls with the Later Mesolithic as traditionally and typologically defined (ca. 8,000–4,000 BC)—a period too broad to be of much analytical value. Numerous surface collections indicate the importance of coastal landscapes, as well as inland areas, but are not suitably chronologically resolved to contribute meaningfully to debate, so the discussion here is limited to reliably radiocarbon dated sites dating to ca. 7,500–5,000 cal BC, and with a primary focus on those located near the coast. The shell middens at Morton (Coles 1971) have long held a position of prominence in discussions of the Mesolithic in East Scotland, and appear to have been sites of occupation for some time, but issues with the reliability of dating at these sites (Warren 2015) renders it difficult to integrate them into considerations of the tsunami event. It is important to stress that the quantity of data available in Scotland is much smaller than Western Norway.

Broadly speaking, the tsunami falls into a period when evidence of hunter-gatherer activity includes pits, middens, and occupation soils. Structural evidence is rare. The younger of two post circles at Lesmurdie Road is dated to ca. 6,200 cal BC. These poorly understood features *may* be large houses, but are not associated with any artefacts (Suddaby 2007). A small tent has been identified at Caochanan Ruadha, >500 m above sea level in the Cairngorm mountains and was occupied at ca. 6,200–6,050 cal BC (Warren et al., 2018). The site is at least 70 km as the crow flies from the coast.

Pits, some with artefacts and some without, are known from before, contemporary with, and after the tsunami and are found in coastal and inland, upland locations. The latter include two datings to 6200 cal BC and without any artefacts at 450 m msl, at Fallago Rig, in the Lammermuirs, about 20–25 km from the sea as the crow flies. A pit on a prominent moraine at 630 m msl at Edramucky Burn, Ben Lawers, dates to c. 7,200–6,700 cal BC and is at least 80 km from the coast (Atkinson 2016). An alignment of 12 pits at Warren Field, inland on the River Dee and dating to the early eighth and seventh Millenia is sometimes claimed to have astronomical alignment (Murray et al., 2009; Gaffney et al., 2013). Inland, at Chest of Dee in the Cairngorms, occupation soils, fire settings and pits have all been identified showing long-term, but discontinuous use of a persistent place, with key episodes of activity at 7,000–6,500, 6,200–6,000 and 5,500–5,000 cal BC (Wickham-Jones et al., 2020).

Some coastal locations for activities including the use of pits appear to have been used prior to and after the tsunami. At Chapelfield, in Cowie, for example, located at the edge of the carse clays at Stirling, Mesolithic activity included the deposition of carbonized material in pits between the early seventh millennium and the mid-fifth millennium BC (but not continuously). Deposition in pits at this location continued into the Neolithic (Atkinson 2002). Excavations at Castlandhill on the north shores of the Firth of Forth found an oval, pit-defined (?) structure *c.*4.7 × 3 m in size (Robertson et al., 2013). Later Mesolithic artefacts were found in post holes, but with no material suitable for radiocarbon dating. A scatter of pits near the structure with two distinct clusters includes examples dating to 6,800–6,600 cal BC and 5,300–5,050 cal BC, with more pits a little further away dating to 4,900–4,700 cal BC. Another pit, again with no artefacts but in this instance sealed with a carefully placed stone layer was found above the River Dee a short distance from the coast at Garthdee, and dates to ca. 5,500 cal BC (Murray et al., 2014). At a very broad scale, this seems to imply some continuity in practice before and after the tsunami.

Middens in the Beauly Firth include examples at Tarradale which are found on both the 17 and 9 m.a.s.l raised beaches with dates on the former ranging from 6,500 to 6,000 cal BC. Middens have been observed in Inverness, but are poorly understood, and another example at Muirtown (Myers and Gourlay 1992) is mid fifth millennium in date. A single radiocarbon date on charcoal from the "lower oyster midden" at West Voe, Shetland is c. 6800 cal BC (Edwards et al., 2009; Ballin 2011), but almost all of the other dated activity on site is very late fifth or even fourth millennium.

Occupation soils are also known, and some are claimed to have associations with tsunami deposits. At Castle Street, Inverness, an occupation soil contains lithics and charcoal (Wordsworth et al., 1986). Two bulk charcoal dates from the occupation soil lie in the mid seventh millennium cal BC[1]. The occupation deposits are claimed to be truncated by Storegga tsunami deposits (Dawson et al., 1990). It is not possible to assess how much time elapsed between the occupation and the tsunami deposits, nor if this location was a long-term focus of settlement. Post-tsunami the site is characterised by beach sand not a forest soil, so there appears to be local environmental change which may have been caused by the tsunami or other longer-term processes of change.

Late 19th century excavations at Broughty Ferry (Hutcheson 1886) are sometimes claimed to show a relationship between tsunami deposits and Mesolithic activity (Dawson et al., 1990). The initial report identified a "black band with flints and rounded stones" sealed by an approximately 60 cm sand deposit. Although the artefacts are now lost, Lacaille considered them to be Mesolithic, and described the overlying deposit as an "exceptional tide which disturbed the refuse of occupation" but it is not clear what the basis is for this claim (Lacaille 1954, 177). Given the lack of modern excavation or stratigraphic interrogation control and techniques, the scant

[1]Two bulk charcoal dates lie in the mid seventh millennium cal BC, but they are inverted, and one has a very large standard deviation.

recording of information from this pre-1900s investigation and lack of any associated dating evidence means that caution is needed in interpretation (Lacaille 1954, 177). Finally, truncated occupation deposits in bedrock hollows were also identified at Longhowe, Orkney. These deposits survived when the ground surface was stripped to construct a barrow: they include microliths and other lithics and hazelnuts dating to 6,820–6,660 cal BC (https://canmore.org.uk/site/91743/langskaill). The site was not coastal at time of occupation.

Glacio-isostatic adjustment models indicate that only the northernmost stretch of the northeast England coast is liable to bear evidence for Storegga tsunami deposits. At Broomhouse Farmhouse, a Storegga deposit was recorded at approximately 2.45–2.80 m above sea level (Shennan et al., 2000), and another was recorded 28 km further south at Howick Burn, 3.10–3.55 m beneath sea level (Boomer et al., 2007, 101). Various Mesolithic materials have been found from around Budle Bay, the Bamburgh headland, and the island of Lindisfarne (Young and O'sullivan 1993; Young 2007), close to Broomhouse Farmhouse, but many of these are undated findspots, or poorly recorded excavations from the early 20th Century, and many would have been less coastally oriented 8,200 years ago than they are today (Young 2007, 22; Bicket et al., 2016).

Further south, recent work led by Clive Waddington and others at the sites of Howick and Low Hauxley have improved our knowledge of the Mesolithic in the northeast of England (Waddington 2007; Waddington and Bonsall 2016). However, both these sites appear to have been abandoned some thousand years prior to the Storegga tsunami (Waddington and Wicks 2017). Only Low Hauxley has Mesolithic evidence from afterwards, but this is limited a single shell midden date of 6170–5,790 cal BC (Hamilton-Dyer et al., 2016), and two dates of over a thousand years later (Waddington, 2016, 53), with insufficient associated archaeological materials from which to infer the nature of human activity at the site from this time.

The Southern North Sea Basin

The Storegga tsunami has previously been theorized as having brought about a swift and catastrophic end to Doggerland, the submerged palaeolandscape of the southern North Sea (Weninger et al., 2008). However, a more nuanced understanding is beginning to emerge in the wake of numerical modelling of the wave's dispersal (Hill et al., 2014; Hill et al., 2017), and the discovery of the first confirmed evidence of the tsunami from a submarine context, "core ELF001A" from the "Southern River" submerged river valley, recovered by the Europe's Lost Frontiers team (Gaffney et al., 2020). Clearly the Storegga tsunami hit some of the coastlines of the southern North Sea with considerable force, but the severity of this impact was probably variable (Walker et al., 2020).

Rapid sea-level rise around this period means that reconstructing contemporary submerged coastlines is difficult (Cohen et al., 2017), but much of Doggerland appears to have become submerged prior to the tsunami (Walker et al., 2020). This includes much of what is now the Dogger Bank (Emery et al., 2019; Hijma and Cohen 2019), which may have only been partly subaerial–a saltmarsh peat horizon, prior to final inundation, has been dated to 8,140 ± 50 BP (Shennan et al., 2000, 303). The shallow palaeobathymetry of this newly submerged topography may have had a significant effect on the wave energy dispersion of the tsunami, concentrating it in some areas, and mitigating it in others. Contrary to earlier propositions, however, the tsunami would not have been the instigator of a permanent sea-level rise (Walker et al., 2020).

There is one stratified, submerged Mesolithic site from the southern North Sea that has been identified and investigated: the Yangtze Harbour site off the Dutch Coast, occupied discontinuously between 8,500 and 6,400 BC (Moree and Sier 2015). Sedimentary evidence of region-wide marine flooding in this area that might have been caused by the Storegga tsunami travelling up the Rhine-Meuse estuary (Peeters, 2015). Several terrestrial Mesolithic sites are known from nearby dune and reclaimed polder landscapes, but evidence of Storegga from this far south remains unconfirmed.

Evidence of the Storegga tsunami in Denmark has been found from a submerged context at Rømø, in Denmark (Fruergaard et al., 2015), and may be present but unconfirmed elsewhere too (Noe-Nygaard, 2005). The projected run-up height at Rømø is between 1.5 and 5.5 m above contemporary sea-level and indicates that parts of the Atlantic Danish and German Bight coast may have been impacted by the tsunami (Chacón-Barrantes et al., 2013; Fruergaard et al., 2015). Shorelines from 8,200 years ago in these areas are, however, now mostly submerged (Astrup 2018), and the relative lack of contemporary Mesolithic archaeology from near the current-day coasts in these areas (Sørensen et al., 2018, Figure 12.1), makes it difficult to infer the impact of the tsunami. In Denmark, the Kongemose period began around 6400 BC, and saw the introduction of some new technological types (Astrup 2018, 23–25), has been posited as a the beginning of a shift towards increased coastal resource exploitation, but this may be a bias in site visibility (Astrup 2020), and in many other respects the Kongemose appears as a continuation of the Maglemose (Blankholm 2008). Although recent progress has been made in finding proxies of the tsunami from around the Southern North Sea basin, there is extremely little archaeological data that can be related to the event. The only submerged and stratified Mesolithic site from this area just predates the event. Perhaps the discovery of further submerged sites or coastal sites in the future may hold potential, but at present the ability to gauge impact in this region is entirely incomparable to areas further north.

DISCUSSION: THE SOCIAL IMPACTS OF THE STOREGGA TSUNAMI?

Evidence of a Significant Natural Phenomenon, but Less of its Human Impact?

The extensive natural sciences research identifying where and when the Storegga tsunami hit provides a fantastic point of departure for discussions about how a punctuated event in prehistory potentially had a major impact on human lives.

Geological deposits allow for estimates of run-up height, as does numerical modelling (e.g., Løvholt et al., 2005). Although the results of these estimates do not always favorably align (geological deposits provide minimum estimates) with one another (Dawson et al., 2020), they do both project that at least parts of the Norwegian and Scottish coastlines would have been struck by fearsomely large waves, with onshore run-up of 25 m or higher in some areas (Smith et al., 2004; Bateman et al., 2021). Indeed, in a recent survey of 145 tsunami deposits from around the Atlantic Ocean basin, 46% (n = 67) are attributed to the Storegga slide (Costa et al., 2021), making it the most widely documented tsunami event from the Atlantic. This begs the question then, what is needed archaeologically to identify disruption to historical contingency? As our overview indicates, between the presented geographic regions, there is great variation with regards to accessible archaeological knowledge from excavated Mesolithic sites falling within the time-frame of our study (**Figure 3** and **Supplementary Table S1**).

While evidence for the tsunami is clearly attested throughout parts of the eastern Scottish and western Norwegian coastlines, evidence of impact relating to Mesolithic peoples remains much more equivocal. Finding evidence of the tsunami is one thing, but inferring its human impact is an altogether different proposition. The widespread distribution of Storegga deposits, including far afield in the Faroes, Iceland and even as far away as Greenland, combined with run-up heights in excess of 25 m recorded in parts of Scotland and Norway, all lend to a notion of a truly terrifying if not catastrophic event.

However, such an assumption without archaeological corollary is problematic. While there is clearly a relationship between the height of tsunami run-up, wave energy, and the potential with which it can devastate a landscape upon breaking, it is problematic to simplistically assume a tsunami's intensity (much less human impact) as a function of magnitude (Papadopoulos and Imamura 2001). Clearly, topographic variability and relative positioning within the landscape are key factors in influencing the potential for human loss and destruction, and this can vary at a highly localised level–measurements of run-up height from the Okushiri tsunami along the Inaho Coast, Japan, show that run-up varied by as much as 4 m across a 3.5 km stretch of coastline (Yeh, Barbosa et al., 2015). Furthermore, while a diverse body of literature continues to develop around how to measure tsunami intensity (e.g.,Papadopoulos and Imamura 2001), these studies are almost exclusively concerned with recent or contemporary tsunami events, and consequently discuss impact relating to built environments rather than the radically different circumstances of a purely hunter-fisher-gatherer populated landscape.

Local topographic variability not only influences where and how badly hit an area within the landscape will be when struck by a tsunami, but it is also a factor in the formation and preservation of geological evidence. The variability of the Norwegian shore makes it difficult to generalise, but most instances of Storegga deposits here have been recorded in lake basins, as a result of the sharp incline of many parts of the western Norwegian coast. In contrast, in Scotland the tsunami has been most frequently recorded as a widespread sand layer within an estuarine mud, sometimes visible within exposed coastal sections (Wickham-Jones 2002; Bondevik 2019; Dawson, Dawson et al., 2020). Moreover, not every area affected by a tsunami, will necessarily leave an onshore archive (Dawson et al., 2020). To further complicate this, while tsunami coverage of a landscape might be widespread, archaeological evidence is restricted to where people were within the landscape, that might also survive subsequent taphonomic processes. Despite the geological documentation of tsunami layers in close proximity to archaeological sites as at Nyhamna (site 29 and 30) and Bømlo (Løvegapet), direct traces of impact at the occupation sites themselves were not identified. Additionally, locations that serve as sediment traps are not necessarily likely to have been attractive places for settlement, where dry, well-drained and flat surfaces may typically have been preferable. Lastly, of course, the destructive power of a tsunami is such that in the event of a highly destructive wave, we might envisage a scenario whereby such a tsunami might destroy contemporary settlements, but also recently formed archaeological deposits. Such a scenario has been hypothesised by Clive Waddington and Karen Wicks for their study of northern Britain (2017).

Limitations of Traditional Archaeological Approaches: or How to Identify Squashed Mesolithic People!

At an individual level, site stratigraphies may be interpreted relative to the event, but any assessment of societal-level impact requires consideration of multiple sites. So far, this has only been undertaken on materials from the northeast UK, and from this it was determined that changes in lithic technology and site recognition could not be invoked as an explanation of population decline–the theory advanced in light of demography modelling (Waddington and Wicks 2017, 708).

From our review, it is clear that some sites have unequivocally continuous records of occupation spanning the tsunami. Yet, the destructive nature of the tsunami might also mean that we are less likely to find places where evidence of the tsunami and Mesolithic archaeology co-occur. As stated above, tsunami deposits that contain archaeological materials are, globally, rarely encountered. As we see it, perceptions of the human impact of the Storegga tsunami have, to date, typically followed one of two lines of enquiry: either 1) inferring impact, sometimes implicitly, from the now sizeable database of geological deposits pertaining to the event from around the Scottish and Norwegian coasts relating to the event; or 2) identifying trends in palaeodemographic models of C14 dates that might relate to these changes.

The first line of enquiry is problematic as it can, without recourse to accompanying archaeological data, effectively reduce Mesolithic people to passive bystanders, with a normative assumption of vulnerability. Alternatively, one has to concede that the range of possible caveats that might exempt a group from wipeout, as simple as positioning within the broader landscape at the time of the event, is too great to exclude (see Blankholm 2018). With regards to the second line of enquiry, hiatus and continuity in stratigraphic layers can be indicative of a number of causal factors. Demographic modelling of population levels throughout different periods of prehistory has enjoyed recent popularity, and several studies have suggested that the 8.2 event may have been exacerbated by the Storegga tsunami (Wicks and Mithen 2014; Waddington and Wicks 2017) (but see Weninger et al., 2008; Blankholm 2018, for different approaches). Identified troughs in the generated curves representing demography during the Mesolithic are interpreted as signalling population decline (see also Solheim and Persson 2018; Damm et al., 2019; Bergsvik et al., 2021; Mithen and Wicks 2021). Other such studies, however, have either found the effects of both these events to be less obviously related to any apparent changes in demography, or less confident in their attribution of significance (Griffiths and Robinson 2018; Maldegem et al., 2021). If nothing else, these approaches clearly highlight the variable effects that changing the study area and data included can have on the conclusion that is reached. Moreover, if the regions, and indeed local areas experienced differential impact from the tsunami, then regional top-down approaches might be better combined with bottom-up, local comparative studies.

Examples of this second approach, stratigraphic discontinuity combined with C14 dating have been used to indicate mobility and settlement at archaeological sites from northern Vancouver coast (British Columbia, Canada) to Oregon (California, and northern Washington, US) where such patterns coincided with earthquake/tsunami activity (inferred tsunami deposits) over a period of 3,000 years (Hutchinson and Mcmillan 1997). Hiatus and discontinuity in occupation must be considered in terms of causal factors–what, if any, are the archaeological signatures we might look for that indicate devastation from a tsunami other than a drop in the number of sites, and how precipitous should such a drop be in order to qualify as compelling evidence of a disaster?

The question of archaeological proxies of impact relates in part to a theorised approach outlined by Goff et al. (2012) which seeks to establish five archaeological proxies of a devastating tsunami event: 1) changes in midden composition, 2) evidence of structural damage, 3) geomorphological change, 4) reworking of anthropogenic deposits and 5) the replication of these findings across multiple sites. So far, however, such an approach has not been systematically applied to considerations of Storegga, and with the aforementioned limitations of the archaeological data, it is not clear to what extent such an approach might yield informative results. Some observed changes in material culture have, for example, been linked to destabilisation as the result of tsunamis and other extreme natural forces in the archaeology of Maori coastal settlements in New Zealand (Mcfadgen 2007).

To further compound the difficulties of understanding the impact of an event such as the Storegga tsunami, we must also attempt to disentangle the consequences of this from the background effects of the 8.2 ka cold event, which was seemingly responsible for a significant and rapid rise in sea-level around the North Sea basin, and perhaps a drop in annual temperatures too. The 8.2 ka climate event lasted about 200 years and is recognized globally. In the regions discussed this paper it would have been experienced as a drop in summer and winter temperatures, fiercer storms and generally more unruly weather (Dawson, Bondevik et al., 2011). In recognising the impact that the 8.2 event might have had on Mesolithic communities, we might see the impact of the Storegga tsunami as a convergent impact (e.g.,Wicks and Mithen 2014; Waddington and Wicks 2017)). The nature of demographic modelling studies makes it difficult to disentangle the broadly synchronous 8.2 cold event and Storegga tsunami events. It is hard to say whether the impacts of these events were convergent, or simply appear as conflated. However, establishing unequivocal evidence of impact relating explicitly to one event or the other is a broader problem for archaeology as a whole.

A final factor to consider, as mentioned earlier, is that tsunamis are an inherently destructive force, and the erosive action of such an event may have removed any recently deposited archaeology in addition to extant settlement (Waddington and Wicks 2017; Mithen and Wicks 2021). The population decline identified in Waddington and Wicks's study began at 6600 BC, several hundred years prior to the 8.2 and Storegga events, with a population rebound centred around 6000 BC. The tsunami may, they argue, have created a taphonomic effect "that has reduced the number of surviving/detectable sites for the centuries prior to the Storegga megaslide event." (Waddington and Wicks 2017, 708) which might explain the misalign in dates. From this they hypothesise a population reduction, and a relocation of the existing population into higher ground, away from the coast–a pattern of aversion in the wake of a disastrous event. The proposed taphonomic filter is an important suggestion but at present requires further substantiation.

SHARED EVENT, YET DISTINCT MESOLITHIC HISTORIES OF VULNERABILITY AND RESILIENCE

The regional variations between the areas discussed above are partly determined by the geological histories of these respective areas, and the differential effects of glacio-isostatic adjustment and variations in the history of archaeological research. In Norway, parts of the coastline have been uplifted since the time of the tsunami, while other areas have remained comparably stable, or become submerged. Complicating this, some of the Norwegian coastlines that were struck by the tsunami have been subsequently transgressed prior to becoming subaerial again (Bondevik 2003). Although, distinct sediment composition allows for differentiation of these deposits in many cases (Bondevik et al., 1998). A large quantity of Mesolithic sites, many excavated recently in advance of development, date to the period of interest.

In Scotland, the sea-level would have been higher than it is at present for some parts of the coast, meaning the coastline contemporary with Storegga is still extant in some places, and perhaps not always far-out to sea in areas where it is submerged (Sturt et al., 2013; Smith et al., 2004: 2315). Eastern Scottish Mesolithic sites are also found on and close to the current coastline, and although some of these areas would have been coastal in the Mesolithic, in some places the coastline of 8,200 years ago is submerged, as in the case of Orkney (Wickham-Jones, 2002). Also challenging for all these regions, is distinguishing between tsunami deposits and storm surges (Bondevik et al., 2019). The available data for Scotland and northern England is much more limited in scope than from Norway.

The Boreal coastlines of southeast Britain, and Doggerland are not only submerged, but also in many places, located some distance from the current shoreline. Consequently, it is not unreasonable to expect that many of the areas impacted worst by the tsunami might be now be underwater (Bondevik et al., 1998; Bondevik et al., 2019). The same is true of parts of the former Danish coast. In Denmark, evidence for habitation of coastal zones is clear from the later Mesolithic, but less apparent prior to 8000 BP. Recent work by Peter Moe Astrup is beginning to challenge this picture, showing that at least some Maglemose sites were located in close proximity to coastal habitats and marine resources (2018; 2020).

Contact between the mentioned regions throughout the Mesolithic, including during and after 8,200 years ago, remains an ongoing question. There is archaeological evidence of long-distance mobility from the northeast to the southwest within Scandina*via* at the start of the Middle Mesolithic (e.g.,Sørensen, Rankama et al., 2013; Damlien 2016). The recolonisation of the northern frontiers of the Britain during the Late Glacial must have involved populations traveling either up through the British mainland or alternatively, perhaps using Doggerland or Scandina*via* as a point of departure, presumably following now submerged coastlines (see Stephen Mithen et al., 2015; Ballin and Bjerck 2016 for discussion). Evidence for this, and the extent to which connections across the North Sea were maintained and continued, however, remain unclear, with the cultural histories of Scotland and Norway throughout the Mesolithic appearing more divergent than similar in most respects.

Doggerland, which would have been an important Mesolithic landscape in its own right, would have facilitated connection between the Britain and northwest Europe until around 7500BC, when the rising sea-levels separated the two (Walker, In Press). As a result of this, it is typically assumed that any connections that might have existed between Mesolithic groups at this time would have at least begun to fragment by the time of the Storegga tsunami. Clear similarities between the Late Mesolithic records of lowland Europe and southern Scandina*via*/northern Germany suggest contact if not some degree of cultural continuity. Around the southern North Sea basin on the continental mainland, clear similarities between the Late Mesolithic records of lowland Europe and southern Scandina*via*/northern Germany suggest contact if not some degree of cultural continuity. The British Mesolithic shows some signs of divergence archaeologically, traditionally seen as lacking trapezoid microliths (although see Warren 2015), but it is unlikely that contact with communities across the water ceased entirely (e.g., Anderson-Whymark et al., 2015; Elliott 2015; Elliott et al., 2020; Momber et al., 2021). While it is not clear that there was not contact across extended distances over land and water between these regions when the Storegga tsunami hit, it does at least appear that different regional traditions had become established with regards to technology, raw material exploitation, landscape utilization and sites. With the Mesolithic populations of these different regions linked, if by nothing else, then by their relationship to the sea, we have good potential for a comparative study with regards to differential impact and responses to the tsunami by different communities of Mesolithic hunter-gatherer-fishers.

It is understandable that there is an inclination among many to characterize the tsunami as having been a disaster or catastrophic event (Bjerck 2008, 68; Weninger et al., 2008) and as Clive Waddington and Karen Wicks (2017, 695) have observed, it is difficult to believe that such an event would not have resulted in at least some loss of life, if not also settlements and resource bases which may have had a further destabilizing effect. The effects of this narrative are most apparent, and indeed perpetuated and compounded through repetition, in much of the media coverage of research into the event[2]. The Storegga event does appear to have been larger than any other Holocene tsunami to have struck the North Sea basin, and tsunamis are often associated with tragic human loss, with several examples from recent decades (perhaps most notably the 2004 Indian Ocean, and 2011 Tōhoku tsunamis) reinforcing this concern (Walker et al., 2020). The idea that this must have been a disaster has been encouraged by notions that hunter-gatherers are inherently vulnerable (Bettinger et al., 2015 [2001], 12), and that tsunamis can strike with little in the way of advanced warning (Edwards 2004, 67). In addition to this, the sheer scale of the tsunami, coupled with dramatized accounts of similar but non-analogous events (e.g., the 2015 Norwegian disaster movie *Bølgen* [The Wave], which shows a tsunami originating from within a fjord system in Møre og Romsdal County), and historical recollections of personal devastation (the Tafjord tsunami, which resulted in 40 deaths, and incidentally provided inspiration for the *Bølgen* movie), help further intuit the assumption that the Storegga tsunami must have been a disaster. The nature and extent of the tsunami's impact and the damage it wrought is up for debate, but it is easy to imagine that, for those who lost loved ones at least, that such an event may have been conceptualized in such a way, even if just at a very personal level.

Despite the readiness with which archaeologists have come to regard the Storegga tsunami as a catastrophic event, however, there remain very few archaeological sites with direct evidence of tsunami deposits, and little apparent evidence of impact in the contemporary archaeological record. Consequently, it is difficult to gauge what the impact of the tsunami was without making bold assumptions about the impact of the wave, and the vulnerability of the people who lived through it. People and settlements would have been affected across these regions, but regionally variable geology, topography (both onshore and bathymetric), and palaeoecology, may all factor in creating different possibilities for physical and hence social impact. To these variables, we may add taphonomy, visibility and accessibility as further compounding factors when it comes to preserving, finding, and recognising archaeological evidence. The general lack of

[2]E.g. https://www.bbc.com/news/science-environment-27224243; http://www.bbc.com/earth/story/20160323-the-terrifying-tsunami-that-devastated-britain; https://www.dailymail.co.uk/sciencetech/article-9648613/Geology-Study-reveals-tidal-wave-demolished-379-MILES-Scotlands-coastline-8-200-years-ago.html

archaeological sites with direct evidence of the Storegga tsunami has led to geological data or other proxies being utilized as indicators of impact. However, these data do not alone tell us much about human impact, nor to the extent to which this event was a disaster for the coastal communities. Do we need to identify tsunami deposits at archaeological sites to understand its impact, or even claim that the tsunami had an impact?

CONCLUDING REMARKS

Investigations of these relatively autonomous regions can then provide good opportunity to gain insight into different developments of groups of people living under relatively similar conditions. If we acknowledge that hunter-gatherer groups may "comprise a spectrum of possible human lifeways" (Warren 2021, 807), we should expect a multitude of responses. Moreover, there is not one correct answer to the question of whether the Storegga tsunami was a disaster. To some, the tsunami would certainly have been deadly and disastrous, yet for others, it was perhaps only a reminder of the hazards of living by the sea. The challenge is then threefold, 1) to find evidence of how communities organised, 2) the disentangling from the 8.2ka climatic cold event, and 3) recognize whether the chosen organisation or social structures or mechanisms made the groups strong facing disasters, or vulnerable?

In order to identify the social impact of the Storegga tsunami, a wide range of approaches are needed. As the coastal Mesolithic population on both sides of the North Sea were dependent on coastal, intertidal, and riverine resources, a tsunami's eroding powers, choking or depleting ecosystems even temporarily, might have had a massive impact on societal economy and subsistence (e.g., Dawson et al., 1990), influencing human-environment relations. Unfortunately, sites with preserved organic material are few, but there is also only so much we can read out of the geological and palaeobotanical records. Indeed, geological and botanical data needs to be contextualised and interpreted relationally to inform on social aspects, potentially shifting group dynamics, power balance, social networks etc. The Storegga tsunami may have led to a noticeable disruption of the historical contingency, which in turn may have opened, or forced societies to change, either intensifying or initiating new practices or traditions, or made societies reorientate their social networks. Alternatively, these societies were robust, or sufficiently flexible for life to soon return to the *status quo*. The regional overview of the quality or detailed knowledge of period specific archaeology also illustrates variability in the archaeological material from which we may hope to garner such inferences. This is a constraining factor on the type of studies possible in the different the regions.

Nevertheless, alternative prospects for inferring evidence of human, or social impact from the extant archaeology might focus on regional variation in lithic materials. Analyses of assemblages might highlight potential discontinuity in knowledge transmission and technology, which in turn may reflect changing expressions of social identity. Another option is to study site distribution patterns. Changes in preferred location of sites may reflect different types of mobility, or an increase or decrease in sedentism (Bjerck 1989; Bergsvik 2001, 2002b; Maldegem et al., 2021). Such approach has previously proved fruitful, like at the Kuril island close to Japan where a change in settlement pattern was detected after tsunamis had hit the coast in the Holocene (Fitzhugh 2012). Moreover, learning from ethnoarchaeological data also has great potential for better understanding possible responses in the wake of the tsunami. Through these approaches, it may be possible to identify mechanisms for knowledge transmission and maintenance of or change in social networks. Such changes may be interpreted as the elements of what constitutes either a state of vulnerability or a capacity for resilience in the face of an extreme force of nature such as the Storegga tsunami.

Ultimately, the idea that coastal Mesolithic groups would succumb to colder weather and a giant wave, without corroboratory evidence from archaeological evidence, seems to build on a presumption that they were primarily vulnerable, or at least lacked strategies to reorganize and rebound when their environment was changing, or their society faced dramatic upheaval. There is thus an interpretative paradox to be aware of: why do we assume that hunter-gatherers were vulnerable? Especially when one of the most prominent explanatory models for change in Mesolithic research involves niche construction. Mesolithic hunter-gatherer-fishers have, in recent years, often been presented as highly adaptable, spontaneous, flexible and well equipped for reorientation and exploitation of a variety of niches in order to survive (Rowley-Conwy 2001; Layton and Rowley-Conwy 2013; Warren 2020). Of course, a sudden freak event may destabilise even the most well-adapted of populations, but such an assumption is still an appeal to external forces that disregards the human variable. An alternative reformulation of the problem might be to ask what makes a Mesolithic society vulnerable, or indeed resilient? Hazards and disasters may challenge social structures and organization, potentially bringing about systemic adaptation in order to stabilise or innovate viable lifeways (Oliver-Smith 1996). Emphasising the social and anthropological aspect of a tsunami, we may move beyond the environmental and physical identification of the Storegga tsunami. We know it happened, we know it must have impacted the coastal communities, but human societies have always dealt with crises and lived with natural hazards, so the challenge remains learning what happened to the Mesolithic societies living before, during, and after it. Combining anthropology, ethnography, with the existing archaeological material from the three regions above, it may be possible to discuss the tsunami event with greater nuance, moving beyond dichotomous scenarios; perhaps a period during which life, meaning and stories, for some, were radically affected or transformed Blankholm, 2008, Riede and Sheets, 2020.

AUTHOR CONTRIBUTIONS

The different contributions of the three co-authors are as follows: AN designed the paper, has written the section about the Norwegian overview, and contributed to the introduction, background, discussion, and conclusion. JW has written the sections about Northeast England, Doggerland and Denmark has contributed to writing the introduction, background, discussion, and conclusion. AN and JW share first authorship. GW has written the section about Scotland, and contributed with input on the introduction, background, discussion, and conclusion. AN has drawn the figures.

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SUPPLEMENTARY MATERIAL

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Formal Tests for Resistance-Resilience in Archaeological Time Series

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The study of resilience is a common pathway for scientific data to inform policy and practice towards impending climate change. Consequently, understanding the mechanisms and features that contribute towards building resilience is a key goal of much research on coupled socio-environmental systems. In parallel, archaeology has developed the ambition to contribute to this agenda through its unique focus on cultural dynamics that occur over the very long term. This paper argues that archaeological studies of resilience are limited in scope and potential impact by incomplete operational definitions of resilience, itself a multifaceted and contested concept. This lack of interdisciplinary engagement fundamentally limits archaeology's ability to contribute meaningfully to understanding factors behind the emergence and maintenance of long-term societal resilience, a topic of significant interest that the field is in theory ideally positioned to address. Here, we introduce resilience metrics drawn from ecology and develop case studies to illustrate their potential utility for archaeological studies. We achieve this by extending methods for formally measuring resistance, the capacity of a system to absorb disturbances; and resilience, its capacity to recover from disturbances, with a novel significance test for palaeodemographic data. Building on statistical permutation and *post-hoc* tests available in the *rcarbon* package in the R statistical environment, we apply our adapted resilience-resistance framework to summed probability distributions of calibrated radiocarbon dates drawn from the Atlantic Forest of eastern Brazil. We deploy these methods to investigate cross-sectional trends across three recognised biogeographical zones of the Atlantic Forest domain, against the backdrop of prehistoric phases of heightened hydroclimatic variability. Our analysis uncovers novel centennial-scale spatial structure in the resilience of palaeodemographic growth rates. In addition to the case-specific findings, we suggest that adapting formal metrics can help archaeology create impact and engagement beyond relatively narrow disciplinary concerns. To this end, we supply code and data to replicate our palaeodemographic analyses to enable their use and adaptation to other archaeological problems.

Keywords: South America, palaeodemography, radiocarbon, archaeology, climate change, resilience, Atlantic Forest, Neotropics

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INTRODUCTION

In this paper, we use radiocarbon frequency data from the Atlantic Forest of eastern Brazil to develop an empirically grounded archaeological test for resistance-resilience, focused on the period of the Medieval Climate Anomaly (MCA). The MCA is a multi-centennial period of anomalous warming between ~1,000 and 700 cal BP (AD 950–1250), originally identified in northern hemisphere palaeotemperature proxies (Bradley et al., 2003; Mann et al., 2009). Narrowing data gaps across tropical South America have found support for its expression as a period of abrupt hydroclimate change over central and eastern Brazil too, with precipitation proxies suggesting depressed rainfall due to a northward shift of the Intertropical Convergence Zone (ITCZ) and lowered moisture delivery across the continent (Novello et al., 2018; Deininger et al., 2019; Lüning et al., 2019). Following the MCA, the Little Ice Age (LIA) manifests in the northern hemisphere as a period of cooling, which in South America shows a signal that varies from wet to dry, depending on the position within the path of the South American Monsoon System (SAMS). Of particular interest in the Atlantic Forest biome is a dry-wet dipole to the northeast and southwest of the South Atlantic Convergence Zone (SACZ), respectively (Novello et al., 2018; Utida et al., 2020). Records from the core of the SACZ, which lies astride the central Atlantic Forest, show a strong multidecadal to centennial-scale variability at around ~900–500 cal BP, on the cusp of the transition between MCA and LIA (Novello et al., 2018). We expand the scope of recent palaeodemographic modelling work in southern Brazil (De Souza and Riris, 2021) and neighbouring regions of South America (Azevedo et al., 2019; De Souza et al., 2019) to encompass the entire Atlantic Forest biome across eastern Brazil and evaluate the resilience of pre-Columbian populations to known climate perturbations that affected this domain.

The Atlantic Forest, originally covering 1.5 million km^2 over a wide latitudinal and elevation range, is recognised as a global biodiversity hotspot, composed of evergreen forests, dry forests, mangroves, and other vegetation formations with high endemism. It is also one of the most endangered Neotropical biomes, with only ca. 12% of its former extent remaining at most (Ribeiro et al., 2011; Marques et al., 2021). In addition, the Atlantic Forest has a long history of human-environmental interaction. At the time of European contact, most of the coastal strip and hinterland of the La Plata basin was inhabited by Tupi-Guarani societies, who practised polyculture and management of secondary forests, as attested by ethnohistorical and archaeological evidence (Scheel-Ybert et al., 2014; Bonomo et al., 2015). This follows millennia of landscape modification by marine-adapted shell mound (*sambaqui*) societies, who practised a mixed economy with forest management and some cultivation (Scheel-Ybert and Boyadjian, 2020). The Tupi-Guarani presence on the coast also overlaps with the arrival of the Aratu tradition, who occupied large circular villages in central Brazil, but whose expansion towards and impact on the Atlantic Forest are still poorly understood (Robrahn-González, 1996). At the same time, the southern Brazilian highlands in particular are increasingly recognised as an anthropogenic landscape, where a peak in human occupation (by the Southern Jê/Taquara-Itararé Tradition) coincides with the expansion of Araucaria forests—one of the vegetation types in the Atlantic Forest biome (Iriarte and Behling, 2007; Robinson et al., 2018; Pereira Cruz et al., 2020)—and the emergence of a mixed agroforestry/horticultural subsistence pattern (Corteletti et al., 2015).

The growing alignment of archaeological and palaeoecological datasets in tropical South America (Mayle and Iriarte, 2014; Iriarte et al., 2020) has helped to underscore the importance of forests to Indigenous subsistence. In what has come to be termed "polyculture agroforestry systems," a subsistence base made up of an extensive mix of cultivated, domesticated, and wild sources (Arroyo-Kalin, 2012; Clement et al., 2015; Roberts et al., 2017; Maezumi et al., 2018; De Souza et al., 2019; Iriarte et al., 2020) with a substantial input of aquatic resources (Albuquerque and Lucena, 1991; De Borges Franco, 1998; Wüst and Barreto, 1999; Hermenegildo et al., 2017; Azevedo et al., 2019; Prestes-Carneiro et al., 2019), pre-Columbian groups are inferred to have been more resilient when compared to contemporary intensive land use systems (De Souza et al., 2019). Furthermore, humid/arid cycles are a known driver of Atlantic Forest composition and extent (Scarano and Ceotto, 2015; Ledru et al., 2016; Barros Silveira et al., 2019). Over the MCA and early LIA period, archaeological data in Amazonia and the central Brazilian *Cerrado* evidence heightened levels of conflict and site abandonment (Azevedo et al., 2019; De Souza et al., 2019). While the heterogeneity of late prehistoric palaeoecological trends cautions against simple mechanistic models of culture change (Bush et al., 2021), it is worth noting that by 750 cal BP population growth in neighbouring Amazonia had likely, at best, stabilised (Arroyo-Kalin and Riris, 2021). We suggest that the reliability and availability of resources under polyculture agroforestry systems may also have been affected by hydroclimatic perturbations and propose this as a mechanism through which abrupt climate change impacted pre-Columbian population trajectories in the Atlantic Forest. Our working hypothesis is that the expression of the MCA across the Atlantic Forest adversely impacted the resource base of pre-Columbian Indigenous groups practicing polyculture agroforestry, which we anticipate is reflected in proxies for ancient population change over time.

To evaluate this hypothesis, we present a novel test of resistance-resilience (Nimmo et al., 2015) specifically developed for summed probability distributions of calibrated radiocarbon dates (SPDs). SPDs are one among several methods that assume the relative abundance of radiocarbon dates will reflect broad trends in "events" over time, as a proxy for relative population change in the past (Shennan et al., 2013; Timpson et al., 2014; Crema and Bevan, 2021). SPDs are, at present, one of the most common means of aggregating radiocarbon dates. Due to this, the study of population dynamics in the past—palaeodemography (French et al., 2021)—is by necessity performed within one or several statistical frameworks to account for the chronometric uncertainties, biases, and sampling problems that are inherent to such data. A major goal of these approaches has been to provide robust alternatives to visual interpretations of SPDs, either through alternative summation methods or the development of statistical models to control for diverse sources of error (Timpson et al., 2014; Crema et al., 2016; Bronk Ramsey, 2017; McLaughlin, 2019; Carleton and Groucutt, 2021). We build upon one of the most widespread such frameworks, available in the R package *rcarbon* (Crema and Bevan, 2021), to implement our approach towards resistance-resilience in the Atlantic Forest biome of eastern Brazil. It affords the ability to control for variation in sampling intensities through binning, mitigation of calibration curve effects on SPD shape, and direct statistical comparison of multiple SPDs concurrently through mark permutation tests (Crema and Bevan, 2021). Although other readily available approaches, such as kernel density estimates or event count modelling (Brown, 2017; Carleton, 2021) are also theoretically amenable to the treatment we propose here, they do not currently have the same range of model-testing functionality that *rcarbon* offers. We also scaffold our approach with Bayesian model-fitting methods (Crema and Shoda, 2021) to build a palaeodemographic context for the present study that iterates on our prior work in the region (De Souza and Riris, 2021).

Our aims are to: (1) develop and apply palaeodemographic tests for resistance-resilience, which we define below, to enable the systematisation of knowledge on this crucial topic, and (2) demonstrate their utility for statistically comparing responses to disturbances between different regions of the Atlantic Forest while evaluating their implications. Before presenting the methods, we draw on recent reviews of resilience in archaeological research (Bradtmöller et al., 2017; Fitzhugh et al., 2019; Degroot et al., 2021; Russo and Brainerd, 2021) to contextualise our method and outline the scope of palaeodemography's potential contribution to the study of resilience in ancient socio-environmental systems. More broadly, we situate this work within the study of "extreme events" in the deep past, bearing in mind the absence of consensus definitions for extremity (Intergovernmental Panel on Climate Change [IPCC], 2012; Gregory et al., 2015), and turn our attention to a systems approach that is focused on empirical benchmarking of culture-climate links, through the lens of palaeodemography (Broska et al., 2020).

RESILIENCE AND PALAEODEMOGRAPHY

Archaeological approaches to resilience are greatly influenced by the work of Gunderson and Holling (2002) on panarchy and adaptive cycling (Redman, 2005; Fisher et al., 2009; Kintigh et al., 2014). Recent reviews indicate that many, if not most, archaeological studies of ancient resilience draw on Resilience Theory (RT) in this sense (Holling, 1986; Folke, 2006; Bradtmöller et al., 2017; Fitzhugh et al., 2019). Within this body of work, adaptive cycling describes socio-environmental systems consisting of repeating phases of growth, conservation, release, and reorganisation in a domain of interest, which can be subsumed within (or themselves contain) cycles that operate across different spatio-temporal scales (Gunderson and Holling, 2002; Middleton, 2017). Due to the challenges associated with identifying appropriate scales and resolving different phases of adaptive cycling in the material record, studies of prehistoric resilience tend to adopt alternative strategies. Methods found within the archaeological resilience literature range from making qualitative point estimates or descriptions of conditions before and after a disturbance, to visual cross-referencing different proxies or time series ("wiggle matching," cf. Bronk Ramsey et al., 2001; Blockley et al., 2018), as well as more rigorous quantification of relationships between different elements of a socio-ecological system (Kelly et al., 2013; Kintigh and Ingram, 2018; Carleton and Collard, 2020; DiNapoli et al., 2021).

In the vast majority of cases, *resilience* is employed largely as an interpretative device (Bradtmöller et al., 2017, p. 4), and consequently, the recognition of resilience (or vulnerability, stability, or fragility) in the archaeological record rests largely upon qualitative criteria (Degroot et al., 2021). Although this may offer internally consistent perspectives on how a socio-environmental system changed in response to disturbances, the findings of any single case study are rarely meaningfully comparable with those of another. Similarly, palaeodemographic studies tend to employ resilience heuristically (Leppard, 2015; Marsh, 2016; Bevan et al., 2017; Blockley et al., 2018; Riris and Arroyo-Kalin, 2019; Walsh et al., 2019; Palmisano et al., 2021), as opposed to a measurable property of a socio-ecological system like diversity, richness, or stability (Cantarello et al., 2017; Van Meerbeek et al., 2021), including in the Neotropics (De Souza et al., 2019; Ebert et al., 2019; Arroyo-Kalin and Riris, 2021). As the systematisation of archaeological knowledge been suggested to be key prerequisite for building coherent large-scale models of feedbacks between culture and climate (Kintigh et al., 2014; Perreault, 2019), we suggest there is a need to redefine resilience analytically and thereby overcome some of these limitations. At present, there are clear obstacles to this goal that are inherent to interpretative approaches.

To do so, we draw on approaches to the study of resilience from quantitative ecology, which has some noteworthy differences from the use of Resilience Theory in archaeology as described above. Although RT as high-level theory (*sensu* Gunderson and Holling, 2002; Folke, 2006) is similarly prominent in the ecological literature (Newton, 2021; Van Meerbeek et al., 2021), one area of vigorous research that has gone largely unappreciated in archaeological circles is its quantification, measurement, and comparison between different cases and in response to different (or common) disturbances. This drive to develop transferable metrics of system resilience (Orwin and Wardle, 2004; Pimm et al., 2019) does not have an identifiable counterpart in our field and stands in contrast to its almost exclusive use as an interpretative heuristic to frame archaeological problems (Redman, 2005; Bradtmöller et al., 2017; **Table 1**). Robust debate surrounds the definition of resilience metrics and the different elements of a socio-ecological system they purport to measure (Ingrisch and Bahn, 2018; Pimm et al., 2019; Van Meerbeek et al., 2021), however, it is clear that building understandings of resilience from concise operational definitions has afforded key insights into long-term biodiversity trends, informed conservation agendas, aided in the communication of scientific results, and provided a platform for ecologists to bridge the gap with stakeholders (Nimmo et al., 2015). We follow others in contending that research on prehistoric societies has a contribution to make to all of these research areas or closely analogous ones (Kintigh et al., 2014). While there is clearly an appetite on the part of archaeologists to adopt *terminology* across disciplines, the field has to date largely avoided the formalism necessary to obtain meaningfully comparable data on resilience (Olsson et al., 2015) that would enable such impacts to be made.

We suggest that radiocarbon-based estimates of palaeodemographic dynamics are exceptionally well-positioned to provide solutions, as they provide an absolute chronological framework for assessing fluctuations that can be cross-referenced to known perturbations and couched within a hypothesis-testing framework. As noted, climate change often figures as an important, high-level driver of prehistoric population turnover and cultural transitions, whether as a source of unpredictability (high variance), extreme (pulse) events, gradual pressure, or other mechanism (Bevan et al., 2017; Blockley et al., 2018; De Souza et al., 2019; Ebert et al., 2019; Riris and Arroyo-Kalin, 2019; Walsh et al., 2019; Palmisano et al., 2021). We now investigate whether the transient, centennial-scale effects of the MCA, in the form of a weakened South American Summer Monsoon, are reflected in persistent changes to palaeodemographic growth rates (expressed as a percent rate of change) across the Atlantic Forest, as in parts of Amazonia (De Souza et al., 2019).

MATERIALS AND METHODS

Archaeological Radiocarbon Dates and Hydroclimate Proxy

For our analysis, we use 1,347 georeferenced radiocarbon dates from the Atlantic Forest, which are part of ongoing efforts to compile all published anthropogenic ^{14}C dates in lowland South America (De Souza, 2021). The South American Atlantic Forest is a megadiverse biome that spans approximately 25 degrees of latitude, from the northeast to the far south of Brazil, and as far inland as Paraguay and northern Argentina (Marques et al., 2021). Changes in the historical extent of these forests is typically compared to its expansion or contraction relative to more open biomes, notably grasslands and arid scrub, a pattern which is historically connected to variation in long-term climate patterns across eastern Brazil (Costa et al., 2018; Barros Silveira et al., 2019). Due to known north-south variability across Atlantic Forest ecoregions, and variation in the MCA across a north-south gradient (Novello et al., 2018), we anticipate that palaeodemographic fluctuations between 1,000–700 cal BP may be similarly spatially structured and/or asynchronous. In other words, *if* hydroclimatic change during our study period impacted environments enough to affect population dynamics, *then* we expect the extent and composition of forests to be a contributing factor to Indigenous responses. To capture potential differences in resistance-resilience between different ecoregions concurrently, we group the radiocarbon dates according to the phylogeographic regions identified by Ledru et al. (2016) on the basis of topographic, climatic, and edaphic criteria. In broad terms, these regions correspond to mixed evergreen forests in the southern area including *Araucaria* forests, semi-deciduous forest in the central area, and dry/open forest in the northern area (Marques et al., 2021). The proposed division also corresponds to the observed pattern of variation in the MCA signal in speleothem records (northeast, core and southwest of the SACZ) (Novello et al., 2018). To account for uncertainty regarding the historic distribution of the Atlantic Forest and whether dated archaeological sites fall fully within its modern boundaries in the strictest sense, we have chosen to include dates that are within 100 km of its consensus extent, using a spatial dataset produced by Global Forest Watch in collaboration with the Brazilian Ministry of Environment and the Brazilian Institute of Geography and Statistics. The database includes all anthropogenic dates since the Late Pleistocene peopling of South America across 543 sites in our study area, as well as dates that post-date the Conquest (**Figure 1**, top).

We supplement this data with a high-resolution (sub-annual) geochemical record of SASM variability from Botuverá cave in Santa Catarina state, southern Brazil (Bernal et al., 2016; Novello et al., 2018). To aid the visualisation of this data and the period of interest in the overall context of Late Holocene hydroclimate across eastern Brazil, we fit a Generalised Additive Model (GAM) to the data using a thin-plate regression spline with the Restricted Maximum Likelihood method in the *mgcv* R package (Wood, 2011). An advantage of GAMs for trend summaries over loess regression is the automatic estimation of penalties and optimisation of smoothing parameter to reduce overfitting (Simpson, 2018). We present this fit for the period 2,000–400 cal BP alongside the record mean and standard deviations (**Figure 1**, bottom), indicating the heightened aridity apparent in the southern end of the Atlantic Forest during the MCA.

Bayesian Palaeodemographic Modelling

To provide an overarching context for our study of the Atlantic Forest ^{14}C record, we analyse the entirety of the radiocarbon dates in our sample via summed probability distributions of calibrated radiocarbon dates (SPDs).

Our previous work in the eastern La Plata basin employed information criterion-based model comparison and Monte Carlo simulation to carry out null hypothesis testing of a fitted multipart palaeodemographic model (De Souza and Riris, 2021). While this approach succeeded in identifying a demographic transition to an exponential growth phase starting after ∼1,900 cal BP that lasted until European Conquest, conventional modelling of radiocarbon data such as this has well-known limitations. Most relevant for current purposes is the conflation of unaccounted-for sampling and calibration effects (Carleton and Groucutt, 2021; Timpson et al., 2021). Here, we adopt a Bayesian inferential framework (Crema and Shoda, 2021) to account for these issues, validate the overall trajectory of our Atlantic Forest SPD during this interval based on this prior knowledge (De Souza and Riris, 2021), and derive posterior samples of relevant demographic parameters.

Guided primarily by this preceding work (De Souza and Riris, 2021), we define a bounded exponential growth model for our Late Holocene radiocarbon dataset in the R package *nimbleCarbon* v0.1.0 (Crema, 2021). This package builds on

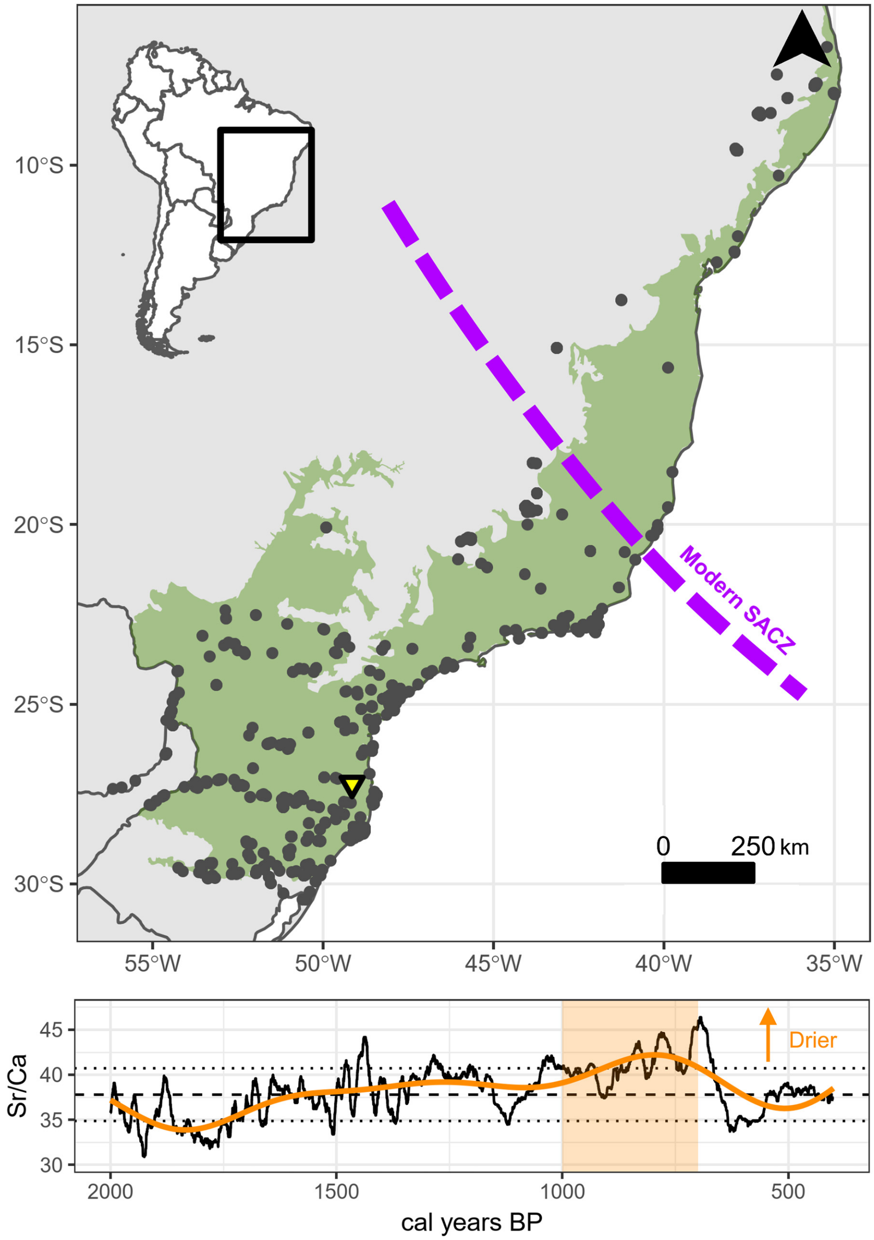

FIGURE 1 | Archaeological and palaeoclimatic overview. Top: locations of radiocarbon dated archaeological sites (grey points) and Botuverá cave speleothem (yellow triangle in the Atlantic Forest (green). Bottom: Botuverá hydroclimatic proxy (Sr/Ca: black line) and smoothed fit (orange line) for 2,000–400 cal BP, with record mean and standard deviations. MCA period highlighted by shading.

the functionality of the *nimble* package (de Valpine et al., 2021), specifically using a Markov Chain Monte Carlo procedure (Metropolis-Hastings random walk algorithm with adaptive sampler) to calculate the probability mass of the SPD at each timestep and obtain posterior samples of model parameters. In this case, our parameters are the start (a) and end (b) points of our period of interest (1,900–500 cal BP) and the growth rate r with an exponentially distributed prior of $\lambda = 1/0.0004$ (Crema and Shoda, 2021). In the context of the archaeology of the Atlantic Forest, this period corresponds approximately to the transition between the shellmound tradition (*sambaquis*) and the expansion of major archaeological ceramic traditions in eastern Brazil, namely, the Tupiguarani, Una/Taquara-Itararé (Southern Jê), and Aratu traditions (Bonomo et al., 2015; Iriarte et al., 2017; De Souza et al., 2020). Because these traditions are generally agreed to have spread or intensified polyculture agroforestry practices, we expect growth rates to be broadly in line with other agrarian or semi-agrarian societies worldwide (Zahid et al., 2016). Following Arroyo-Kalin and Riris (2021) we also consider the possibility that populations had stabilised by or before Conquest, which we

TABLE 1 | Summary of fitted Bayesian models.

Model	Parameter	$\hat{R}$	ESS	HPD$_{lower}$	Median	HPD$_{upper}$
Exponential	r	1.000867	10598.946	0.1207	0.1428	0.1654
Logistic	r	1.000471	8154.6374	0.1274	0.1527	0.1809
	k	1.003110	5148.9537	0.1931	1.286	4.5938

The Gelman-Rubin diagnostic $\hat{R}$ indicates convergence of the MCMC samples of the growth rate r between chains in both models, but not the carrying capacity parameter k in the logistic model. HPD values are reported as percentages.

model via a logistic growth model with an additional carrying capacity parameter k, whose prior is set as an exponential distribution truncated between 0.001 and 0.2 after Crema and Shoda (2021). For both models we ran two chains of 30,000 MCMC iterations each, with 1,000 burn-in steps and a thinning interval of three. We use the inbuilt diagnostics to check for convergence and adequate mixing. Posterior predictive checks were achieved in an analogous fashion to the more common regression-based methods in *rcarbon* (Crema and Bevan, 2021) we have previously used (De Souza and Riris, 2021), namely by: repeatedly sampling random calendar dates from fitted models based on the posterior parameters, "back-calibrating" into ^{14}C dates with randomly assigned errors, calibrating the datasets, and aggregating them into a simulated SPD envelope based on 500 iterations of this procedure (Timpson et al., 2014). We have not pruned our dataset, but bin radiocarbon dates from the same site that lie within 200 years of one another. The analysis is fully reproducible with the code provided in **Supplementary Material**.

A Test for Resistance-Resilience

In addition to the broad-scale perspective afforded by the Bayesian palaeodemographic modelling, we seek to recover cross-sectional differences in human responses to prehistoric climate change in the Atlantic Forest. To this end, we present a novel *post-hoc* significance test that adapts the functionality of "point-to-point" testing (Edinborough et al., 2017) to the established mark permutation test (Crema et al., 2016). The latter advantageously does not suffer from the same issues surrounding growth model definition as regression-based null hypothesis testing, while the former class of tests has demonstrable utility for evaluating the presence and significance of shorter-term (centennial-scale) "events" in SPD timeseries between two defined points in time (p_1 and p_2). Code to replicate our *post-hoc* test is provided in full in **Supplementary Material**. Per standard protocol in the aggregate analysis of radiocarbon dates, we bin dates originating from the same site that fall within 200 years of one another to minimise the overrepresentation of well-dated sites in our time series. We do not prune our dates. For the permutation tests, we calibrate dates using the using the ShCal20 curve (Hogg et al., 2020), except for those obtained on marine samples, in which cases we used the Marine20 curve (Heaton et al., 2020) and average ΔR offsets and errors based on the 10 nearest published values.[1] SPDs for the permutation tests are left unnormalised to minimise calibration curve artefacts in their shapes (Bevan et al., 2017).

[1] http://calib.org/marine/

For our test, we adapt ecological indices for resistance and resilience to the analysis of SPDs (Orwin and Wardle, 2004; Nimmo et al., 2015). Combining these system properties in a bivariate analysis enables the intuitive comparison of the behaviour of a proxy during a period of interest over a geographical region (**Figure 2**). In straightforward terms, resistance can be considered the capacity of a population to absorb and maintain its state in the face of disturbances. Analytically, resistance is defined as the deviation of a proxy from a baseline following a perturbation, standardised relative to the baseline (Orwin and Wardle, 2004):

$$Resistance = 1 - \frac{2 \times |G_b - G_x|}{G_b + |G_b - G_x|} \quad (1)$$

where G_b is the SPD rate of change at the baseline p_1, taken to be the start of a perturbation, and G_x is the index value after a defined period of time. Both metrics are bounded between -1 and 1, however, if using Equation 1 as-is, negative values of G_b (which are common in SPD-derived rate of change estimates) can lead to very small divisors when the difference between G_x and G_b is also small. In effect, this may cause Equation 1 to return values in excess of ± 1. A simple and effective solution, which we advocate here, is to take the absolute value of G_b in the divisor too:

$$Resistance = 1 - \frac{2 \times |G_b - G_x|}{|G_b| + |G_b - G_x|} \quad (2)$$

While any point in time may be chosen for G_x, the *maximum* deviation from baseline conditions is recommended for pulse perturbations, such as abrupt climate change (Van Meerbeek et al., 2021, p. 10). We therefore set this point (p_3) as the *minimum* rate of change experienced between p_1 and p_2. It should be underscored that our code (**Supplementary Material**) provides flexibility for any point in time between p_1 and p_2 to be chosen.

Resilience is defined as the extent to which the proxy is able to return to the reference condition following disturbance, standardised by the total relative change:

$$Resilience = \frac{2 \times |G_b - G_x|}{|G_b - G_x| + |G_b - G_e|} - 1 \quad (3)$$

Here, G_b and G_x are as in Equation 1, while G_e is the condition of the proxy at the end of the perturbation (p_2).

A resistance value of 1 shows no effective change (maximal resistance to perturbations), zero resistance indicates a relative change of 100% of the baseline value, while negative values indicate the extent to which growth rates decline over the period

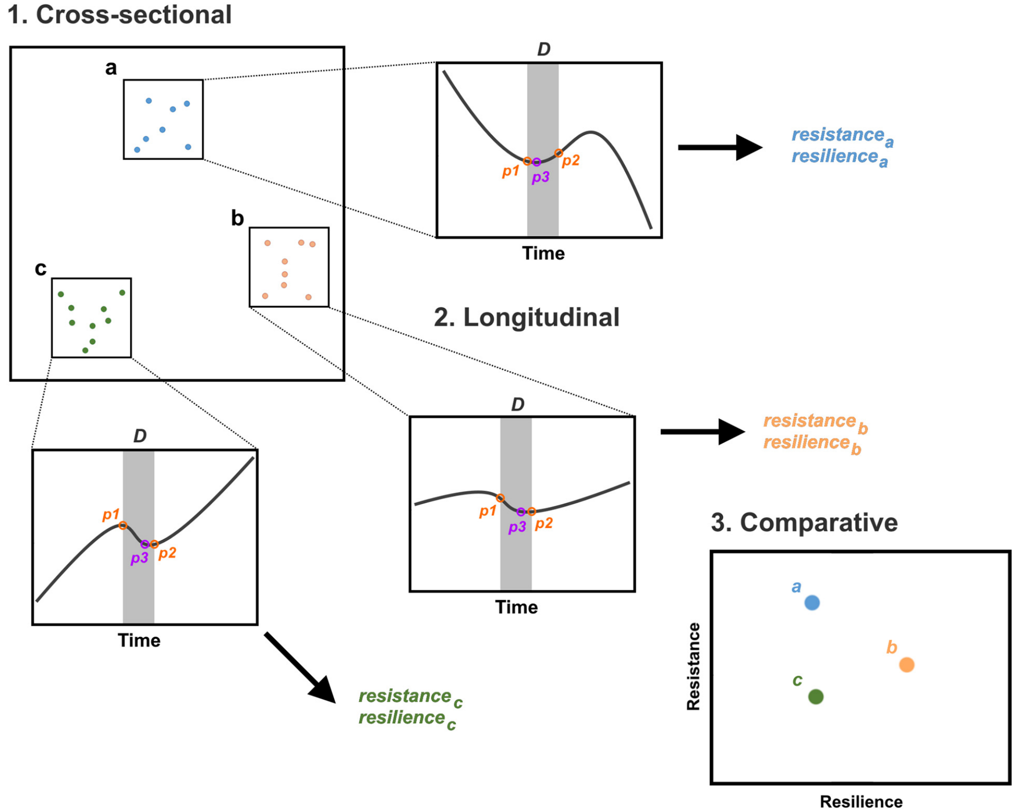

FIGURE 2 | Schematic outline of analytical approach. Cross-sectional data corresponding to the radiocarbon records of different geographical regions are rendered (*via* summed probability distributions) into longitudinal data. Measurements before (p1), after (p2), and during (p3) a disturbance D are taken from the palaeodemographic proxy and used to estimate resistance and resilience. Metrics provide an empirical basis for comparing spatiotemporal trends.

of interest. For resilience, a value of 1 indicates full recovery at the end of a perturbation, 0 indicates no recovery from maximum impact. Negative values of resilience are returned when $|G_b - G_e| > |G_b - G_x|$, which can only occur when G_x is manually set at a point other than the maximum deviation (minimum growth rate) and is therefore not relevant here.

The expected ranges of Equations 2 and 3 are shown in **Figure 3** for different parameter combinations. It is worth noting that because of their double exponential shapes, resistance and resilience are equal to zero for two different values of G_x: when G_x is itself equal to 0 and when G_x is two times G_b (**Figures 3A,B**). This means that when G_b is positive, zero resistance (100% change) is returned when the growth rate doubles (to 0.04, here). Similarly, when G_b is negative, zero resistance is returned when the growth rate decreases by the same proportion. The same is true of resilience when varying the endpoint (**Figure 3C**): if the start- and end-values (G_b and G_e) are the same, the formula yields 1, indicating that the system in question is fully resilient and successfully bounces back to its original condition. However, the equation does not distinguish directionality in the proxy. In other words, and as in the case of resistance, if a system bounces back and *exceeds* the original growth rate, the formula will return a value <1. This is counterintuitive to how archaeologists typically interpret resilience, as noted above, and demonstrates that these features of the equations must be kept in mind. Change to a system, even if "beneficial," cannot necessarily be regarded as an instance of resilience. We return to this point in the discussion.

Finally, we take advantage of the inbuilt functionality of the mark permutation test to compare the empirical resistance-resilience metrics with those obtained from envelopes of simulated SPDs. In effect, the permutation test generates a distribution of expected values of resistance and resilience for each region. Our analyses consist of determining whether and how *observed* values deviate from these *expected* values, which we highlight with a two-tailed test of significance of whether a given metric is significantly above or below the global aggregate. This is distinct from the p-value obtained through the mark permutation test itself, which we also report separately (Edinborough et al., 2017). We apply our point-to-point test for resistance-resilience to the "rate-of-change" version of the mark permutation test, as this allows easier comparison with the growth rate parameter (r) estimated through the Bayesian model fitting described above. Rather than binary states of resilience/vulnerability, our test indicates the relative location of empirical patterns along a bounded spectrum. To guard against our results being conditional solely on the choice of start- and end-dates, bearing in mind the likely existence of lead-lag relationships between our growth rate proxy and hydroclimate,

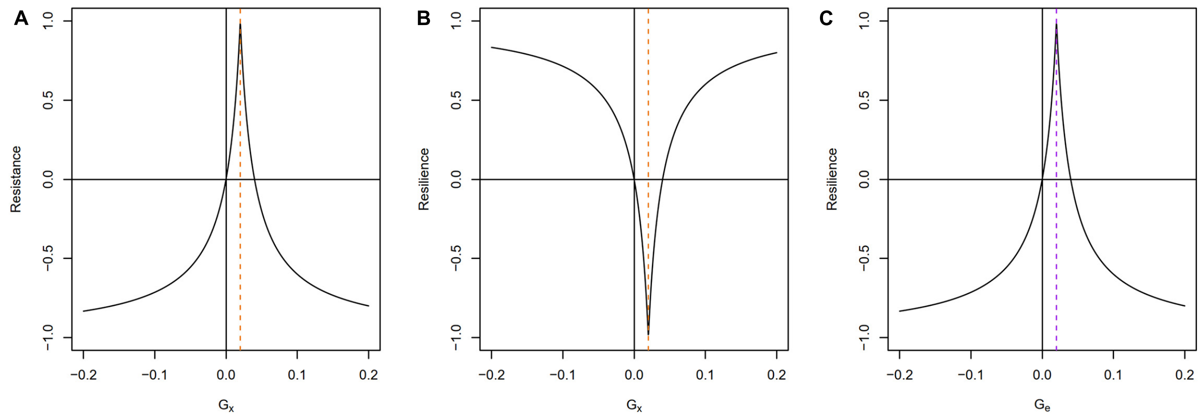

FIGURE 3 | Resistance and resilience as functions of G_x and G_e. G_b is held constant at 0.02 (vertical dashed lines). **(A)** Resistance is equal to zero for two different values of G_x, when $G_x = 0$ and when G_x is two times G_b. **(B)** Resilience as a function of G_x. Note that different values of G_x may return the same Resilience index. **(C)** Resilience after Orwin and Wardle (2004), with a varying end point (G_e), and constant start (G_b) and minimum (G_x). Resilience equals 1 only when $G_e = G_b$. Lower and higher values of G_e yield Resilience <1.

TABLE 2 | Model comparison summary.

Model	WAIC	Δ WAIC	Weight
Exponential	6311.029	0	0.99999996170574
Logistic	6345.185	34.15593	0.00000003829426

we also perform sensitivity analyses with the point-to-point test. As the chosen frame of reference for the MCA is 300 years (1,000–700 cal BP), we also consider start- and end-dates within 30 years (10% of total time span) on either side of these dates in 1-year increments (1,030–670 cal BP) and report the ranges of the indices for these parameter combinations. Here we use 9,999 random mark permutations, with a running mean and backsight of 100 years. We recommend that the backsight, which is effectively an arbitrary parameter choice, be scaled to the duration of the phenomena under study. In this case, we believe *a priori* that centennial-scale change would make this choice acceptable. In principle, further sensitivity tests could also take changes in the backsight value into account as with the choice of date ranges.

RESULTS

Bayesian Modelling and Parameter Estimation

The results of the Bayesian model fitting and diagnostic checks (**Table 1** and **Supplementary Figures 1–3**) indicate adequate mixing and a sufficient effective sample size for both models. In good agreement with prior work on a subset of this radiocarbon dataset, the pre-Columbian population trajectory of Atlantic Forest conforms well to both exponential and logistic growth models between 1,900 cal BP and the start of Portuguese colonisation after ∼500 cal BP. In comparative perspective, we find that the exponential model performs better than the logistic (**Table 2**). Considering also that the *k* parameter converged to a lesser degree in the logistic model, we proceed with the more parsimonious exponential fit for subsequent posterior predictive checks, although in reality differences are minor (**Supplementary Figures 2**, **3**). The 95% confidence envelope obtained from 500 simulated SPDs conditioned on posterior samples of the fitted model (**Figure 4**) shows that the empirical SPD is generally well within the predicted range, excepting close to the end of the analytical time range, when radiocarbon dates become sparser.

Additionally, the results highlight the 95% range of the marginal posterior distribution of the exponential growth rate between ∼0.12 and 0.165% (**Table 1**), which is high relative to *long-term* estimates obtained elsewhere (Zahid et al., 2016) but approximately in line with recent palaeodemographic work (Crema and Shoda, 2021). The results may be, in part, an artefact of a constrained frame of reference, during a known period of significant expansion of pre-Columbian farming cultures (De Souza et al., 2020; De Souza and Riris, 2021). The Bayesian modelling does not directly impact the results of the resistance-resilience tests, but rather, sustains the findings of previous work in eastern Brazil, while also accounting appropriately for sampling error and calibration effects. These results inform our subsequent tests and invest them with the knowledge that, in aggregate, pre-Columbian cultures of the Atlantic Forest were undergoing largely uninterrupted exponential growth during the Common Era. Short-term perturbations, such as the MCA, must therefore be seen in the context of this overall trajectory.

Resistance-Resilience

The resistance-resilience test highlights key differences between the southern, central, and northern regions of the Atlantic Forest. Our sensitivity testing returned a relatively constrained range of values for both metrics within 30 years of the start and end of the MCA (**Figure 5**, bottom left), indicating that the choice of start date either side of 1,000 and 700 cal BP does not qualitatively alter the results. The obtained values for resistance across all

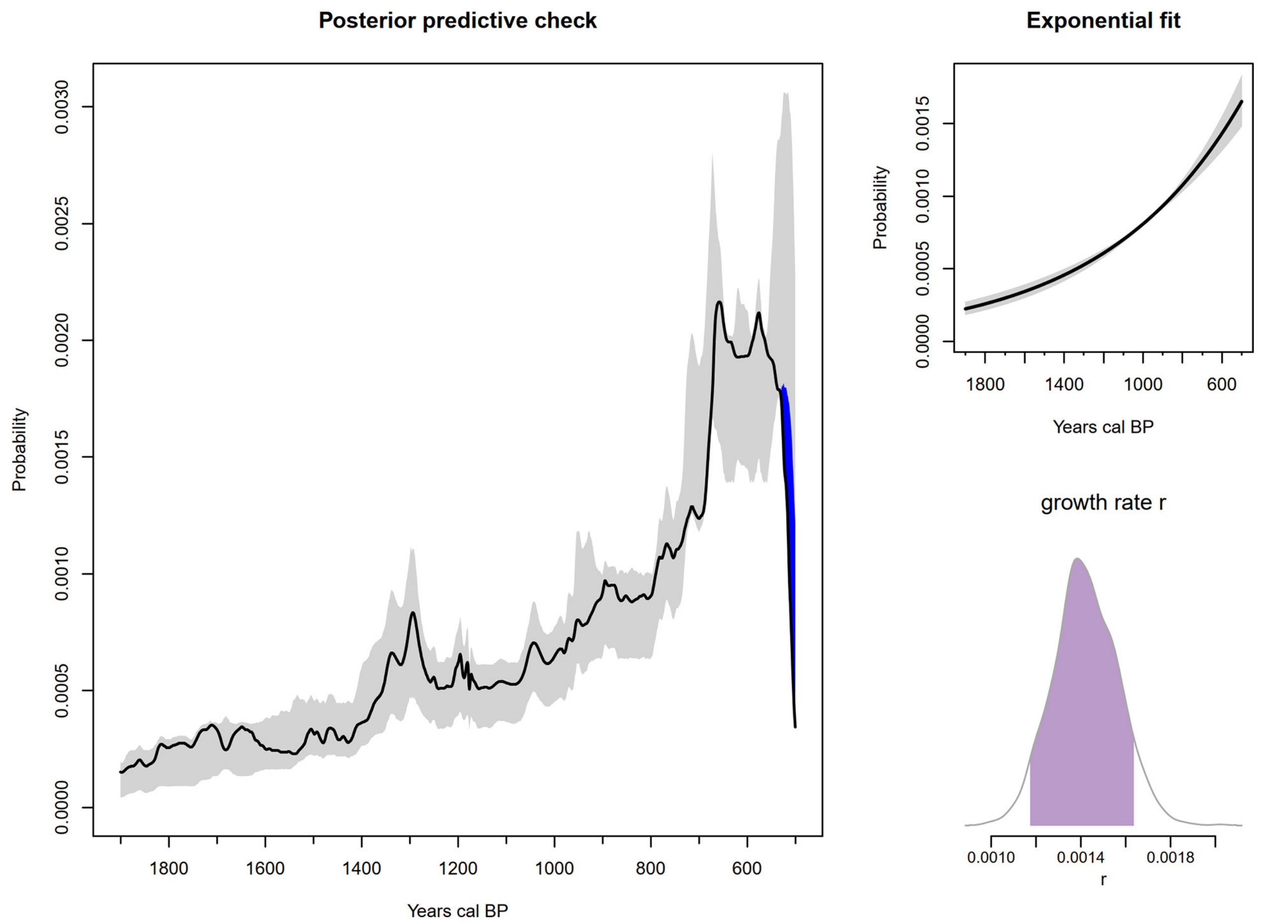

FIGURE 4 | Results of Bayesian radiocarbon analysis. Left: results of posterior predictive check, showing the empirical Atlantic Forest SPD (black line) within the prediction range of the fitted model (grey envelope), excepting close to the Conquest. Bottom right: marginal posterior distribution of the growth rate r over the interval 1,900–500 cal BP. Top right: exponential model fit.

three regions are statistically significant from their counterparts between 1,000–700 cal BP, while resilience returns no results that are distinguishable from the null hypothesis of no regional differences (**Table 3**). Before delving into the regional patterns, it is worth underscoring that the regions all have the same *direction* of change during the MCA. That is, the effects of the MCA disturbance on growth rates appear to be qualitatively similar, with generally negative trends observed, but differ in magnitude, timing, and ultimate impact. This underscores the importance of considering more than one index and grouping of dates concurrently; single metrics or settings are not as informative.

The Central and Southern regions have resistance values on the same order of magnitude, reflecting the stagnation of growth rates close to zero in the wake of the MCA in both these settings (**Figure 5**). The timing of this phenomenon unfolds over two centuries in the Central Atlantic Forest, while in the Southern region, analogous impacts occur in less than a century. This implies that the "on-the-ground" experience of climate impacts may have been more acute in the southern Atlantic Forest compared to the centre and north. We return to the extremely low resistance in the Northern subset in the discussion, noting that it reflects a drop from an essentially stationary population to one contracting at a rate of −0.66% during the MCA.

We are cautious about overinterpreting the metrics for resilience, bearing in mind that there are no significant regional differences (**Table 3**). Qualitatively, all three rate of change time series have visual similarities during the 1,000–700 cal BP interval, i.e., a limited or non-existent return to pre-disturbance rates of change. Somewhat lower values for resilience in the Central and Northern areas may be related to their comparable lags of 20 and 83 years, respectively, as opposed to 209 years during which to recover in the south. In other words, the more abrupt, yet shorter, MCA impacts on populations in the south may have translated into a longer and more sustained recovery period. The Northern region stands out as the least resistant *and* least resilient region, with growth rates at 1,000 cal BP, as noted, close to zero that fall well below zero by 700 cal BP. It is, moreover, the only region to undergo a statistically significant negative deviation in the mark permutation test during the MCA, further marking out the narrow coastal strip of Atlantic Forest

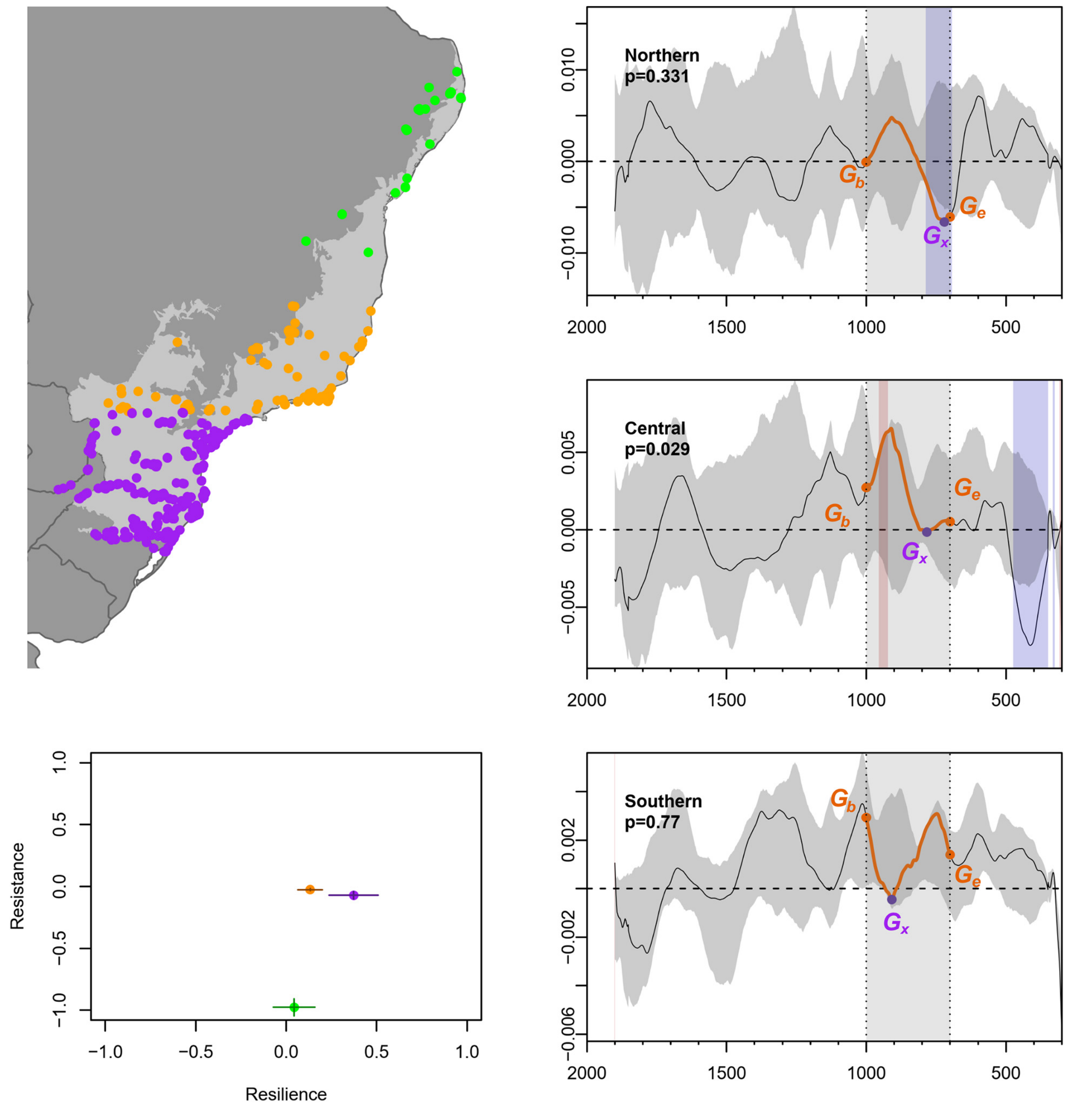

FIGURE 5 | Results of point-to-point permutation test for resistance-resilience. Right column: Rate of change of SPDs in Northern, Central, and Southern subsets of the Atlantic Forest, with p-values for the underlying permutation test. Simulation envelope is based on 1,000 random mark permutations. Orange dots and shading show the defined start- and end-points of the MCA, purple dots are the minima of the time series between these points. Note that with a 100-year backsight, the time series starts at 1,900 cal BP. Bottom left: comparisons of resistance-resilience between regions.

TABLE 3 | Resilience-resistance metrics and significance test for Northern, Central, and Southern subsets of Atlantic Forest radiocarbon record, and time in years between start of disturbance and time series minima (lag).

Region	Resistance	*p*-value	Sig.	Resilience	*p*-value	Sig.	Lag (years)
Northern	−0.9758	0.002	***	0.0442	0.2312	ns	280
Central	−0.0265	0.002	***	0.1328	0.6166	ns	217
Southern	−0.0708	0.002	***	0.3736	0.9964	ns	91

*All resistance values are highly significant (*** ≤ 0.002).*

as unusual in the context of this study. The significant global *p*-value in the Central region is almost certainly largely because of the large negative deviation around ∼500 cal BP. The coastal strip here is coincidentally also the location of the first Portuguese colonies in Brazil, but we cannot conclusively attribute this pattern to the Conquest.

In summary, the results reveal low resistance to abrupt hydroclimatic change among our subdivisions of the Atlantic Forest following the start of the MCA, although apparently differing in abruptness of impact. There is also a consistently low ability to recover by the end of the MCA period, with resilience being less than half of its pre-disturbance value (<0.5) across all regions. Despite apparent commonalities and lack of statistically significant deviation, it is worth noting that by 700 cal BP, Northern growth rates are negative, Central growth is virtually stationary, and Southern rates are well above zero. As noted above, the interface between the MCA and LIA was a period of continuing climate change across tropical South America (Novello et al., 2018; Azevedo et al., 2019), which may be key to contextualising these qualitative differences, although we presently lack the resolution and sample size of radiocarbon dates to directly investigate further so close to European Conquest (Riris, 2019).

Our study of Atlantic Forest palaeodemography reveals correlations between abrupt climate change and key parameters, with a degree of spatiotemporal variability that suggests not all areas were equally affected. The results of our analysis introduce novel perspectives on current knowledge about Late Holocene palaeodemography in South America (Azevedo et al., 2019; Arroyo-Kalin and Riris, 2021; De Souza and Riris, 2021), complementing the findings of previous top-down demographic model-fitting on a broad scale with more focused interrogation of local records. It is plausible that impacts may have been differentially mediated in one or more ways. We now turn to exploring the implications of these findings for our case study specifically, as well as for the study of prehistoric resilience more broadly.

DISCUSSION

Our findings affirm that a delayed demographic transition occurs in the Atlantic Forest relative to the Amazon basin following the adoption and development of sedentary agroforestry (De Souza and Riris, 2021). In contrast, in the Amazon, centres of local domestication and early adoption of exotic crops date to the early to mid-Holocene (Watling et al., 2018; Lombardo et al., 2020). Due to this, it is possible that the ability to reach carrying capacity would have been attained earlier in the Amazon than in the Atlantic Forest. Although we detected minimal differences between the logistic and exponential model fit (**Supplementary Figures 2**, **3**), an exponential model of growth, besides being more parsimonious, is compatible with the cultural trajectories of the Atlantic Forest against those of the Amazon over the period of interest (Arroyo-Kalin and Riris, 2021). Before continuing, we underscore the persistence of Indigenous populations over our period of study. In the context of the last 1,500 years before the Conquest, Indigenous people were still experiencing unabated exponential growth (**Figure 4**). The relatively late occupation of the Atlantic Forest by farming populations must, however, be considered within its changing environmental context. The best example is the dispersal of the Tupi-Guarani, extremely rapid to the point where determining the precise chronology and direction of spread becomes unfeasible (Riris and Silva, 2021). Events of accelerated demic expansion, perhaps due to the migrant societies finding a new or relatively unexplored niche, may have contributed to the observed exponential growth, suggesting the Atlantic Forest societies were far from reaching carrying capacity at the eve of the Conquest. Furthermore, the role of late Holocene climate-driven forest expansion in the Atlantic Forest biome has to be considered (Smith and Mayle, 2017). As in other global cases of the expansion of agriculturists (Russell et al., 2014), the increase in the areas that could be exploited by polyculture agroforestry is likely to have facilitated the Tupi-Guarani dispersal (Iriarte et al., 2017). The expansion and contraction of certain niches would have influenced the dispersal and growth not only of the Tupi-Guarani, but also of Jê societies, whose subsistence relied on *Araucaria* forests in southern Brazil (Iriarte and Behling, 2007; Pereira Cruz et al., 2020).

Bearing these points in mind, we note that low resistance metrics for the Northern region, coupled with comparatively higher resilience observed in the centre and south, appear at first to correlate with the latitudinal gradient in the signal of the MCA observed in eastern Brazilian speleothems, which show a stronger deviation north of the SACZ (Novello et al., 2018). The speleothems at the core region of the SACZ, corresponding to our central sites, exhibit increased climate variability at the MCA-LIA transition (Novello et al., 2018), which may explain the decline in growth rates at the end of the MCA period (**Figure 5**). The northeast region of Brazil is expected to be the most sensitive to hydrological changes; climate simulations have confirmed its susceptibility to biome shifts when compared to the southern and central parts of the Atlantic Forest domain (Ledru et al., 2016; Costa et al., 2018). Relative biome (in)stability may therefore be an important factor in mediating the resistance and/or resilience of pre-Columbian populations to abrupt change, to a greater degree than absolute states such as "open" or "closed" vegetation (alternatively, forest or grassland). Quantifying tropical ecosystem stability—and hence the viability of different subsistence strategies in terms of resistance-resilience—against the backdrop of palaeodemographic dynamics is likely a useful avenue for future work. The main factor behind the observed north-south trend in resistance may be hydroclimatic regime variability, as the southern region receives precipitation from southerly, extra-tropical, oceanic sources in winter (Cruz et al., 2005; Campos et al., 2019). This is in agreement with the observation that, in the early to mid-Holocene transition (∼8,200 cal BP), the impacts of precipitation variability were lessened in more climatically stable regions, such as the southern part of South America (Riris and Arroyo-Kalin, 2019). Climate therefore seems a likely candidate for the main driver of the observed differences in resistance-resilience in our study area. Consequently, we reject the null hypothesis of no change to palaeodemographic growth rates across the Atlantic Forest during the MCA.

The different responses of Atlantic Forest societies during the MCA provides additional context for the expectations posed by De Souza et al. (2019), who argued in central-eastern Amazonia that polyculture agroforestry should provide a more resilient economic basis in the face of climate change than specialised, intensive land use systems. By separating palaeodemographic responses into the components of resistance and resilience, we are able to qualify this inference; the capacity to rebound following abrupt disturbances appear to be common across the agroforestry systems under study (resilience $p > 0.05$ in all cases), but responses to initial impacts (notably its timing and relative magnitude) appears to depend on local circumstances to a greater degree. In a topographically and biogeographically diverse environment, such as the Atlantic Forest, this is a relatively intuitive finding. Our findings parallel ecological resilience studies, where multiple metrics are found to be more capable of revealing different facets of the systems under study than single indices (Cantarello et al., 2017). Comparative studies will likely help to add further nuance, as well as better understandings of the components (species, cultivars, land use systems) that made up different forms of polyculture agroforestry in the past, which certainly had considerable internal variation. To this end, in addition to climatic/vegetation variability within the Atlantic Forest range, socio-cultural factors could be behind some of the observed differences in resistance-resilience. The available data suggest that the societies throughout the studied area practised similar forms of polyculture agroforestry, albeit in different niches (De Souza et al., 2020; Pereira Cruz et al., 2020), yet multiple distinct forms of social organisation existed prior to Conquest. Recent studies have emphasised pre-Columbian monumentality in southern Brazil as an indicator of territoriality and inter-group competition (De Souza et al., 2016), however, the emergence and maintenance of corporate architectural traditions can also be viewed as evidence and facilitators of strengthened intra-group cohesion (Iriarte et al., 2013). A possible consequence of more explicitly manifested and formalised social structures includes an ability to coordinate and manage resources above the kin level. Although we have focused on MCA climate as a driver of palaeodemographic impacts, we suggest that future work should consider quantitative approaches towards social *and* environmental factors as mediators of these impacts, and thus, investigate their possible role as facilitators of demographic and societal resilience.

We have focused here on the potentially deleterious effects of abrupt hydroclimate variability on population growth, highlighted previously elsewhere in lowland South America (Azevedo et al., 2019; Riris and Arroyo-Kalin, 2019). Our approach expects that the system(s) under study display resistance and resilience if baseline conditions are maintained or are returned to, respectively. There are, however, other scenarios for which our tests may be suitable, including inverse to those presented here. Returning to the indices as illustrated in **Figure 3**, one can also imagine "perturbations" to cultural systems such as the invention and spread of a technological innovation that *raises* growth rates over an interval of time. This hypothetical scenario would also result in values of <1 being returned in our metrics. Such a result is not because a given cultural system or group was (necessarily) adversely affected by rising growth rates, but because the nature of the system has measurably changed by the adoption of an innovation, reflected in its "low" resilience. The equations, and by extension our tests, are agnostic about whether change is a net positive or a net negative. We feel it is important to underscore this point, as it is contrary to commonplace understandings of resilience in the archaeological literature, which tends to interpret signs of "improvement" (i.e., increasing growth rates) as "high" resilience (Bradtmöller et al., 2017). Another, perhaps more intuitive, way to view resilience in this sense is that the prior cultural system was vulnerable to the introduction of an innovation, and so "collapsed" into a novel regime incorporating it. As always, caution must be exercised when deploying metrics; their broader societal and, in this case, palaeodemographic contexts are important for enabling considered interpretations of their meanings. The equations and indices make no distinction about the significance of low or high resistance-resilience values—careful consideration of the cultural system as a whole must accompany interpretation. Our aim is to encourage careful use in future applications, as the benefits of systematising the archaeological study of societal resilience are potentially great: comparability, communicability of results, rigour, and facilitating interdisciplinarity and impact.

CONCLUSION

This paper has sought to develop novel methods for the archaeological study of resilience in prehistory, a topic of significant concern (Bradtmöller et al., 2017; Russo and Brainerd, 2021). We have, both previously and separately, argued for the systematisation of the study of resilience in palaeodemography (De Souza et al., 2019; Riris and Arroyo-Kalin, 2019), in parallel to similar calls elsewhere (Bird et al., 2020). We are motivated by the need to make the archaeological study of resilience more rigorous and transparent, an essential part towards building interdisciplinary dialogue (Moser et al., 2019, p. 37). Here, we have drawn on mature research in quantitative ecology to propose a common framework for measurement of resilience in archaeology. Our method, which takes advantage of probabilistic, continuous time series data, can also be viewed as an answer to collapse-centric narratives on past societal responses to abrupt change (Middleton, 2017, p. 81; Koch et al., 2019; Degroot et al., 2021). We argue that the approach encourages attention to particular circumstances in archaeological and historical perspective, while also enabling the formalism that typifies the ecological resilience literature, and which we regard as a prerequisite to developing a comparative, deep time perspective on coupled socio-environmental changes and their consequences. We have demonstrated this by testing palaeodemographic responses to disturbances across and between biogeographically relevant zones of the South American Atlantic Forest during the Medieval Warm Period to explore the implications of hydroclimatic variability for the pre-Columbian societies of this biome. The resulting analysis of longitudinal and cross-sectional trends in palaeodemography reveal notable regional differences.

It remains hard to argue that there is a single "correct" way of viewing resilience (Middleton, 2017). Nonetheless, building a perspective that by its nature is rooted in probabilistic evidence of past population changes, itself is based on the ubiquitous use of archaeological radiocarbon dates, certainly has advantages that other proxies do not. Notably, our approach provides explicitly defined, quantitative, and reproducible alternatives to interpretative approaches, which accompany this paper for future use and refinement (**Supplementary Material**). We acknowledge that point estimates of resistance and/or resilience are likely imperfect reflections of a more complex picture in the past and that there will always be alternatives to the equations and tests we have implemented. Even so, we suggest that directly comparable data on prehistoric resistance-resilience provide a more useful point of entry into identifying what factors (behaviours, adaptations, institutions, ecologies) mediate the severity of disturbance impacts than *incomparable* ones, as well as whether trade-offs exist between different factors in terms of robustness and fragility. These issues already form the focus of substantive research (Peregrine, 2020), and the present work charts a path through them by focusing on measurable features of ancient population dynamics. Furthermore, our approach enables the archaeological study of resilience to locate commonalities of language with the ecological resilience literature.

Our method therefore paves the way for the systematic and rigorous evaluation of inferred disturbances to human societies and culture-climate links in general. We suggest that other well-known phases of abrupt climate change, for example the Younger Dryas/Bølling-Allerød, the Pleistocene/Holocene transition, the 8.2 and 4.2 ka events, and data permitting, the "Columbian Exchange" (Hamilton et al., 2021) would be ideal test beds for the approaches we advocate. While attention here has mainly been on climate as a driver, abrupt social change or reorganisation may be equally important, and interesting, targets for comparative analysis (such as periods of warfare, Edinborough et al., 2017). Archaeological palaeodemography is also uniquely positioned to offer enhanced estimates of effective population size and density, which are key to understanding the deep time earth systems impacts of humanity more comprehensively (Klein Goldewijk et al., 2017; French et al., 2021; Morrison et al., 2021). Finally, we anticipate that continuing analytical refinements in Bayesian inference (Carleton, 2021; Crema and Shoda, 2021) as well as hereto unexplored methods such as symbolic transfer entropy (Camacho et al., 2021) will open up the study of causal links between population resilience and induced disturbances.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

PR and JS: conceptualisation and writing. PR: analysis and figures. Both authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fevo.2021.740629/full#supplementary-material

Supplementary Figure 1 | Results of Bayesian radiocarbon analysis with logistic prior. Left: results of posterior predictive check, showing the empirical Atlantic Forest SPD (black line) within the prediction range of the fitted model (grey envelope), excepting close to the Conquest. Bottom right: marginal posterior distribution of the growth rate r over the interval 1900–500 cal BP. Top right: marginal posterior distribution of the carrying capacity k over the same interval.

Supplementary Figure 2 | Exponential model trace plots and goodness-of-fit diagnostics.

Supplementary Figure 3 | Logistic model trace plots and goodness-of-fit diagnostics.

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Bridging Legends and Science: Field Evidence of a Large Tsunami that Affected the Kingdom of Tonga in the 15th Century

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The pre-colonial history (i.e. before the 16th century) of Tonga and West Polynesia still suffers from major gaps despite significant scientific advances in recent years, particularly in the field of archaeology. By the 14th century, the powerful Tu'i Tonga kingdom united the islands of the Tongan archipelago under a centralised authority and, according to tradition, extended its influence to neighbouring island groups in the Central Pacific. However, some periods of deep crisis were identified, e.g. in the mid- 15th century, marked by an abrupt cessation of inter-archipelago migration on the deep seas in the Pacific, significant cultural changes, and a decrease in accessible natural resources. The origins of these disturbances are still debated, and they are usually assigned to internal political problems or loss of external influence vis-à-vis neighboring chiefdoms. However, the hypothesis of a major natural disaster was rarely suggested up to now, while field evidence points to the occurrence of a very large tsunami in the past, including the presence of numerous megablocks that were deposited by a "red wave" (or *peau kula*, which also mean tsunami in the Tongan language) according to a local myth. Drawing on a body of new evidence from sedimentary signatures and radiocarbon dating of charcoal and marine bioclasts, geomorphology, and sedimentology, in support of previously published archaeological data, we argue that a large tsunami inundated large areas of Tongatapu island in the mid-15th century with runup heights up to 30 m, and that the Tu'i Tonga kingdom was severely impacted by this event. We also discuss the likely sources of this tsunami.

Keywords: tsunami, megablock, sedimentology, radiocarbon dating, bioclasts, legend, southwest Pacific

1 INTRODUCTION

Located in the South Pacific Ocean, the archipelago of Tonga has almost 170 islands, 36 of them inhabited, and divided into three main groups, namely Vava'u, Ha'apai, and Tongatapu archipelagos (**Figure 1**). The pre-colonial history of Tonga and West Polynesia still suffers from major gaps despite significant scientific advances in recent years, particularly in the field of archaeology. By the 13th century, the Tongan kings named the Tu'i Tonga ruled several nations over the Southwest and South Central Pacific for more than 300 years, sparking historians to refer to a "Tongan Maritime Empire" (Clark et al., 2014). By the 14th century, a powerful chiefdom united the islands of Tonga under a centralised authority and, according to tradition, extended its influence to neighbouring island groups in the Central Pacific (Dickinson et al., 1999; Barnes and Hunt, 2005; Clark and Reepmeyer, 2014; Cochrane and Rieth, 2016; Burley and Addison, 2018). However, some periods of deep crisis were identified, especially in the middle of the 15th century, marked by an abrupt cessation of inter-archipelago migration on the deep seas in the Pacific (Goff and Nunn, 2016) and significant cultural changes. The origins of these disturbances are still debated, e.g. internal political problems (Burley, 1998), or loss of external influence vis-à-vis neighboring states such as Samoa. While the hypothesis of a major natural disaster was never suggested, a local legend in Tonga refers to a gigantic *peau kula* or "red wave" (which is also the Tongan word for tsunami) that covered the whole island of Tongatapu in the Past (Morton, 2003).

Based upon a combination of palaeotsunami and archaeological data out of Tonga, several scholars have

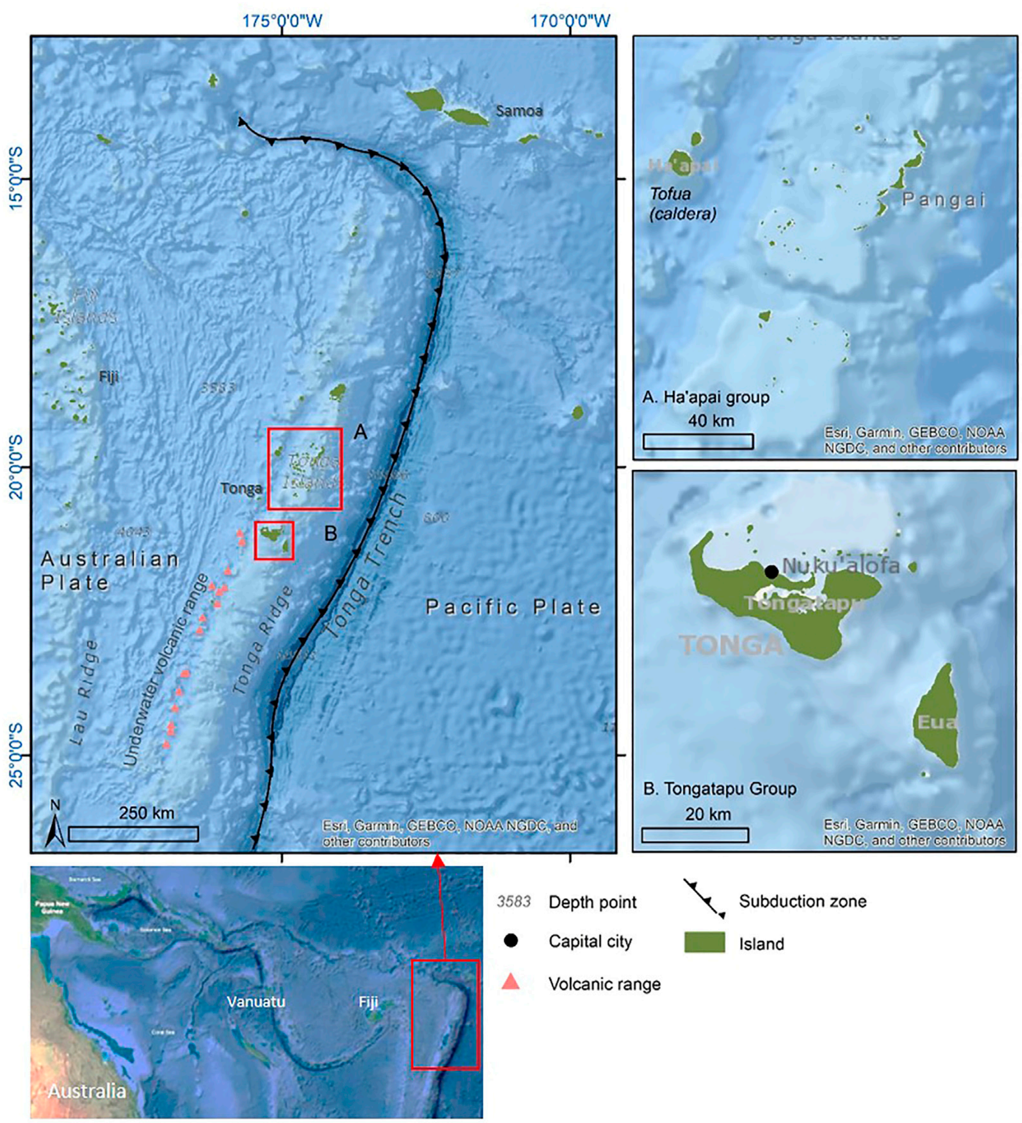

FIGURE 1 | The Tongan archipelago in the Southwest Pacific.

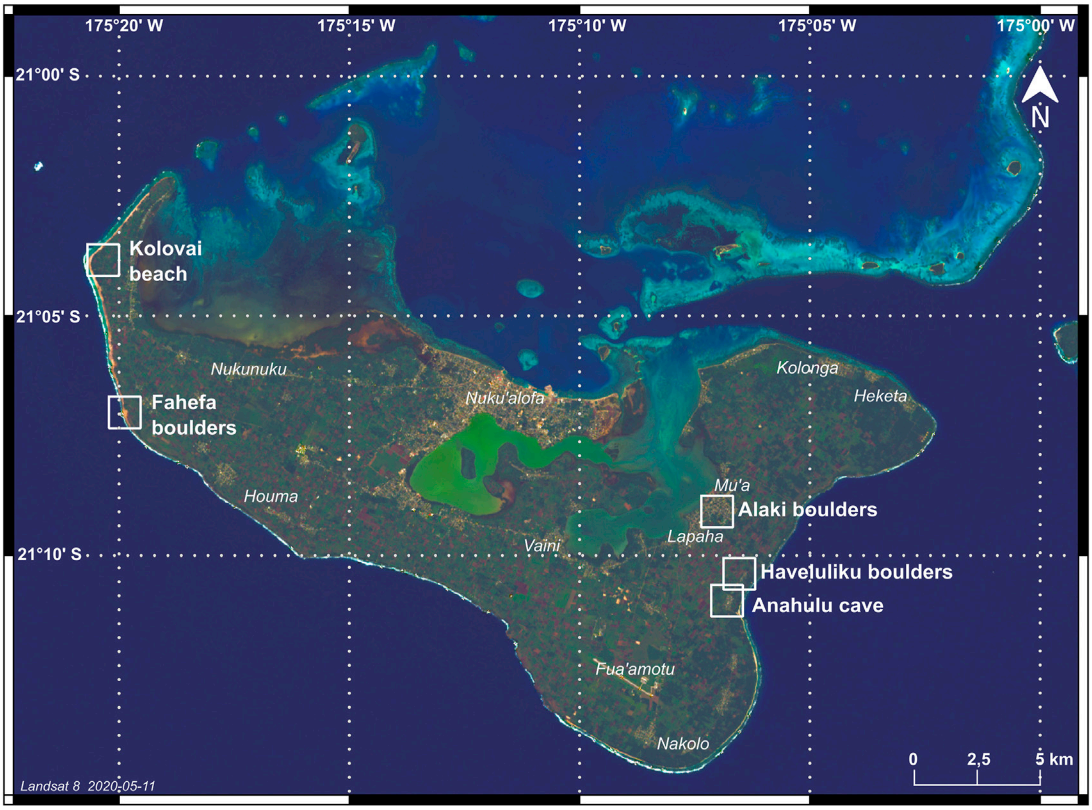

FIGURE 2 | Map of Tongatapu showing study sites.

already evidenced the occurrence of a "region-wide single, high-energy coastal event" over the southwest Pacific Ocean around the 15th Century (Goff et al., 2011a). In New Zealand, a minimum runup of 11–15 m a.s.l. was estimated at the Kapiti Island, near Wellington, and a maximum of 65 m a.s.l. along Ngararahae Bay on the west coast of the North Island (Goff and Chagué-Goff, 2015). This widespread tsunami strongly affected the prehistoric Maori settlements in this country (McFadgen, 2007; Goff et al., 2012), where they were installed since the end of the 13th Century after a mass migration event (Walter et al., 2017). In the Great Barrier Island and several other sites, archaeological records and Maori oral traditions (*pūrākau*: King and Goff, 2010) show a significant break in the occupation, either temporary or permanent, around the mid-15th century CE (Goff and McFadgen, 2001).

Evidence of a large-scale tsunami was also reported from the east coast of Australia, where several coastal midden sites reworked by seawater in the Sydney area also date back to the mid-15th century (Bryant et al., 1992; Nott, 1997). Further North, sedimentary evidence in coastal sediments indicates significant tsunami inland inundation and runup all around the island of Futuna, dated ca. 1,450 to 1500 CE (Goff et al., 2011a). Other unequivocal sedimentary evidence of a similar event is found in Rurutu (Austral Islands: Bollt, 2008). This region-wide tsunami might have highly contributed to landward movement from bays and coastal platforms to hills and inland sites in the mid-15th century (Leach and Leach, 1979).

In order to corroborate–or deny-the "red wave" legend in Tonga, we carried out a field survey with the aim to investigate sedimentary features at five sites in Tongatapu. This island is made up of up to 250 m of Pliocene and Pleistocene coral reef limestone (Cunningham and Anscombe, 1985), which rises at its highest point to some 65 m above sea level (a.s.l.) at the southern end of the island (Harrison, 1993). The limestone is covered by tephra deposits, which decrease in thickness from the west (up to 5.5 m) to the east (<1.5 m), indicating that they were deposited from volcanic sources west of Tongatapu against the prevailing winds (Spennemann, 1997). Drawing on a robust body of new compelling evidence from radiocarbon dates, geomorphology and sedimentology, we argue that the Tu'i Tonga kingdom was also severely impacted by a large tsunami in the mid-15th century.

2 MATERIALS AND METHODS

2.1 Field Investigation

We investigated five sites in Tongatapu where tsunami signatures were identified (**Figure 2**). One of these sites, at Fahefa village, displays huge coral boulders located between 10 and 22 m asl which were already studied by Frohlich et al. (2009). The second site, called Haveluliku, was the subject of an unpublished preliminary study by a Japanese team, which measured the size of some blocks. The three other sites, namely Kolovai, Alaki and Anahulu cave were discovered and investigated by our team during a field trip in October 2018.

Sedimentary deposits were studied at natural or man-made outcrops (cliffs, embankments) and in hand shovelled trenches, including one trench in the Anahulu cave. Several sandy deposits were found and sampled beneath some megablocks suspected to have been deposited by a tsunami. These deposits cannot therefore be unambiguously more recent than the block above them. The faces of the trenches were refreshed and levelled with the help of a narrow trowel. For all sites, the stratigraphic units were identified, thoroughly described and sampled for: 1) sedimentological analysis: grain size characterization to infer hydrodynamic conditions prevailing during deposition; petrographic nature of the sediments; micro-fossils determination; 2) radiocarbon dating on shells, foraminiferal samples and charcoals. For the Anahulu cave site, preliminary coring was carried out to assess the depth of sediment trapped in the cave to determine the location with the most significant sediment filling. A 128 cm deep pit was excavated down to the limestone bedrock using a shovel and a crowbar. For the tsunami boulders, which may have been bulldozed by the turbulent tsunami front (Maui rock, Haveluliku and Alaki sites), investigations focused on their landward side under which marine sediments would remain trapped. Excavations were thus carried out to clear the base of the boulders. In addition, the morphometrical component of the roughly ellipsoidal boulders were measured (i.e. length, width, and height) in order to calculated approximate volume (π.Le.Wi.H/6) and masses, using a density of ~2.0 g/cm^3 for these massive coral limestone boulders (Spiske et al., 2008).

2.2 Laboratory Analysis

Several types of analyses were carried out in laboratory. Protocol details of the following analyses are provided in the SI Appendix—Material and methods. Grain size measurement of 12 sand and finer particles were performed at the Laboratory of Physical Geography in Meudon, France, using a Beckman Coulter laser diffraction particle size analyser LS 13 320. It measures particles size over a single range of 0.04–2000 μm. The determination of foraminifera was carried out at the University of Strasbourg from 100 g of sediment taken from samples collected in the field (details in *SI* **Supplementary Appendix S1.1**). The composition of major and trace elements of volcanic material (pumice fragments) was performed in three laboratories: analysis of major, minor, and trace elements were made on pumice samples by ICP-AES and ICP-MS at the Laboratoire Magma et Volcans, Clermont-Ferrand, France, and the SARM-CRPG (Centre Pétrographique et Géochimique), Nancy, France (details in *SI* **Supplementary Appendix S1.2**). Analysis of melt inclusions, matrix glasses and fluid inclusions was performed at the Department of Geography, University of Cambridge (details in *SI* **Supplementary Appendix S1.2**).

Twenty-one charcoal and bioclasts (marine shells, foraminifera) samples were dated using Accelerator Mass Spectrometer (AMS) and radiometric methods at the DirectAMS Radiocarbon Dating Laboratory in Seattle, United States (details in *SI* **Supplementary Appendix S1.3**). An important difficulty with respect to dating a tsunami deposit is that during run-up, erosional processes incorporate previously deposited material into the sediment mix, e.g., old shells and foraminifera samples that have previously stagnated at the bottom of the sea or on the beach up to several centuries after the death of the animal (Ishizawa et al., 2020). Therefore, the results conducted using bulk sediment samples merely represent a maximum age of deposition. Another issue for the age estimation of tsunami deposits is that they are not commonly found within a sedimentary sequence. Therefore, it is usually difficult to obtain the required number of 14C ages for Bayesian modelling (Ishizawa et al., 2020).

2.3 Tsunami Numerical Modelling

We performed numerical modelling of tsunamis triggered by earthquakes, caldera-forming volcanic eruptions and volcano flank collapses (details in *SI* **Supplementary Appendix S1.4**), and meteorite impact. The simulations were performed using two simulation codes already tested and recognised by the scientific community, i.e. VolcFlow (Kelfoun and Druitt, 2005) and Comcot (Wang and Power, 2011). VolcFlow, which is based on a depth-averaged approach of the equations of mass and momentum balance, has been already used for all types of tsunamis. The tectonic tsunamis were computed by imposing several amplitudes and wavelengths at the boundaries of the calculation domain. To generate the caldera tsunamis, a downward vertical velocity of the caldera floor is imposed (Nomikou et al., 2016). For volcano destabilizations, the mass is released immediately and the velocities of the destabilized rocks and, consequently, the waves characteristics are controlled by the rheology assumed (Kelfoun et al., 2010; Giachetti et al., 2012; Paris et al., 2017). The tsunamis from meteorite impact were simulated for a large range of initial wave amplitudes and related radii (methods detailed in Costard et al., 2017).

3 RESULTS: EVIDENCE OF A LARGE TSUNAMI IN TONGATAPU IN THE 15TH CENTURY

Our results are presented following the same West-East geographic transect of this island.

3.1 Kolovai

In the north-western peninsula of Tongatapu, Duphorn (1981) described a widespread sandy deposit termed "Pumice Terrace" (because it contains rounded pumice), covered by a layer of dark grey compact ash fallout deposit. This "Pumice Terrace" has been interpreted as a relict beach related to a +2–3 m mid-Holocene sea level highstand (Roy, 1990). In the same area, we sampled a deposit located 6 m a.s.l. and 70 m away from the Kolovai Beach (**Figure 2**). This deposit displays typical features of a tsunami

TABLE 1 | Radiocarbon age of tsunami deposits.

Sample ID	Material	Coord.(decimal degrees)	Stratigraphy	Layer	Depth (cm)	Conventional radiocarbon age				
						Uncal Bp[a]	1s error	Cal CE[b] (1s error)		Cal CE[b] (2s error)
KOL.1.5	Charcoal	–21.088972–175.351667	Original deposit. Base of the pumice layer	—	86	451	32	1,447–1,487 (84%) 1,489–1,497 (11%) 1,604–1,607 (5%)	1,467 ± 20 (84%)	1,431–1,508 (82%) 1,586–1,621 (18%)
KOL.1	*Charcoal*	*–21.088972–175.351667*	*Reworked sand (interpretation)*	—	*105*	*108*	*26*	*Post 1,695*	—	*Post 1,684*
KOL.1.7	*Charcoal*	*–21.088972–175.351667*	*Reworked sand (interpretation)*	—	*130*	*Modern*	—	*Post 1950*	—	*Post 1950*
MAU.1A3	Charcoal	–21.134750–175.344444	Rock shelter. First human artefact after tsunami	3	7	397	35	1,459–1,509 (55%) 1,552–1,557 (3%) 1,583–1,622 (42%)	1,484 ± 25 (55%) 1,602 ± 19 (42%)	1,456–1,517 (43%) 1,524–1,534 (3%) 1,535–1,627 (54%)
MAU.1B2	*Shell*	*–21.134750–175.344444*	*Consumed shell (interpretation)*	—	—	*481*	*26*	—	—	—
ANA.2.2G	Shell	–21.208194–175.103833	Within sand layer left side	22	23	951	25	1,465–1,651	1,558 ± 93	1,388–1792
ANA.A5	Foram	–21.208194–175.103833		22	23	2025	25	435–646	540 ± 105	300–747
ANA.22D	Foram	–21.208194–175.103833	Within sand layer right side	22	25	2,107	27	340–573	456 ± 116	224–665
ANA.1.A7	Charcoal	–21.208194–175.103833	Middle of the pumice (–3 cm from top)	18	48	828	28	1,226–1,255 (73%) 1,261–1,271 (27%)	1,240 ± 14 (73%)	1,212–1,283
ANA.1.7C2	Charcoal	–21.208194–175.103833	—	18	50	1,316	32	681–750 (90%) 768–773 (6%) 821–827 (4%)	715 ± 34 (90%)	672–774 (78%) 785–798 (3%) 807–867 (19%)
ANA.1.16	Shell	–21.208194–175.103833	Base of the pumices	16	54	1,650	25	808–1,028	918 ± 110	697–1,136
ANA.1.B15	Foram	–21.208194–175.103833	—	15	65	2,419	25	38 BCE - 214	88 ± 128	174 BCE - 335
HAV.3	Shell	–21.204416–175.104603	Within sand layer	—		1,094	28	1,333–1,514	1,423 ± 90	1,274–1,639
HAV.4.AV4	foram	–21.204416–175.104603	Within sand layer	—	30	1,066	22	1,352–1,541	1,446 ± 94	1,294–1,652
HAV.4.AV1	Shell	–21.204416–175.104603	Within sand layer	—	30	1,445	27	1,033–1,237	1,135 ± 102	909–1,318
HAV.7.1S	*Shell*	*–21.204416–175.104603*	*Consumed shell*	—	*45*	*modern*	—	*Post 1950*	—	*Post 1950*
HAV.7.2S	*Shell*	*–21.204416–175.104603*	*within sand layer (confirmed by the garden owner)*	—	*56*	*411*	*23*	—	—	—
HAV.9.2AS	*Shell*	*–21.204416–175.104603*	*Consumed shell (interpretation)*	—	*23*	*391*	*23*	—	—	—
HAV.9.3S	Shell	–21.204416–175.104603	Within sand layer	—	45	865	23	1,509–1727	1,618 ± 109	1,448–1862
MAS.20	Charcoal	–21.188098–175.123609	—	—	20	510	34	1,425–1,452	1,438 ± 13	1,403–1,461 (99%) 1,473–1,478 (1%)
MAS.38	*Shell*	*–21.188098–175.123609*	*Consumed shell (interpretation)*	—	*38*	*Modern*	—	*Post 1950*	—	*Post 1950*

[a]*Uncal BP dates from DirectAMS.*
[b]*Data from CALIB RADIOCARBON CALIBRATION PROGRAM.*
Stuiver, M., Reimer, P.J., and Reimer, R.W., 2020, CALIB 8.2 (WWW program) at http://calib.org, accessed 2020-10-13.
Terrestrial material (charcoal) were dated using SHCal20.
Marine samples originated from the open ocean environments were calibrated using MARINE20, with a DeltaR value of 11+-83 years as recommended by Petchey and Clark (2011), or Clark and Reepmeyer (2014).

deposit (Goff et al., 2011a), e.g.: 1) poorly sorted white sand, which is not consistent with a palaeobeach; 2) abundant individual shells and shell-rich sub-units, and coral fragments; overtopped by 3) a 15 cm-thick layer of rounded dacitic pumice (SiO_2 > 63 wt%, Na_2O + K_20 < 5 wt%: *SI Appendix*, **Supplementary Figure S1**, **Supplementary Table S1** and

FIGURE 3 | Tsunami boulders in Tongatapu. **(A)** The sacred Maui Rock in Faheha, 10 m a.s.l. (~780 m^3); **(B)** Second largest megablock at Fahefa, 13.5 m a.s.l. (~230 m^3); **(C)** Boulder at Haveluliku, 30 m asl; **(D)** The sacred Masila boulder at Alaki (Mu'a town).

Supplementary Table S2), which may have been floated by a flow. This composition is representative of the volcanoes along the Tonga-Kermadec Trench (Bryan et al., 1972). These rocks differ from most other circum-Pacific andesite-dacite suites in their very low content of alkali, especially low K_2O (almost always <0.8%). Light differences between the samples indicate that the pumice have been eroded from the Kolovai beach, either by a tsunami or a storm surge similar or higher than the one that have been generated by typhon Harold in April 2020 The altitude of this pumice layer may indicate the maximum runup of the tsunami wave, i.e. 6 m. A charcoal embedded in this layer is dated 1,467 ± 20 years CE (**Table 1**), which would indicate a mid-15th century tsunami event.

3.2 Fahefa Village, Site of the Maui Rock

A line of seven massive coral limestone boulders is located at Fahefa village, 100–400 m from the reef edge of the western shore of Tongatapu (**Figure 2**). The largest boulder, called Tsunami Rock or Maui Rock (*Maka Tolo ʻa Maui* in the local language) reaches 15 m long, 9 m high, and may weights up to 1,600 tons (**Figure 3A** and **Supplementary Table S3**). According to Tongan tradition, there are two tales about this Rock (Gifford, 1924, https://www.kanivatonga.nz/2017/09/tongan-legends-portray-maui-as-a-scientist-but-in-poetic-language-say-scholars). One of them relates that the god Maui used this boulder together with a magical rope from the hair of the goddess Hina to anchor the Sun and slow it down from racing across the sky. Another legend tells that Maui hurled the boulders ashore in an attempt to kill a giant man-eating fowl and saved people, the giant fowl referring to the waves—as also suggested by the "Maui throwing stones" legend encountered in Haveluliku (see below). This second tale could be interpreted as a metaphoric reference to a tsunami, which brought these massive boulders to the surface of Tongatapu. Based on scientific evidence, these boulders are considered as the largest known tsunami erratic in the world (Frohlich et al., 2009). All lying from 10 to 20 m a.s.l., they could not have rolled downhill from elsewhere because the island is flat. They are located hundreds of meters from the reef and made of the same coral limestone reef material offshore, but cannot under any circumstances have been deposited by a cyclone.

Using the methodology of Nandasena et al. (2011), we calculated the minimum wave heights required to transport the boulders along the west and southeast coast of Tongatapu (**Supplementary Table S3**). The equation we used for a free boulder displacement is based on four parameters, i.e. size, density, and distance from shore of the boulder, considering two scenarios of Froude number (F). Along the Fahefa coast, the minimum wave height required to transport the largest boulder, i.e. the so-called Tsunami Rock, ranges from 23 m (F = 0.75) to 13 m (F = 1).

On the basis of 230Th ages, Frohlich et al. (2009) argue that the Maui rock must have been deposited either within the past 7,000 years or ca. 122,000 years, rather than at intermediate times when sea level was 15–120 m lower than present. However, there is no trace of limestone dissolution at the bottom of the boulders, which suggests an age of a few thousands or even hundreds years at most. Furthermore, the volcanic soil surrounding the boulders in the lowlands is much thinner than that found at higher elevations (Cowie, 1980), even in remote areas not subject to anthropogenic erosion (due to agricultural or tourist pressure like at the Maui rock). Despite the absence of datable material within the remaining thin surficial

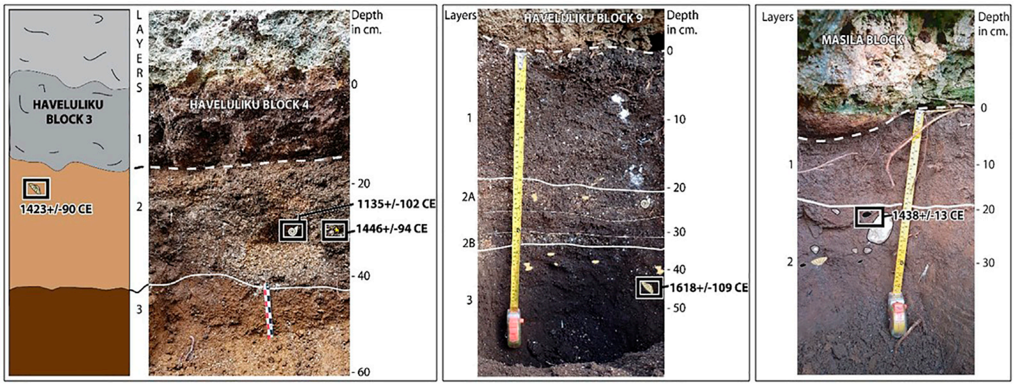

FIGURE 4 | Sediment layers interpreted as tsunami deposits below the boulders at Haveluliku and Alaki.

soil, we argue that the volcanic soil could have been eroded by the tsunami very recently, a few centuries at most. A large cavity under the Maui rock has trapped thick sandy deposits containing sea shells (e.g. MAU1b2 sample in **Table 1**), probably carried by the wind during cyclones. This natural cavity, due to the shape of the boulder, could have rapidly served as a shelter against heavy rains soon after the boulder deposition. This could explain the presence of a hearth at the base of the sandy deposit in the cavity, in contact with the basal coral limestone. We excavated this hearth for radiocarbon dating, which gave an age around the 15th or 16th century (**Table 1**).

3.3 Haveluliku Boulders

On the eastern coast of Tongatapu, a group of eight coral limestone boulders are located in the village of Haveluliku at 30 m a.s.l. and 500 m from the sea shore (**Figures 2**, **3C** and **Supplementary Table S3**). The largest boulder is $8 \times 3 \times 3.20$ m, i.e. about 70 m^3, and may weights about 140 tons. Some of the local residents we interviewed reported a higher number of boulders decades ago, that were gradually dismantled by the local community and used as building material. According to a local myth, these blocks were thrown up to Haveluliku by Maui, a giant chief, from the neighbouring island of Eua. As Maui was annoyed at being woken up by a rooster every morning, he picked up stones to throw them at the rooster, which fled from Eua to Tongatapu where he ended up wounded. In the old Tongan poem by Tufui displaying this legend, the rooster is fowl (Gifford, 1923, p.12). Some Haveluliku inhabitants refer to the blocks as the "Maui throwing stones" deposited while chasing chicken(s). Interestingly, as the term "white chicken" means "foaming waves" in Tongan, this legend might be a metaphor for a tsunami. However, this interpretation is tenuous as roosters are very widely associated in Polynesian mythology with voracious human or semi-divine warriors or enemies (Richter-Gravier, 2019), and not the sea specifically; it is more likely that this myth refers to the destruction of a dominant community (maybe by a tsunami).

The boulders lay on a surface formation mainly formed by a 25–30 cm thick layer composed of coarse and slightly pedogenized marine sand mixed with marine shells and occasional rounded pumices (**Figure 4**). Some erosional figures within the deposit makes the case for a transport by a landward turbulent flow, which cannot be a storm surge at this altitude (up to 30 m a.s.l.). The anthropic origin being ruled out, this deposit can only be attributed to a large tsunami that hit the southern coast of Tongatapu.

As an additional argument for this interpretation, the deposits below the boulders are poorly sorted as attested by the S0 that evolves between 4.246 and 2.663 (while 1 corresponds to a good sorting: *SI Appendix*, **Supplementary Figure S2**). The spreading and multimodal shape of the granulometric curves, in addition to some erosional figures within the deposits, reflect an en-masse deposition of the sediment transported by a highly turbulent flow, which cannot be a storm surge at this altitude (30 m a.s.l.). Such a particle size distribution cannot be associated with either an aeolian-type deposit (e.g. from a cyclone) or an anthropogenic origin. This deposit can therefore only be attributed to a large tsunami. Based on the model of Nandasena et al. (2011), the minimum wave heights required to transport the largest boulder at Haveluliku ranges from 11 m (F = 0.75) to 6.2 m (F = 1) (**Supplementary Table S3**).

A confirmation of the high turbulence during sediment transport from the sea to Haveluliku is reflected by the rate of foraminifera wear and tear. A comparative study of the foraminiferal content of the beach closest to Haveluliku and the sands trapped beneath the boulders shows that the wide variety of species present on the beach is reduced to the clear dominance of a single species in the deposit: *Baculogypsina sphaerulata* (Parker and Jones 1860). When alive, this species prefers shallow conditions, i.e. <5 m. These habitats are characterized by coral sand and constant wave disturbance (Hallock, 1984; Hohenegger et al., 1999). In this shallow zone, these star-like Large Bentic Foraminifera (LBF) display 3 to 7 sharp points. On the beach, the attrition due to the permanent movement of the sea reduces the sharpness of the branches which are smaller, and sometimes reduced to small bulges. The turbulent transport by the tsunami waves on a 500 m distance from the seashore to Haveluliku village has produced an intense

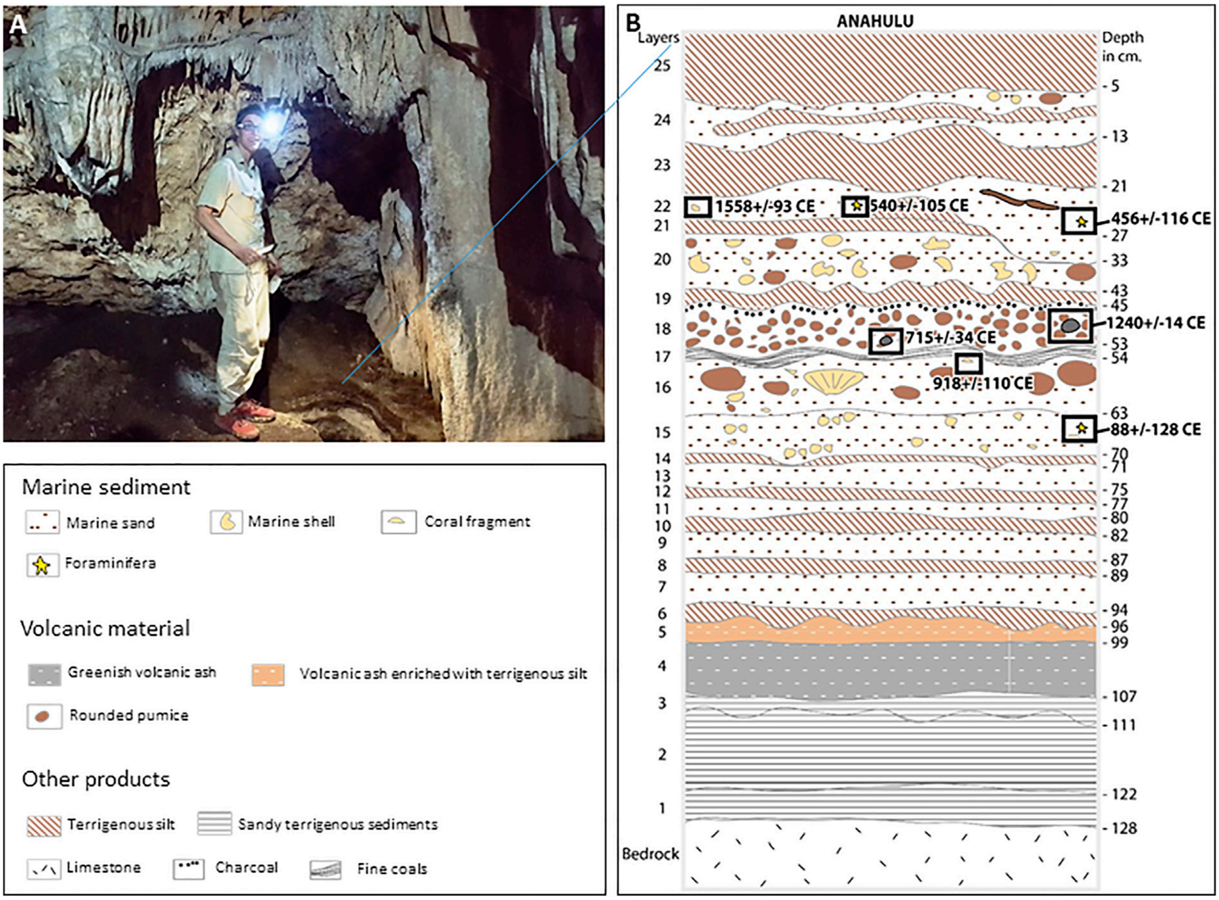

FIGURE 5 | Sedimentary sequence within the Anahulu cave, showing two sequences of tsunami deposits. 1–3: Predominantly sandy terrigenous sediments. 4: Greenish volcanic ash. 5: Volcanic ash enriched with terrigenous silt. 6–14: silty layers alternating with layers of slightly coarser material, interpreted as periodic entries of eroded material from the slope upstream of the cave through fractures. 15: Coarse marine bioclastic sand, with numerous shell fragments and clasts of coral limestone. 16: Coarse marine sand with abundant large shells, rounded pumice up to 9 cm in diameter and terrigenous cave bottom material. 17: 2-cm layer of fine coals. 18: 8-cm layer of small well rounded pumice. 19: Thin layer of brown compact silt. 20: White bioclastic sand mixed with terrigenous silty material, numerous coral debris, shells and pumice. 21: Brown silts. 22: Marine sand sometimes enriched with terrigenous silts. Presence of rip-up clasts. 23–24: alternating terrigenous elements and stretched marine sands. 25: Blackish silty layer containing recent anthropic artifacts.

friction and the *Baculogypsina sphaerulata* found in large number under the boulders therefore exhibit spherical shapes. The lack within this deposit of all the other foraminifera present on the beach must be related to their weak resistance to shocks and attrition.

Radiocarbon dating of four shells and 1 foraminifera sample (*Baculogypsina sphaerulata*) within the sand deposits below three boulders at Haveluliku (HAV 3, HAV4, and HAV9 display a wide range of ages, from the ninth to post-1950 (**Figure 4**). According to testimonies of local inhabitants, the largest and most recent shells are leftovers of food consumed and then buried under the Block 7. Excluding these recent shells, the other bioclasts that have been dated are considered part of the tsunami deposits. The oldest bioclasts, dated to several centuries before the event, were eroded near the shoreline and then transported and deposited by the tsunami. The most recent one believed to have been deposited by the tsunami have been dated to the 15th century CE.

3.4 Anahulu Cave

About 500 m away from the Haveluliku boulders in the southern direction, we identified at least one but probably two tsunami deposits at the bottom the Anahulu cave (**Figure 5A**), which entrance is facing the sea at 9 m altitude. Its name “Anahulu” means « cave of dried leaves” (Gifford, 1923), because it was so dark in the cave that the Tongans had to burn torches of dried leaves to penetrate and explore it. Along a 130 cm deep trench realised inside the cave, we identified 25 layers above the calcareous bedrock (**Figure 5B**). The basal sequence (1–3) is underlain by limestone bedrock and is characterized by predominantly sandy terrigenous sediments resulting from soil erosion above the cave. This sequence is overlain by a layer of greenish volcanic ash (4) whose facies evolves upward by enrichment in terrigenous silt (5). Resting on these deposits with a slightly erosive base, silty layers regularly alternate with layers of slightly coarser material (6–14). This sequence seems to correspond to periodic entries of eroded material from the slope upstream of the cave through fractures in its ceiling.

Layer 15, weakly erosive on layer 14, marks a clear change in the origin of the sedimentation. Composed of coarse marine bioclastic sands, it contains numerous shell fragments and clasts of coral limestone. Its top part (16) contains abundant large whole shells, isolated rounded pumice up to 9 cm in diameter and is enriched in terrigenous cave bottom material. This coarse heterometric material is covered by an 8 cm layer of small well rounded pumice (18). The dacitic composition of these pumices (63–69 wt% SiO_2, 3.4–4.6 wt% Na_2O + K_2O: **Supplementary Table S2** (geochimie glasses) differs from the basalt-andesite ignimbrites formed during the latest paroxysmal (VEI 5–6) explosive eruption of Tofua volcano ca. 1,000 years BP, located ca. 160 km from Tongatapu (*SI Appendix*, **Supplementary Figure S2** and **Supplementary Table S1**). The top of this marine sequence 18) corresponds to a 2 cm thick layer of fine coals. The tsunami origin of this marine sequence (15–19) is beyond doubt, because the entrance of the cave is too high to be reached by the sea during the largest cyclones (i.e., of Cat. Five on the Saffir-Simpson scale) like Harold in 2020 or Gita in February 2018, which is considered as the strongest to have hit Tonga in its history. This first marine sequence is separated from a more recent one by a thin layer of brown terrigenous silt (19).

This second marine sequence (20–24) more than 35 cm thick rests on the silt layer (19) with an undulating contact. At the base, layer 20 is composed of white bioclastic sands mixed with terrigenous silty material. It contains numerous coral debris, foraminifers, sea shells and pumice. Layer 22 also corresponds to pure marine sands sometimes enriched with terrigenous silts. Its contact is erosive on the underlying layers (20 and 21) which it locally cuts in unconformity. The high energy of the water during the deposition of this layer is attested at the base by the presence of silty rip-up clasts typical of highly turbulent flows with a high capacity to erode the terrigenous substratum. The top of the marine sequence (23–24) shows alternating terrigenous elements and stretched marine sand that indicates a back and forth movement of sediment-laden water in the confined context of the cave at the end of a high energy marine flooding. The entire deposit is fossilized by a blackish silty layer (25) containing more or less recent anthropic artifacts. For the same reasons as for the first marine sequence (15–19), this second marine sequence (20–24) is interpreted as a tsunami deposit.

Seven samples were radiocarbon dated, including two charcoals, two shells and three foraminifera, at different depths of the stratigraphic sequence in the cave (**Figure 5B** and **Table 1**). The youngest radiocarbon date calculated for the lower sequence is 1,240± 14 years CE. It was obtained on a charcoal within the pumice layer (18), 48 cm deep. The youngest radiocarbon date of the stratigraphic sequence in the cave was obtained on a sea shell in the upper tsunami sequence (layer 22). The calculated age of 1,558 ± 93 CE is consistent with the most recent one obtained for the Haveluliku boulders and at Kolovai beach, i.e. around the 15th century.

The presence of a charcoal layer overlain by a terrigenous silty deposit shows that the two marine sequences were separated by a short period. It is not clear however, whether the whole succession refers to two different tsunamis, or to a single tsunami composed of two main waves. In the former case, the dates obtained suggest that the two different tsunamis were separated by no more than three centuries. However, while the charcoal may have an intrinsic age older than the tsunami deposit they are found (e.g., older inner rings of a tree: Ishizawa et al., 2020), the lower marine sequence could belong to the first wave of a single tsunami, and be the same age as the upper marine sequence, i.e., 15th century. Under this hypothesis, the terrigenous silty layer (19) that separates the two units may have formed rapidly by erosion of the cave roof during the interval between the two tsunami waves.

3.5 The Masila Boulder at Alaki, Mu'a City

Along the Fanga 'Uta lagoon, located in the northern part of this island, we found only one coral boulder of about 3 cubic metres in the town of Mu'a. Locally called Masila, this sacred boulder for the inhabitants is topped by a tree (**Figure 3D**). As there are a large number of undisturbed archaeological sites dated to around 2,800–2,700 years in the coastal deposits of the lagoon, it is unlikely that this isolated boulder was deposited by a tsunami a few centuries ago, even if a charcoal located at a 20 cm depth beneath this boulder was dated 15th century (**Table 1**).

4 DISCUSSION

Using stratigraphic data, sedimentological analyses, and radiocarbon dates, this study argues that a large tsunami struck and flooded the lowlands of Tongatapu Island up to over 30 m a.s.l. around the mid-15th century. The timing and size of this event are consistent with a region-wide tsunami identified elsewhere in the southwestern Pacific Ocean, which raises the question of its origin and of the human impacts of this tsunami.

4.1 Lack of Evidence for the Origin of the Tsunami

Based on geomorphological field data and numerical tsunami propagation models, we review here the different sources and processes that may have caused the mid-15th century tsunami.

4.1.1 Earthquake Without Co-seismic Slope Failure

Based on the Global Historical Tsunami Database (NCEI-NOAA), there are actually no historical record describing tsunamis exceeding 8–10 m runup anywhere in Tonga produced by either the largest historically known regional earthquakes (up to MW 8.4) or by far-sources teletsunamis. Computer simulations of earthquake-triggered tsunami along the Tonga-Kermadec Trench (TKT: **Figure 1**) were performed by Frohlich et al. (2009). The authors selected a worst case earthquake scenario of Mw 9, with a slip of ~30 m along faults and dimensions ~120 km × 1,000 km. Simulations provided peak-to-trough amplitudes of ~12 m on the west side of Tongatapu. This value is at the lower limit of the wave heights needed to move the largest Fahefa boulders, e.g. Maui Rock, making this source possible, but quite unlikely without a local coseismic submarine landslide. Accordingly, while acknowledging that there may be numerous unknown sources for the large tsunami identified in New Zealand at the same period, Goff et al. (2011a) and Goff and Chagué-Goff (2015) suggested that two different tsunami events may have occurred: one of them resulting from a large earthquake triggered along the Tonga-Kermadec Trench (TKT); and another one due to a local fault rupture, with or without co-seismic flank collapse, off the New Zealand west coast.

4.1.2 Pyroclastic Density Currents (PDCs) Entering the Sea

Located north of Tongatapu, Tofua volcano (**Figure 1**) displays a 5 km-wide caldera with steep inner walls rising up to 200 m above sea level. This island has been mantled by thick ignimbrite, which form high pumice cliffs in the south slope of the volcano. Radiocarbon dating of a carbonised tree trunk recovered from the base of the ignimbrite sequence gave an age of 970 ± 50 years BP (Caulfield et al., 2011) corresponding to a calendar age range of 1,044–1158 CE (using CALIB 8.2), which is inconsistent with a 15th century tsunamigenic eruption. In addition, numerical modelling performed by one of the coauthors (KK) using VOLCFLOW code show that voluminous PDCs or debris avalanche entering the sea from the south flank of Tofua do not provide tsunami waves higher than 15 m at Tongatapu and only 5 m at the SE shore where the highest boulders have been described (*SI Appendix*, **Supplementary Figure S3**). Furthermore, the basalt-andesitic composition of the Tofua ignimbrite (Caulfield et al., 2011) is not consistent with the Low-K dacite composition of the pumice fragments found within the mid-15th century tsunami deposits ((*SI Appendix*, **Supplementary Figure S1**).

4.1.3 Eruption-Triggered Flank-Collapse

Slope failures several kilometres wide were reported to have generated megatsunamis due to the entry into the sea of large-scale debris avalanches (Giachetti et al., 2012). In such case, the closer the volcano is, the higher the runup on the exposed shore, with maximum values being reached in the axis of the collapse. Scarps resulting from flank collapses are common morphological landforms on the submarine stratovolcanoes along the Tonga Ridge (Massoth et al., 2007). Computer simulations of tsunamis generated by flank collapses of volcano #2 performed by Frohlich et al. (2009) were successful to produce peak to-trough amplitudes of 14 m at 100 m water depths off western Tongatapu, which suggests a higher tsunami wave and runup at the coast. In this study, new computer simulations of an immediate collapse of 15 km^3 from Volcano 2 reproduces similar waves of 15 m on the southeast coast of Tongatapu (*SI Appendix*, **Supplementary Figure S3**), which could be consistent with a 30 m runup height. However, the amplitude of tsunami waves decreases rapidly with distance when triggered by a volcanic flank collapse (Walters et al., 2006), making the generation of a tsunami affecting the entire southwest Pacific unlikely. Interestingly, the position of the proposed tsunamigenic submarine volcano, as well as that of the other potential volcanic sources presented in the next section, fits well with the Maui myth documented by Gifford (1923). Indeed, he identifies the "flying stones" that chased the giant moa as coming from the direction of Eua Island, specifically striking the southern coast of Tongatapu.

4.1.4 Collapse of a Volcanic Island During a Caldera-forming Eruption

It is recognised that calderas formed rapidly and "en masse" during explosive eruptions of silicic magmas (e.g. dacite) might trigger a tsunami (Cas and Wright, 1991). However, tsunamigenic processes capable of generating high tsunami runup during caldera-forming eruptions are still debated, as different processes may be involved (Paris, 2015): the caldera collapse itself (which is poorly constrained and may vary widely in terms of duration), pyroclastic flows entering the sea, underwater explosions, earthquakes, slope instabilities and shock waves. With runup higher than 30 m a.s.l., the tsunami that has been identified ca. 1450 CE in Tonga looks as strong as the one generated by the Krakatoa eruption in 1883 CE (Simkin and Fiske, 1983). Therefore, the tsunamigenic caldera-forming eruption would probably have had a Volcanic Explosivity Index (VEI) ≥ 5 or even 6 (Self, 2006).

The strong bipolar sulfate spikes identified in polar ice cores from Greenland and Antarctica point to two tropical eruptions, in 1,452–53 CE (Gao et al., 2006; Cole-Dai et al., 2013; Esper et al., 2017) and 1,457–58 CE (Sigl et al., 2013). The identification of sulfate aerosols in polar ice discards the hypothesis of submarine eruptions, as it would have prevented sulfate gases to reach the stratosphere. The source of these eruptions remains to be identified. Kuwae volcano in Vanuatu was the first to be proposed as the most likely source of one of these large eruptions in the mid-15th century (Witter and Self, 2007; Goff and Chagué-Goff, 2015). According to marine and field observations, its 12 × 6 km wide submarine caldera was formed during a single eruption supposed to have ejected the equivalent of 30–60 km^3 DRE (dense rock equivalent) in the form of pyroclastic flows and ashfall deposits (Robin et al., 1994; Witter and Self, 2007). However, the Kuwae eruption was initially dated 1,425–1430 CE (Monzier et al., 1994), and further correlated—with doubtful scientific argument—to bipolar sulfate spikes identified by polar ice cores. Indeed, this link is mainly based on a local myth suggesting the collapse of this volcano in the sea, but without providing any precision concerning the date of the eruption. Furthermore, the limits of the underwater caldera are hypothetical (Nemeth et al., 2007; Caulfield et al., 2011), and the most proximal palaeotsunami deposit in Vanuatu is very small, both in elevation above sea level and thickness (Goff et al., 2008; Goff et al., 2011b). More recently, geochemical analysis of 1,457 cryptotephra found in the South Pole ice core definitely dismisses Kuwae as the only source of the 1458 CE unidentified eruption (Hartmann et al., 2019).

Shallow-water calderas are ubiquitous along the Tonga Ridge (*SI Appendix*, **Supplementary Figure S4**: Massoth et al., 2007), and none of them have been dated yet. The good state of conservation of the walls of some of them and the apparent weakness of erosion on certain slopes pleads in favour of a rather young age, possibly a few centuries. Therefore, some of the "vanished islands" of the Pacific reported in Polynesian legends (Nunn and Pastorizo, 2007; Nunn, 2008) could correspond to ancient collapsed volcanoes of Tonga. Observations during recent submarine eruptions in Tonga along the Tofua arc (Brandl et al., 2020), and computed drift trajectories of sea-rafted pumice using numerical models, indicate that pumice rafts are always directed westward from their source, in accordance with the southwest Pacific surface wind fields and ocean currents. Therefore, considering that at least part of these pumice clasts have been expelled by a tsunamigenic volcanic eruption, the volcanic source should have been located quite close from Tongatapu. With the aim to identify the former volcanic islands before their total collapse, we reconstructed the precaldera altitude of all submarine volcanoes located along the south part of the Tonga ridge, from volcano #1 to volcano #19 (*SI Appendix*, **Supplementary Figure S4**). As plotted in Fig. S4, only 7 out of 19 calderas resulted from the total collapse of a former emerged volcano (*SI Appendix*, **Supplementary Figure S5**), whereas the other volcanoes were already submarine at the time of the caldera–forming eruption (*SI Appendix*, **Supplementary Figure S6**). Volcanoes #1 and #2, which are the closest from Tongatapu, were identified as candidates for a possible mid-15th century stratospheric eruption. However, difficulties in calibrating caldera formation models due to the lack of *in situ* observation make assessments of the speed of caldera collapses doubtful. It would seem, however, that the rate of caldera collapses is too slow to generate significant tsunamis, except if the total collapse of the volcanic island is preceded by one or more flank collapses, which appear to be much more tsunamigenic (Paris, 2015).

4.1.5 An Unidentified Meteorite?

The ability of bolide impacts to generate tsunamis capable of leaving long-term traces on coastal areas has been extensively discussed (Crawford and Mader, 1998; Wünnemann et al., 2007). It has been shown that Indigenous oral traditions and legends contain historical accounts of actual meteoritic events from across Australia, particularly Queensland and Victoria (Hamacher, 2013). Based on Aboriginal and Maori stories, Bryant (2001) suggested that the southeastern coast of Australia was struck by a tsunami induced by a cosmic impact in the Tasman Sea within the last 600—years. A 40-km wide crater candidate for a remarkable tsunami event that could have affected the Tongan archipelago was identified by David Sandwell 450 km away from maps of gravity gradients derived from satellite altimetry (Dallas Abbott, pers. comm.). Based on this hypothetical source located along the Tonga Trench (**Figure 1**), we performed numerical simulations using COMCOT (*SI Appendix* **Supplementary Figure S7**). A vertical water surface displacement of 165 m at the impact (following Kharif and Pelinovsky, 2005) may have only generated a ~6 m high wave at a water depth of 220 m off Tongatapu, due to a rapid dissipation of its energy. The maximum wave height recorded at the western coast of this island is around 10–15 m, whereas it does not exceed a few meters along the coasts of New Zealand.

In summary, it is very unlikely that a single event of very high magnitude, whether seismic or cosmic in origin, would have generated a tsunami that affected the entire southwest Pacific coastline, from New Zealand to Wallis and Futuna through Tonga archipelago, in the 15th century. This implies that this region of the world must have been subjected to multiple telluric events at this time, some near New Zealand as suggested by Goff and Chagué-Goff (2015), and another near Tongatapu, possibly a volcanic eruption with flank collapse.

4.2 Tracking the Societal Impacts of the Mid-15th Century Tsunami in Tonga and Beyond

The hypothesis of a devastating tsunami in Tongatapu in the 15th century has never been mentioned in the literature. Could several facts that have been hotly debated by historians and/or archaeologists for years find a scientific explanation in a natural disaster caused by a tsunami? We focus this discussion on two main issues.

4.2.1 The Exceptionally High Number of Mounds on the Island

The island of Tongatapu is covered with nearly 10,000 tombs and mounds (revealed through LiDAR survey: Freeland et al., 2016), the origin of which is still under debate. Relatively little is known about the people who built and used the majority of mounds, with only a handful having been excavated (Davidson, 1969; Spennemann, 1989). Tongan traditions differ significantly on the issue of mounds and tomb age, as well as to who built the tombs and who was buried in them. Clark et al. (2008) suggested that it might be the result of a deliberate or inadvertent hiding of tomb history. On the basis of their sheer numbers, most "generic" mounds in Tonga are assumed to be burial places for subordinate chiefly and commoner lineages (Burley, 1998). One could think that the exceptionally high number of funeral structures could be linked—at least for some of them - to the construction of mass graves following a major disaster in order to limit epidemics, as was done in Aceh, Indonesia during the 2004 tsunami. Several arguments, however, plaid against of this highly speculative hypothesis. First, as so few mounds have been excavated, we have actually no idea if these are generally burial features or not (E. Cochrane, pers. comm.). Second, if the 10,000 mounds were largely burial mounds, one would think such a catastrophic population loss would be recorded in oral tradition and perhaps even reflected in population numbers and demography when Europeans arrived two centuries later. This, however, is not the case (Burley, 2007). Third, the construction of mass graves following a major disaster seems highly unlikely in the absence of a modern state coordinating the retrieval of victims' bodies. Gathering and identifying bodies, to say nothing of organising formal burials in large-scale earthworks, is likely to have been beyond the capacity of survivors.

4.2.2 The Construction of Ha'amonga 'a Maui or Trilithon, and the Relocation of the Tu'i Tonga Capital

Some of the tombs are monumental, especially in the sites of the two former capitals of the Tu'i Tonga Empire. The site of the oldest capital, Heketā, at the eastern edge of Tongatapu (**Figure 2**), displays nine stone structures spread over 350 m of land that gently slopes towards the exposed limestone coast (Clark and Reepmeyer, 2014). The principal structure of this site, and the most famous monument in Tonga, is the sacred *Ha*'amonga 'a Maui ("burden of Maui"), a unique megalithic trilithon, which comprises three coral limestone slabs (*SI Appendix*, **Supplementary Figure S8**). In Tongan tradition, the trilithon is believed to have been built by the god Maui, as the stones would be too huge for mortals to handle. However, Clark and Reepmeyer (2014) have recently shown that the coral limestone of the trilithon come from the nearby coast, where it was carved on site. Radiocarbon dating of three marine samples that have been collected beside the west upright of the trilithon provide ages of the monument construction between 1,320 and 1460 CE (Clark and Reepmeyer, 2014), i.e. soon before the relocation of the Tu'i Tonga capital from Heketā to Lapaha (**Figure 2**), that occurred around the mid-15th century (Clark et al., 2008). The reason of this relocation remains unclear. Campbell (2015) suggests that for a political power that had to rely on long-distance travel, Lapaha was a superior location, providing a safe anchorage where large voyaging canoes could be brought safely ashore. Nunn (2007) considers that the political instability, the abrupt end of long-distance travel and the shift of settlements from the coasts to inlands across the Pacific (which may include the move from Heketa to Lapaha) may have originated in the effects of the Little Ice Age that began around 1300 AD. For a few centuries indeed, lower temperatures and stormier weather were disruptive, especially as the resulting 70–80 cm drop in sea level profoundly affected the food resources available in coastal areas (Nunn, 2007). However, the hypothesis of a widespread settlement shift has been challenged by Fitzpatrick (2010, 2011) who claims that it is not supported by data across the Pacific (cf. Allen, 2006). Could the occurrence of a tsunami have helped motivate this choice to relocate to a safer area? The bracket date of the trilithon's construction does not exclude the possibility that the monument was erected soon after the tsunami, as a means of resilience in order to assert the great power of paramount chiefs over nature, as observed in other civilizations. It should be borne in mind, however, that this hypothesis remains highly speculative and is not based on any proven fact, but only on a date agreement.

5 CONCLUSION

In the Tongan traditions, several legends related to the god Maui are related to huge blocks of coral limestone perched at an altitude up to 30 m a.s.l. along the southeast coast of Tongatapu and up to 20 m a.s.l. along the west coast. But so far, no one has linked these legends to scientific data. The largest one weighs ~1,600 tons and is considered as the largest boulder deposited by a tsunami worldwide, previously dated to 120,000 BP or late Holocene. Based on radiocarbon dating of organic material collected under some of these boulders, and within other sandy tsunami deposits recently discovered on the west and southeast part of Tongatapu, we can confidently claim that a large tsunami occurred during the 15th century. However, it is unlikely that this tsunami destroyed the Tui' Tonga kingdom, as it mainly affected the sparsely populated southern coast of Tongatapu, while most people lived around the lagoon along the northern coast. Despite the lack of compelling evidence, we state that this event possibly triggered some cultural upheavals, such as the relocation of the capital of the Tui'i Tonga empire or the emergence of monumental funerary architecture at the aftermath of the disaster.

Although the origin of this large tsunami still remains uncertain, we provide a series of arguments in favour of a caldera-forming eruption that would have caused the total collapse of an ancient island volcano, probably located along the Tonga ridge less than 150 km southwest off Tongatapu. The majority of the large explosive eruptions of the Common Era and beyond remain unidentified, partly because some of them are related to former volcanic islands which disappeared underwater. In order to identify the volcanic source of the mid-15th southern Pacific tsunami, further investigation should focus on the identification and characterisation of submarine active and dormant volcanoes and extensive tsunami modelling. A catastrophic tsunami at the same period has also been identified in other islands of the Southwest Pacific such as New Zealand or Wallis and Futuna, but numerical modelling show that a single gigantic tsunami generated by a mega-earthquake, a caldera-forming eruption or even a big meteorite is unlikely.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

FL designed the study and wrote the paper in collaboration with JM, PW, RP, and KK, FL, JM, PW, OW, AM, TT, and FK conducted fieldwork in Tonga. Laboratory analyses were made by SS-C and MT (sedimentology), FM, MB, and CV (geochemistry). RP and KK run tsunami modelling. MM developed the geomorphological model of submarine volcanoes. AF drew the figures on the geochemical data and interpreted them. JM and OW collected Tongan tales and legends. TK provided administrative permissions and information on the Tonga geology and History. CG provided information on tsunami events in the Western Pacific.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.748755/full#supplementary-material

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HYPOTHESIS AND THEORY
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The 4.2 ka Event and the End of the Maltese “Temple Period”

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The small size and relatively challenging environmental conditions of the semi-isolated Maltese archipelago mean that the area offers an important case study of societal change and human-environment interactions. Following an initial phase of Neolithic settlement, the “Temple Period” in Malta began ~5.8 thousand years ago (ka), and came to a seemingly abrupt end ~4.3 ka, and was followed by Bronze Age societies with radically different material culture. Various ideas concerning the reasons for the end of the Temple Period have been expressed. These range from climate change, to invasion, to social conflict resulting from the development of a powerful “priesthood.” Here, we explore the idea that the end of the Temple Period relates to the 4.2 ka event. The 4.2 ka event has been linked with several examples of significant societal change around the Mediterranean, such as the end of the Old Kingdom in Egypt, yet its character and relevance have been debated. The Maltese example offers a fascinating case study for understanding issues such as chronological uncertainty, disentangling cause and effect when several different processes are involved, and the role of abrupt environmental change in impacting human societies. Ultimately, it is suggested that the 4.2 ka event may have played a role in the end of the Temple Period, but that other factors seemingly played a large, and possibly predominant, role. As well as our chronological modelling indicating the decline of Temple Period society in the centuries before the 4.2 ka event, we highlight the possible significance of other factors such as a plague epidemic.

Keywords: Malta, collapse, climate, abrupt, aridity, extreme events, plague, radiocarbon

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INTRODUCTION

The Maltese archipelago, covering 316 km^2 in the central Mediterranean (**Figure 1**), has a rich archaeological record. The Temple Period [~5.8–4.3 thousand years ago (ka)] is, as its name suggests, most famous for its thirty or so megalithic “temples” (**Figures 1**, **2**), as well as other sites such as the Ħal Saflieni hypogeum (**Figure 3**), and has been widely discussed in the literature (e.g., Trump, 1966, 2002; Evans, 1971; Bonanno, 1986, 2017; Bonanno et al., 1990; Cilia, 2004; Malone et al., 2009a, 2020b; Sagona, 2015; Fenech et al., 2020). Renfrew (1973, p. 161) for instance suggested that temples “lay claim to be the world’s most impressive prehistoric monuments.”

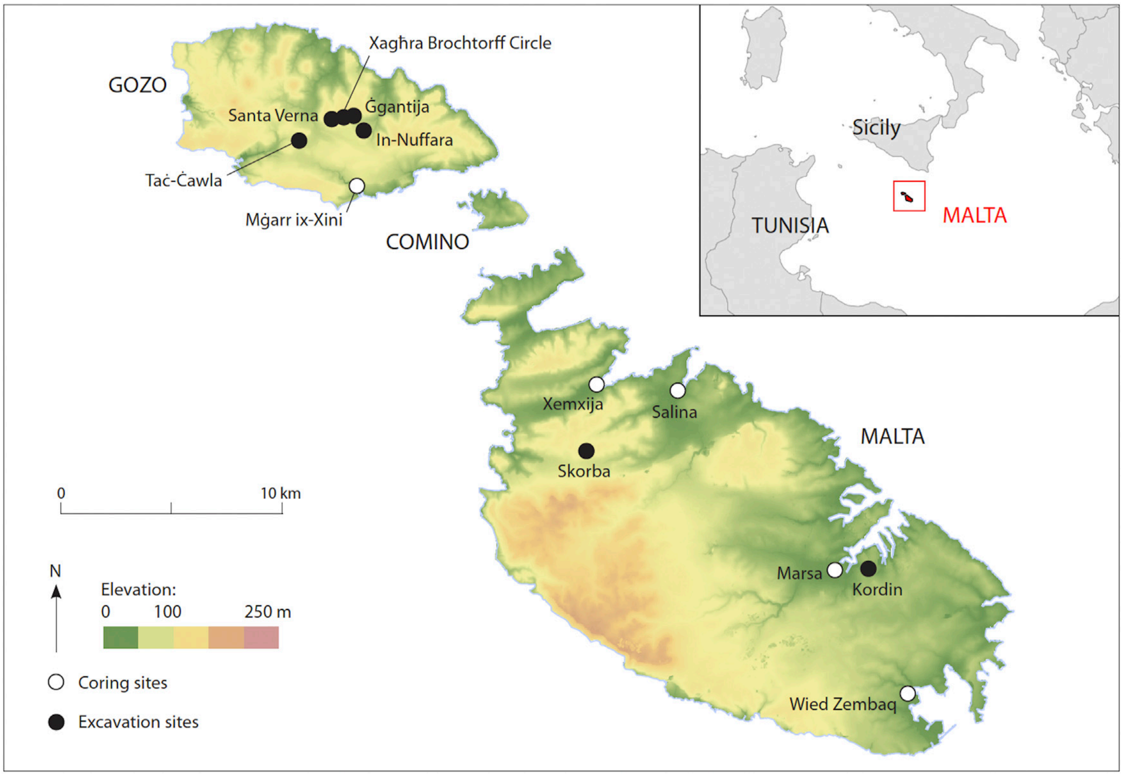

FIGURE 1 | Map of key archaeological sites and palaeoenvironmental coring sites (reproduced from Malone et al., 2020b; CC-BY-ND licence).

FIGURE 2 | Examples of Maltese megalithic "temples." Top: Ħaġar Qim, Bottom: Mnajdra. Human scale: 107 cm high.

FIGURE 3 | Part of the remarkable Ħal Saflieni hypogeum, where passages and chambers were dug out to create a long-term Temple Period burial site. (Photo courtesy of Heritage Malta. Photo credit: Clive Vella. Copyright image not to be reused without permission of Heritage Malta).

Various possible reasons for the end of the Temple Period have been suggested, including famine, drought, disease, the arrival of new groups of humans, and societal unrest (e.g., Trump, 1966, 1976, 2002; Evans, 1971; Bonanno, 1986, 1993, 2017; Stoddart et al., 1993; Malone and Stoddart, 2013; Broodbank, 2015; Cazzella and Recchia, 2015; Sagona, 2015). While traditionally seen as a "collapse" of "catastrophic suddenness" (Trump, 1976, p. 605), in recent years some have suggested that the end of the Temple Period is better seen as a more gradual process (e.g., Cazzella and Recchia, 2015; Sagona, 2015; Pirone, 2017; McLaughlin et al., 2018). Sagona (2015, p.115) for instance suggests that people "turned their back on the old way of life because they had an economic alternative." Conversely, the similar timing of the end of the Temple Period and the 4.2 ka climatic event has been suggested to indicate a possible correlation (e.g., Broodbank, 2015; McLaughlin et al., 2018; Grima et al., 2020).

The 4.2 ka event is widely discussed as a short-term, decadal to centennial, climate change event (see also Stewart et al., this volume). Others, however, have also seen it as a longer-term episode from ~4.3 to 3.8 ka. To some, the 4.2 ka event can be seen as a "global megadrought" (e.g., Weiss, 2015, 2016, 2017; Ran and Chan, 2019). In the case of the Mediterranean region and surroundings, it has been argued that from the Atlantic to Mesopotamia it was a coherent and synchronous climate event which saw an abrupt decline in precipitation (e.g., Weiss, 2015, 2016, 2017; Adams, 2017). However, others have pointed to considerable climatic variability at this time (e.g., Kaniewski et al., 2018; Bradley and Bakke, 2019). In several parts of the world there were actually wetter rather than drier conditions at 4.2 ka (e.g., Railsback et al., 2018). Even in and around the Mediterranean which is often regarded as a key area where the 4.2 ka event caused drought, there were areas where precipitation seemingly increased, such as parts of the Maghreb, Iberia, and the Balkans (e.g., Bini et al., 2019; Zielhofer et al., 2019). There are various possible reasons for this apparent discord. Precipitation in the Mediterranean primarily reflects winter rainfall as a result of the North Atlantic Oscillation. The weakening of this is seen as the reason for drought induced by the 4.2 ka event, yet how this interacts with other climate systems may be complex (e.g., Di Rita et al., 2018; Bini et al., 2019; Perşoiu et al., 2019). While driven by North Atlantic circulation, much of the precipitation in the Mediterranean reflects local cyclogenesis that is influenced by the climatic conditions of the surrounding areas, such as the position of the Intertropical Convergence Zone (ITCZ) and the North African high-pressure cell to the south of the Mediterranean (e.g., Rohling et al., 2015).

While some of the apparent complexity of Mediterranean palaeoclimate may reflect poor chronological resolution of palaeoenvironmental archives, it does seem that climate varied considerably around the Mediterranean around 4.2 ka (e.g., Di Rita et al., 2018; Kaniewski et al., 2018; Bini et al., 2019; Finné et al., 2019; Perşoiu et al., 2019; Peyron et al., 2019). As discussed in **Supplementary Material 1**, records from Sicily and Italy frequently indicate arid conditions in the later third millennium BC, but the details of this vary considerably. In some records, peak aridity is ~4.4 ka, while in others it is ~4 ka. Unpacking the extent to which such variation reflects chronological uncertainty, microtopographic and geographic variability, and genuine regional scale climate differences is a challenging exercise.

The Mediterranean and surroundings saw significant societal changes around 4.2 ka. In areas such as southern France (Carozza et al., 2015) and Italy (Leonardi et al., 2015; Pacciarelli et al., 2015; Stoddart et al., 2019) the transition from the Chalcolithic to the Bronze Age occurred around this time. The more generally discussed changes putatively relating to the 4.2 ka event occurred within the Bronze Age societies of the eastern Mediterranean (e.g., Jung and Wenninger, 2015; Adams, 2017; Lawrence et al., 2021; Palmisano et al., 2021), as the transition to the Bronze Age occurred earlier here. The end of the Old Kingdom in Egypt has long been suggested to relate to aridity at 4.2 ka (e.g., Bell, 1971; Williams, 2019), as has the collapse of the Akkadian Empire (e.g., deMenocal, 2001; Weiss, 2015, 2016, 2017). In the case of the Akkadians for instance, it has been claimed that an estimated reduction in rainfall of 30–50% in Mesopotamia in less than 5 years caused the "sudden, abrupt, unforeseen" collapse of the Akkadian Empire (Weiss, 2015, p. 39).

Other researchers have, however, raised concerns regarding correlation between these societal changes and aridification at 4.2 ka. Moreno García (2015), for instance, suggests that the end of the Old Kingdom was actually driven by political conflict between central and regional powers in Egypt (see also Kanawti, 2003). Likewise, the Akkadian Empire was under both external pressure, such as the regular incursions of the Gutians from the Zagros Mountains, and internal pressure, as shown by the "Great Rebellion" a few years before 4.2 ka, which was only put down by killing thousands of people (Tinney, 1985).

While critics of "environmental determinism" may highlight such political and historically contingent aspects, it remains true that significant and seemingly synchronous changes did occur in several societies around 4.2 ka (e.g., Broodbank, 2015). It is also the case that for both Egypt (e.g., Stanley, 2019) and Mesopotamia (e.g., Carolin et al., 2019) there is environmental evidence of significant climate change around 4.2 ka. Clearly though, the way that environmental change impacts human societies depends on a variety of aspects of resilience and vulnerability. Palmisano and others (2021, p. 23), for instance, highlight evidence for population decline around 4.2 ka in many parts of Southwest Asia, yet suggest that this should be "viewed in the context of the preceding demographic boom." In other words, in regions where such booms had not occurred, and consequently had not given rise to urban areas reliant on other areas for food supply, we should expect different societal reactions to the 4.2 ka event. From rural and non-elite perspectives, the 4.2 ka may have been felt very differently (e.g., Schwarz, 2007; Chase et al., 2020). Likewise, other areas saw very different kinds of change to those seen in Egypt and Mesopotamia. For instance, while mainland Greece shows indications of collapse (e.g., Wiener, 2014), on Crete there was an increase in social complexity and a seemingly prosperous society at 4.2 ka (Wiener, 2014; Broodbank, 2015; Manning, 2017). Given the distinctive societal characteristics which were common to Mediterranean islands, such as Cyprus and Malta, we might expect distinct responses to the 4.2 ka event in such settings. We see here a particular perspective on the theme of islands as pertinent natural "laboratories" (e.g., Sahlins, 1955; Mead, 1957; Evans, 1973, 1977; Malone et al., 2020b).

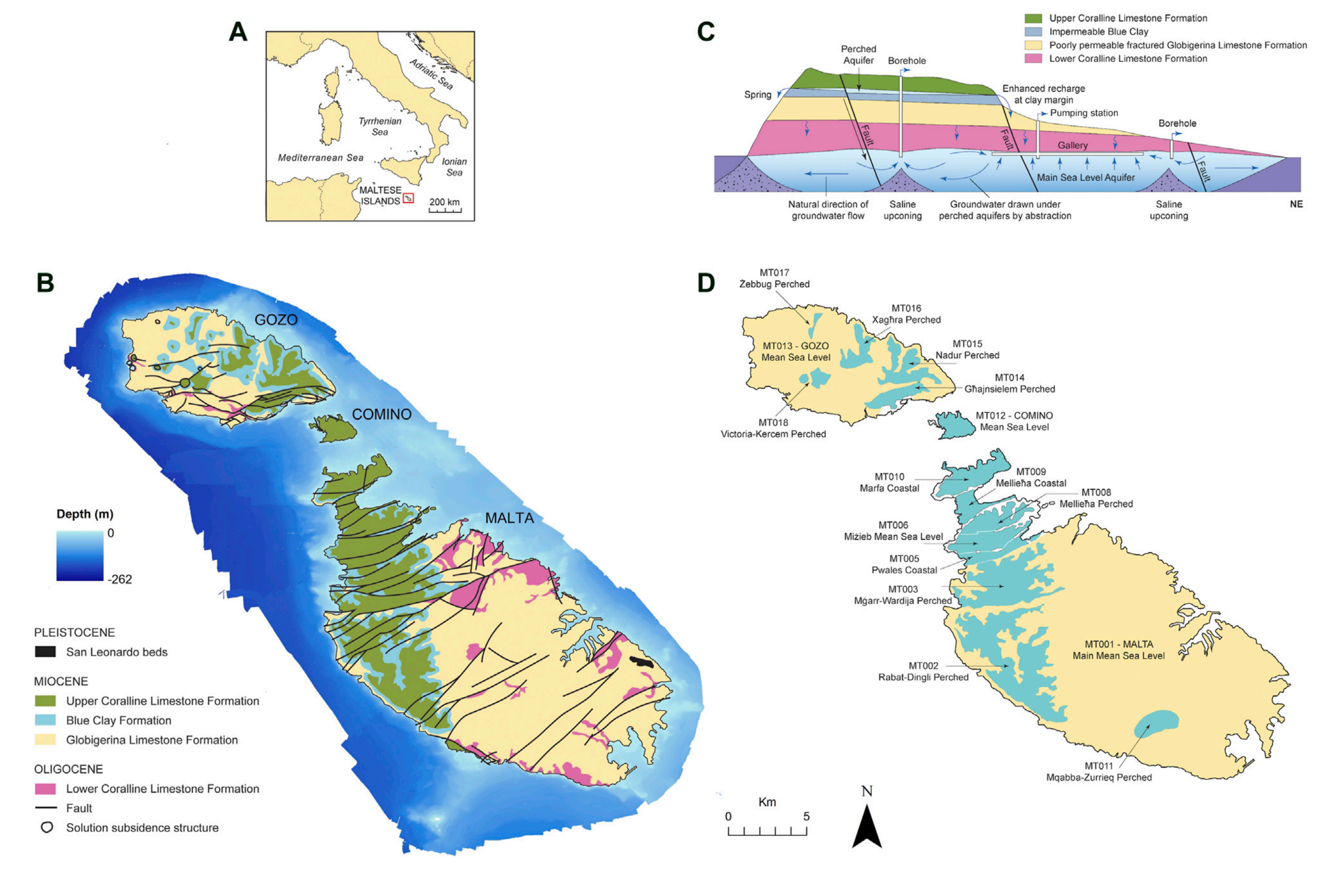

FIGURE 4 | The location **(A)**, geology, faulting, and bathymetry **(B)**, and aquifer structure **(C,D)** of the Maltese Islands (Geological map redrawn from Oil Exploration Directorate, 1993; Bathymetric map from ERDF LIDAR data, 2012; aquifer data from Malta Resource Authority, 1994).

Finally, an important lesson in the dangers of assumed correlation comes from the east Mediterranean Levant. There the "collapse" of urbanised Early Bronze Age society had traditionally been suggested to correlate with the end of the Old Kingdom of Egypt, that is with the 4.2 ka event. However, radiocarbon dating in recent years has pushed back the end of the Early Bronze Age III to several centuries before 4.2 ka, at around 4.5 ka (e.g., Genz, 2015; Adams, 2017; Greenberg, 2017; Höflmayer, 2017). Rather than collapse, it seems more a case of adaptation. Specific examples such as that of the southern Levant, and the general risks in "wiggle matching" processes which occurred within several centuries of each other should be kept in mind.

Against this background, we now turn to Malta. Our aim is to explore the end of the Temple Period, including the idea that this relates to the 4.2 ka event. We review various relevant aspects of geology, material culture, chronological modelling, agriculture and water management, trade and connectivity, and the possibility of a plague epidemic.

Maltese Geology, Climate, and Ecology

The Maltese Archipelago consists of two main islands, Malta (246 km^2) and Għawdex (Gozo) (67 km^2), along with several smaller islets. Malta is located just under 100 km south of Sicily, 300 km east of Tunisia, and 350 km north of Libya (**Figures 1**, **4**). Geologically, the islands consist of an Oligo-Miocene (~30-5 million years ago) sequence of sedimentary rock formations (**Figure 4**) (e.g., Pedley et al., 2012; Scerri, 2019; Chatzimpaloglou et al., 2020a). Most of the sequence consists of limestone, with relatively hard, and karstic, Upper and Lower Coralline Limestones bracketing the sequence. Above the Lower Coralline Limestone is the Globigerina Limestone, which includes phosphatized hardgrounds, and limited chert. Overlying this is the Blue Clay Formation. Subsequent tectonic and geomorphological processes bring a complexity to the landscapes of the archipelago (Hunt, 1997; Schembri, 1997; Gauci and Schembri 2019).

As well as being resource poor in terms of raw material such as metal ores and knappable stone, Malta is a semi-arid region. Precipitation often takes the form of short but intense winter storms, with high evaporation during long and hot summers. Unfortunately, high-resolution palaeoclimatic and palaeoecological data is scarce for the Maltese Islands. Precipitation data for the recent past highlights the considerable variability in annual rainfall, which presumably also applied in the past. In the 1854–1995 period, for instance, the lowest annual rainfall recorded was 191 mm, while the highest was 1,031 mm (Schembri et al., 2009). Plotting annual

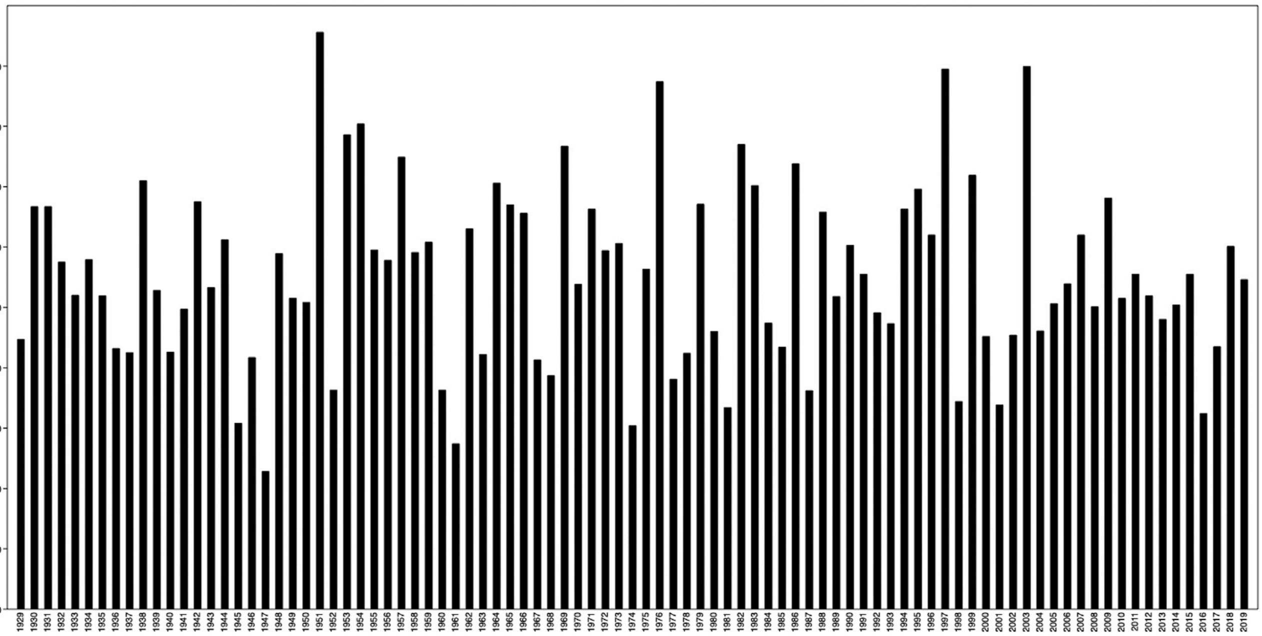

FIGURE 5 | Annual rainfall (mm) in Malta, 1929–2019 (Data provided by the National Meteorological Office, Malta International Airport).

precipitation data from 1929 to 2019 (data provided by the National Meteorological Office, Malta International Airport) further highlights this variability. The annual average for this period is 555.8 mm, yet variability is fairly high, as 25% of years had less than 447 mm, and 25% had more than 663 mm (**Figure 5**). Variability does not seem strongly patterned, in that while years vary considerably, this does not form decadal patterns. There is also important variation in the seasonality of rainfall; for instance, high or low levels of rainfall in the autumn are a significant component of annual differences.

Water availability, of course, does not only reflect precipitation, but also other factors such as infiltration and evaporation. Evaporation in Malta is high, particularly during the long summers. However, the geology and topography of the islands mean that relatively large aquifers are present (**Figure 4**). The impression of surface aridity can therefore be misleading, given the presence of year-round springs (e.g., Newbury, 1968). Likewise, in recent years the high flood runoff in the urban areas gives the impression that a large amount of rainfall may have been lost to the sea in the past. However, it actually appears that traditionally little water was lost to the sea in direct runoff (Singh, 1997).

The largest aquifer is located where infiltrating water meets sea level, the Mean Sea Level aquifer. This, however, is believed to only have begun to be accessed in the 17th century AD (Grima, 2016, p. 30), and only widely exploited from the 19th century (Buhagiar, 2008). Before this, the Perched Aquifers overlying the impermeable Blue Clay formation were important sources of water (Newbury 1968; Micallef et al., 2000). At least a proportion of the water in the Perched Aquifers seems to be decades old (Newbury, 1968; Stuart et al., 2010), suggesting that decades of aridity would be needed for springs to dry up. However, all is not equal given the varied topographic and hydro-geological structure of the islands. In Malta, for instance, springs are concentrated in the west, where the Blue Clay Formation is present (**Figure 4**), yet the best agricultural land is located in the centre and east (Alberti et al., 2018). Factors such as water management by humans are therefore key, as we will return to later.

In terms of Maltese palaeoclimate and palaeoecology, pollen records from cores taken in near-shore settings have been prominent (**Figure 1**). While valuable, there are a number of limitations to these records. These include the difficulties in separating natural and anthropogenic signals in pollen changes, preservational and taphonomic biases, and often poor chronological control. It is also important to note that insect pollinated plants rarely feature in the pollen records, yet the majority of Maltese plants are insect pollinated. In terms of chronological uncertainty, we describe below approximate dates as discussed in the various publications, but the uncertainties inherent in age-depth models based on a few chronometric estimates should be kept in mind.

Carroll et al. (2012) and Gambin et al. (2016) presented pollen records from sediment cores. The basic contradiction between these records highlights the complexity of the proxy, and of local climatic/ecological conditions. Gambin et al. (2016) record suggests relatively open conditions in the pre- and post-Temple periods, with wetter conditions at the peak of the Temple phase. In contrast, Carroll et al.'s (2012) record suggested that once humans were established in the pre-Temple Neolithic there has basically been a similar pattern in pollen over most of the last 7,000 years, with rapid deforestation and then a predominantly anthropogenic signal, dominated by rain-fed cereal agriculture. With the caveats about factors such as chronological resolution kept in mind, such studies may also indicate considerable spatial variability within the Maltese Islands, with the pollen records saying more about very localised vegetation patterns than about overall climate. An important point made by Carroll et al. (2012, p. 24), however, is that there was a substantial decline in cereal pollen around 4.3 ka, which they suggest may be linked to regional aridification. So dramatic was this change that they suggested that the record may indicate abandonment of the islands for a few centuries. Gambin and others (2016) suggested that the landscape became more open, and the climate more unstable, over a longer time period of ~4.5 to 3.7 ka.

More recently, as part of the FRAGSUS Project several new cores were recently published (Hunt et al., 2020) and pollen studied (Farrell et al., 2020). Here again, taphonomic biases are evident, and it is challenging to reconcile signals from the different cores. We will return later in the paper to some of the implications of the presence of particular taxa in these records, but for now our interest is in the general tendencies displayed. From the Salina Deep Core, Farrell and others (2020, p. 86) discuss a phase with an estimated age of ~4.5 ka as being marked by steppe vegetation, which was degraded compared to the previous phase, and changes indicating a more arid landscape and/or great grazing pressure. Other cores such as Salina 4 and Wied Żembaq 1 present a similar narrative, of a seemingly degrading landscape in the later half of the 3rd millennium BC. The Salina 4 and Wied Żembaq cores agree with the record of Carroll et al. (2012) for an absence or extreme rarity of cereal pollen, yet in Gambin et al. (2016)'s record, this was not the case. Farrell and others (2020) suggest that the decline in cereal pollen, and rise in tree and shrub pollen, may actually reflect changing agricultural/cultural practices rather than primarily climate, and perhaps the changing distribution of different activities in the landscape.

Mollusc data from the cores provides important palaeoecological information (Fenech et al., 2020; see also; Fenech, 2007; Schembri et al., 2009). Given the strongly local ecological tolerances of mollusc taxa and perhaps lesser taphonomic biases compared to pollen, variation in mollusc composition represents a key data source for Maltese palaeoenvironment. An important point is that there is little evidence from molluscs for leaf litter species in the earlier Holocene that would then indicate abrupt deforestation with the arrival of people and the start of the Neolithic (Fenech et al., 2020, p. 156). The changes visible in the Wied Żembaq 1 and 2 cores from ~4.3 ka are described by Fenech and others (2020, p. 128) as showing "aridification of the landscape, disappearance of freshwater streams; breakdown of denser vegetation, increase in erosion." Likewise, molluscs in the Xemxija core indicate aridification in the ~4.8 to 4.5 ka timeframe followed by a "prolonged drought" that Fenech et al. (2020, p. 153) suggest may correlate with the 4.2 ka event. This was shown by the abrupt disappearance of freshwater species such as *Oxyloma elegans* and *Bulinus truncatus.*

Finally, environmental change in the Maltese Islands would not merely have reflected the impacts of climatic change, but also other factors such as changing sea level and more abrupt events such as tsunamis and storms. The presence of large boulders, weighing up to 60 tonnes, which have been moved by the sea to several metres above sea level by either tsunamis or intense storms (Mottershead et al., 2014, 2019; Biolchi et al., 2016; Causon Deguara and Gauci, 2017; Mueller et al., 2019), indicate conditions which could have caused considerable damage in low-lying areas (See Marriner et al., 2017 for a wider Mediterranean perspective).

Given the limitations of the Maltese palaeoenvironmental archives, archives from the wider central Mediterranean region can also be used to cast light on the likely character of climatic change in the Maltese Islands at the end of the third millennium BC. We discuss this in **Supplementary Material 1**.

Recent Developments in Archaeological Research on the End of the Temple Period

Many key archaeological sites in Malta were excavated before the development of modern archaeological fieldwork methods, resulting in the loss of much information. Work in recent decades has generally been on a more modest scale, but some significant findings bring a new perspective to the end of the Temple Period. The current state of knowledge in terms of the chronology of major cultural changed (McLaughlin et al., 2020a) describes the Tarxien phase, the final clear phase of the Temple Period as dating to ~4.9 to 4.4 ka, with the early Bronze Age of the Tarxien Cemetery phase beginning ~4 ka. A crucial development is the idea of a phase in between, characterised as the Thermi phase, from ~4.4 to 4.2 ka.

The traditional view emphasised a clear and prolonged hiatus between the Tarxien phase of the Temple Period and the Tarxien Cemetery phase of the Early Bronze Age (e.g., Zammit, 1930). However, the identification of a distinctive pottery form, in a Maltese setting called "Thermi Ware," in both late Temple Period and Early Bronze Age contexts led to suggestions of continuity across these periods (e.g., Cazzella and Recchia, 2015; Sagona, 2015). Thermi Ware is characterised by a thickened rim, often with internal decoration, particularly triangles. It has long been recognised in Malta (e.g., Evans, 1953, 1971; Trump, 1966; Malone et al., 2009a) and the similarities to material from the Aegean, at sites such as Thermi and Troy, emphasised. The presence of Thermi Ware in Malta has been taken as indicating the arrival of small groups of people, perhaps ~4.4/4.3 ka (e.g., Copat et al., 2013; Recchia and Fiorentino, 2015). Aside from the example of two shards of purported Thermi Ware in Ġgantija layers at Skorba (Trump, 1966)—presumably these are intrusive, or the stratigraphy was more complex than recognised (e.g., Cazzella and Recchia, 2015)—Thermi Ware in Malta is exclusively known from the late Tarxien phase and subsequent Tarxien Cemetery phase. It has therefore recently been proposed to define a specific "Thermi Phase," which shows continuity of the Tarxien phase, but with the addition of Thermi Ware. Key to the increased role of Thermi Ware has been work at Tas-Silġ (Recchia and Cazzella 2011; Cazzella and Recchia 2012; Copat et al., 2013) and Taċ-Ċawla (Malone et al., 2020c).

Thermi Ware has often been discussed in relation to the Early Helladic II/III periods in the Aegean, but also shares close similarities with material from the Cetina Culture of the Balkan side of the Adriatic (e.g., Maran, 1998; Cazzella and Rechia, 2015; Pacciarelli et al., 2015; Rahmstorf, 2015; Recchia and Fiorentino, 2015). These similarities in pottery style, have been suggested to indicate a source in the Adriatic and spread to the Aegean, Italy, and Malta in the final centuries of the third millennium BC. The initial presence of small amounts of characteristic pottery, i.e., what is called Thermi Ware in Malta, has been taken to indicate not mass population movements, but rather the movement of small groups of "traders" and other kinds of specialists (Rahmstorf, 2015). Broodbank (2015) describes this spread across the Adriatic and into the wider central Mediterranean as an "eruption", correlating with the 4.2 ka event (p. 352). A crucial aspect here, bearing in mind the variable character and impacts of the 4.2 ka event, is that the Adriatic has the highest rainfall in the Mediterranean (Broodbank, 2015, p. 350). The spread of the "Cetina Culture" material culture may therefore reflect that some societies in this region were more environmentally buffered than others.

Recent excavations at Taċ-Ċawla in Gozo have yielded important new data (Malone et al., 2020c). Fieldwork in 2014 recovered 50,679 pottery shards, weighing almost 400 kg. The site was repeatedly occupied from the early Neolithic onwards. Of particular interest was the recovery of Thermi Ware from the site, not in large amounts (n = 58), but in association with Temple Period material at a site lacking subsequent Bronze Age activity, making reworking unlikely. Taċ-Ċawla demonstrates a late surviving (perhaps to ~4.2 ka) continuation of the Temple Period, but with the addition of Thermi Ware.

Another key aspect is that although sharing clear similarities with material from the Adriatic and Aegean, the geochemical characteristics of Thermi Ware pottery in Malta indicate that it was locally made (e.g., Malone et al., 2020d). There is also evidence for "hybrid" pottery, combining both typical Tarxien characteristics and typical Thermi/Cetina characteristics (Copat et al., 2013). The emerging view then suggests the arrival of small groups in the late Tarxien period, who may have played a role in triggering economic and social changes in the islands (e.g., Recchia and Fiorentino, 2015).

Tarxien is famous as the most intensely decorated of the Maltese temples, with various elaborate spiral designs and other decorations (e.g., Grima, 2001, 2003). It is possible that the boat engravings on a megalith from Tarxien South Temple (e.g., Pace, 2004; Sagona, 2015) represents the arrival of new people in Malta, although the age of the engraving is unclear (Fenwick, 2017; Tiboni, 2017). One point that we emphasise is that if the engravings were formed after the deposition of the sterile layer (i.e., in the Bronze Age or more recently), they could only have been done in a squatting position, and this low position would be unusual. Could these relate to the arrival of people associated with Thermi Ware? Perhaps analogously, at Kordin III temple, a large boat-shaped stone was placed across the opening of the central room, seemingly indicating a symbolic meaning (Grima, 2003; Pace, 2004). With currently available data it is challenging to situate such examples in the general corpus of Temple Period symbolism.

In closing this section, we note that the evidence suggests a two-stage process in which Thermi Ware marks the final chapter of the Temple Period, but there then seems to be a hiatus before the beginning of the Bronze Age proper from around 4 ka (e.g., McLaughlin et al., 2020a). It does not so much seem to be a process of continuity, then, but rather a more convoluted end of the Temple Period.

Destruction and Desecration? Damage to Temples and Their Contents

Another significant aspect in understanding the end of the Temple Period concerns evidence for fire and other damage in late Temple Period settings.

At this point it is useful to evaluate recent perspectives on what "temples" actually were. We use the word temple as an established shorthand, yet caution is needed in assuming their function. We can consider the function of temples from several scales. At a landscape scale, analyses of how they relate to various geographic elements have been considered by Grima (2004, 2008). A key point of this work is that temples appear as "liminal areas between the plains and the sea" (Grima, [2004], p. 245). Continued studies support this view, with Caruana and Stroud's (2020, p. 456) geographic information system (GIS) analysis suggesting to them that temples acted as "gateways between sea and land". We take this as a suggestion that temples played an important role in interactions between resident communities and groups arriving by boat.

At the site level, a "ritual" function is easy to suggest, often expressed in religious or cultic terms (e.g., Robb, 2001; Barrowclough, 2007), yet clarifying what exactly that means is challenging. The temples have often been described as indicating the growing power of a "priesthood" (e.g., Trump, 2002), and that part of the "collapse" of Temple Period society may relate to conflict between this priesthood and other social elements. This notion of internal social unrest has been discussed by authors including Bonanno and others (1990, p. 202–3) and Malone and Stoddart (2013). However, when we look at individual temples, it is also possible that significant functional changes occurred within the lifespans of the structure. It is possible that pragmatic aspects, such as food storage, were also involved in temples (e.g., Sagona, 2015). Many other possible functions can be imagined, from display zones for dead bodies before the remains were transferred to hypogea, to places where initiation rituals involving psychedelic drugs were carried out. There seems to be a rather contradictory relationship between the suggested social/ritual function of temples and their architecture. While they have been described using terms such as "administrative centres" (Renfrew, 1979) and "club houses" (McLaughlin et al., 2018), they have also been described as "low, confined spaces, dark, convoluted and probably amplifying sounds and smells" (Robb, 2001, p. 182). This seemingly contradictory character suggests, to us, a need for interpretive caution.

In contrast to ideas of chiefdoms and powerful priesthoods, some researchers have suggested a more egalitarian characterisation of Temple Period society (e.g., McLaughlin et al., 2018). Cazzella and Recchia (2015) emphasised the large

FIGURE 6 | Tarxien temple. Note fire damage (reddened areas).

numbers of people buried in hypogea, who surely could not all belong to an elite. Likewise, Thompson et al. (2020) discuss how the diversity of burial practices and high numbers of non-adult remains and approximately equal ratio of the sexes at the Xagħra Circle are consistent with an egalitarian society. Cazzella and Recchia (2015) also discussed how the final stages of construction at Tas-Silġ meant a "less confined scheme of entry" (p. 96), in contrast to the frequent idea that temples show increasing restriction of access to certain areas (e.g., Trump, 2002). There is likewise little evidence for inter-personal violence in the Temple Period (e.g., Magro-Conti, 1999; Thompson, 2019).

Against this seemingly peaceful and stable backdrop, several sites have produced findings indicating possible abrupt changes at the end of the Temple Period. At Tarxien extensive evidence of burning (**Figure 6**) has been suggested to reflect the possible destruction of the temple at the end of the Temple Period (e.g., Magro Conti, 1999; Trump, 2002). There are, however some significant caveats. In the Tarxien Cemetery phase of the early Bronze Age, Tarxien was reused by people who cremated the dead (Zammit, 1930). There has been discussion on the chronology of fire damage at Tarxien, some of which may have been earlier (e.g., Evans, 1971) and some later (Pace, 2004) than the end of the Temple Period. The possibility that there was a major fire at the end of the Temple Period is perhaps supported by the widespread signs of burning at the site, not merely where the Bronze Age deposits occurred, and stratigraphic observations. Evans (1971, p. 151), for instance, in discussing Zammit's notebooks, point out how in part of the site there was a "5 cm layer of black ash" just beneath the sterile layer which separates the Temple Period and Bronze Age deposits. In the paved outer apses of the Central Temple, fire damage may even be noted below floor level at a point where the paving is missing, raising the question of whether an earlier fire predates the paving of this area.

To Zammit (1928), the sterile layer discussed above was a natural deposit which slowly accumulated, suggesting that by the start of the Bronze Age the islands had long been abandoned. This view has been challenged from several perspectives. Firstly, it is clear that this deposit actually varies considerably across the site. As cited by Evans (1971, p. 150) from Zammit's notebook; for instance, in one spot the sterile layer was a "dark brown soil" 76 cm thick, elsewhere it was a 38 cm thick "grey or reddish-grey soil." The meaning of this lateral variability is unclear, and there have been different interpretations of Zammit's publications and notebooks, with Bonanno (1993) suggesting that the sterile layer was only found in the part of the site covered by the Bronze Age deposit, and Sagona (2015) arguing that Zammit suggested it covered the entire site. Trump (2002, p. 286) was happy to accept that the sterile "silt" later formed naturally, as Zammit suggested, but with the caveat that it could have happened much more rapidly than Zammit thought. Given the sterile nature of the deposit, it could represent a rapidly windformed deposit. Others have argued that the sterile layer was not natural at all, but had been deliberately deposited at the site. Evans (1971) and Bonanno (1993) suggested that it was taken there in the Bronze Age to create a flat base for the cemetery. Such a preparation may also have had ritual significance, arguably sealing in the powerful and potentially dangerous ritual potency of an earlier cultic system. Sagona (2015) suggests that the sediment was taken there at the end of the Temple Period as an act of "decommissioning." Available data make it impossible to finally resolve the age and formation process of the sterile layer.

Another category of findings relates to the possibly deliberate smashing of temples and objects such as figurines (Vella, 1999). Examples include Trump's (2002, p. 238) suggestion that at Skorba large pieces of rock had apparently been smashed out of the temple walls before the Bronze Age. At Tarxien, Zammit (1930, p. 79) interpreted the distribution of things like broken pottery in different parts of the site as suggesting that they were "broken intentionally before the collapse of the buildings." However, without good chronological resolution it is challenging to link signs of damage to the very end of the Temple Period. At Tas-Silġ, Cazzella and Recchia (2015) suggest the temple structure saw collapses during the Tarxien phase, which were not repaired, although activity continued at the site. Another interesting aspect here concerns the lack of surviving evidence for stone roofing material, given the general view that temples were originally roofed (e.g., Torpiano, 2004; Robinson et al., 2019). Sagona (2015, p. 130) sees this as another reflection of "decommissioning." Other possibilities include

FIGURE 7 | Statues and figurines from Malta. Left and centre: figurines from Ħaġar Qim (48.6 and 23.5 cm high), Right: Broken giant statue from Tarxien (1.1 m high, the complete statue might have been nearly 3 m high when complete). (All photos courtesy of Heritage Malta. Copyright images not to be reused without permission of Heritage Malta).

deliberate destruction of roofs to prevent use of the site or the possibility that roofs were made of wood and not stone (e.g., Robinson et al., 2019).

Figurines and statues are a major feature of Temple Period material culture (**Figure 7**) (e.g., Bonanno, 2004; Monsarrat, 2004; Vella-Gregory, 2005; Vella-Gregory, 2016; Malone and Stoddart, 2016). Several examples of possibly deliberate damage to them have been discussed. The giant statue at Tarxien (**Figure 7**) is commonly regarded as having been broken by recent quarrying activity (e.g., Zammit 1930; Evans, 1971), although this interpretation is not without ambiguities (e.g., Vella, 1999; Pace, 2004; Sagona 2015) and the possibility of earlier deliberate damage cannot be excluded. Another damaged statue, from the multi-period site of Tas-Silġ, offers stronger evidence for deliberate damage. Vella (1999) pointed out that the damage being accidentally caused by ploughing seems unlikely, as careful evaluation of the damaged surface shows marks from different tools. This suggests "purposeful mutilation," but it remains hard to say when this was done (see also Sagona, 2015, p. 132).

A final, key, example comes from the Xagħra Circle. In this case, a finely shaped statue over 60 cm high had been "smashed almost beyond recognition" (Malone et al., 2009b, p. 283) which seemingly "could not have occurred naturally" (Malone and Stoddart 2013, p. 77). These authors suggest this may represent an "act of closure," and emphasise the abandonment of the site around the same time as the damage. Other authors have agreed that the smashing of the statue was deliberate (e.g., Monsarrat, 2004; Bonanno, 2017). Crucially, the smashed statue pieces occur in excavated and dated contexts.

The precise location data for each fragment provided by Malone et al. (2009) shows the narrow vertical distribution of the fragments; 80% of the fragments are found within 30 cm of the mean elevation (**Supplementary Material 3**). Given the presence of statue pieces in features such as the "display zone," a depression up to 50 cm deep containing thousands of bones, a little vertical spread is unsurprising. We collated radiocarbon dates published by Malone et al. (2019) for contexts in which pieces of the smashed statue were found. A majority of the fragments were found in four key contexts (514, 783, 931, 942), while the rest were found in ones and twos in other contexts. A crucial point here is that radiocarbon ages calibrating to around 4.4–4.2 ka have a relatively large errors due to the slope of the radiocarbon calibration curve at this time. This means it is not possible to have ages with error ranges of less than hundreds of years. Some of the Xagħra Circle radiocarbon dates may therefore extend as late as 4.2 ka, but these estimates may be hundreds of years older given the error ranges. In such a situation, chronological modelling offers a useful way to understand such dates. The code and data for the chronological modelling described in this and the following section can be found at https://github.com/wccarleton/malta42 for R code, and doi: 10.5281/zenodo.5354992 for additional large data files.

To evaluate the chronology of the smashing of the Xagħra Circle statue, we used OxCal to create a set of Bayesian chronological models involving the statue-associated radiocarbon samples. This evaluated how discrete the cluster of statue-associated radiocarbon samples appeared to be in time. A very discrete cluster would lend support to the idea that the statue pieces remained in their initial depositional contexts, and can therefore be well dated. In contrast, more temporal dispersion and gradual tapering of sample dates toward the present would indicate the converse: that the statue pieces were redeposited and/or there was still active deposition into the statue-associated contexts for some time after the initial breaking. This exercise aims to both cast light on the date in which the statue was smashed, but also to use this as proxy for the chronology of the end of the Temple Period occupation of the site, as this seemingly occurred shortly after the smashing of the statue.

As discussed further in **Supplementary Material 2**, we compared four chronological models. The models differed in terms of the boundaries we specified for the start and end of the statue deposition process—these boundaries constitute the priors in Bayesian chronological models. Using the "Agreement Index" (Bronk Ramsey, 1995, 2008) we explored how well the data from the site fitted the different models. The best fitting model, as shown in **Figure 8**, has an initial "Tau" boundary followed by a terminal uniform boundary. This means that the group of samples contains some early material, followed by a gradual rise in the accumulation of samples, and then an abrupt termination. While different scenarios are consistent with the

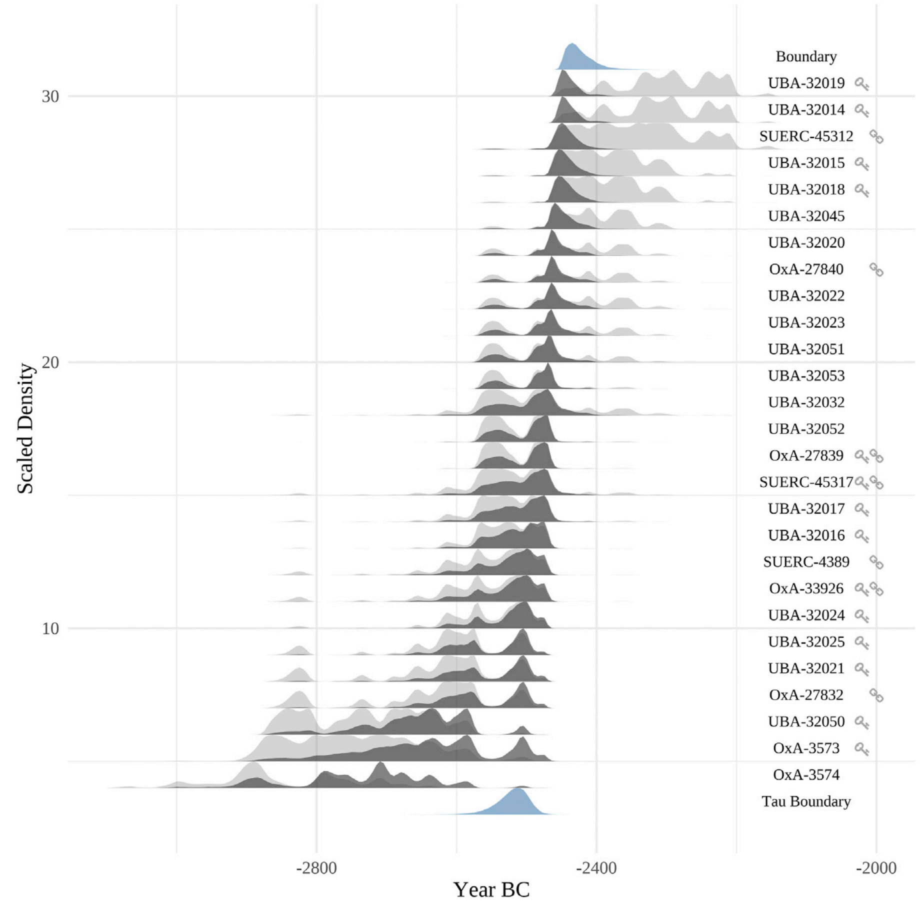

FIGURE 8 | Chronological modelling of radiocarbon dates associated with fragments of the broken Xagħra Circle statue. Blue distributions show start and end point of the preferred model in Oxcal. Key symbol shows samples from key contexts, link symbol shows samples which are from articulated remains.

most likely model (**Supplementary Material 2**), the probable scenario is that the statue was smashed at the end of the identified chronological period. The model suggests that the smashing occurred after 4.5 ka and before 4.4 ka. The key point that we emphasise here is that this suggests the breakage occurred centuries before the 4.2 ka event.

Chronological Modelling of the End of the Temple Period

The previous section highlighted the utility of chronological modelling to elucidate aspects of Maltese prehistory. Here we explore the wider utility of Maltese radiocarbon dates in the 5.5 to 3.75 ka timeframe (excluding radiocarbon estimates with large errors), with the aim of exploring the end of the Temple Period from the perspective of patterns in radiocarbon data. Recent research has added many archaeologically associated radiocarbon dates for the Maltese Islands (French et al., 2020a; Malone et al., 2020a). This means that a relatively large number of ages are available for a small landmass. However, just under half of the total number of dates are on human bones from the Xagħra Circle (Malone et al., 2019).

Our aim here is to explore the relationship between the frequency of Maltese radiocarbon dates through time—as a proxy for archaeologically visible human activity (see **Supplementary Table 1**)—and climate. We used a radiocarbon-dated event-count model (REC; Carleton, 2020; see also Stewart et al., 2021) to explore the relationship between Maltese radiocarbon-dated event counts and regional precipitation amounts. REC models have been developed as an alternative to the commonly used summed radiocarbon probability approach, which was critiqued by Carleton and Groucutt (2020). As discussed above in **Supplementary Material 1**, this is not a straightforward exercise as suitable climate data is not available from the Maltese Islands. We therefore evaluated regional climate records from nearby Sicily and Italy. The Sicilian records include useful records such as pollen profiles, but, as discussed above, the meaning of pollen records is often ambiguous, and published papers lack the kind of quantitative datasets needed for chronological modelling exercises. We therefore use oxygen isotope ($\delta^{18}O$) data from a speleothem from Renella Cave in central Italy as our climate proxy (Drysdale et al., 2006; Zanchetta et al., 2016). While a directly local archive remains desirable, using a high-resolution

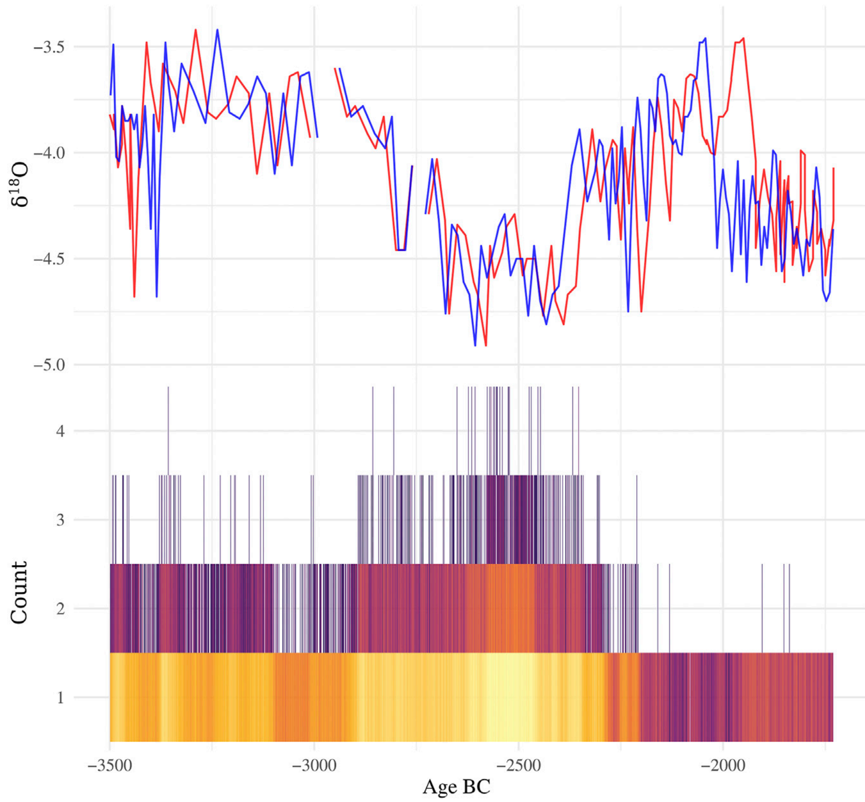

FIGURE 9 | The $\delta^{18}O$ record from Renella Cave, with blue line showing published age-depth model (Zanchetta et al., 2016 and red line our age-depth model from OxCal. More negative values indicate more rainfall, and less negative values indicate more arid conditions. Radiocarbon dated event count (REC) ensembles at bottom summarises multiple sequences of events which are compatible with the data, i.e., years in which archaeological activity is present. Brighter colours and higher *y*-axis values indicate a greater chance of archaeological activity at that time. See Carleton (2020) and Stewart et al. (2020) for more information on the REC model approach.

central Mediterranean archive is the best that can currently be done, and general regional paleoclimate data suggests similar patterns in Italy and Sicily, and by analogy, Malta (**Supplementary Material 1**).

Using the REC model approach, we created two Negative Binomial REC models. For one model, we compared event-count sequences based on all of the dates in the Maltese archaeological radiocarbon date database to the $\delta^{18}O$ record (**Figure 9**). In the other model, we compared only the dates from the Xagħra Circle (**Figure 10**). The event-count sequences were created by sampling the relevant calibrated radiocarbon date densities with replacement many times. Each random draw was then collated into a single count series by counting the number of events dated to a given time, where the times are determined by a temporal grid. This grid was defined by the temporal resolution and span of interest, i.e., 3500–2730 BC. Along similar lines, the $\delta^{18}O$ record samples were produced by first creating ensembles of the relevant age-depth model in OxCal and then assigning time-stamps to the palaeoclimatic observations with those sampled age-depth models. A fully reproducible explanation of this data preparation is available in **Supplementary Material 3**.

Our results overall indicated a negative relationship between the $\delta^{18}O$ proxy and radiocarbon-dated event counts (see **Figure 11**). In the first analysis, involving all dates, the posterior distribution of the key regression parameter had a mean close to −1 and roughly 93% of the density was negative. In the second, where we only included dates from Xagħra, the posterior distribution of the regression coefficient for the $\delta^{18}O$ covariate had a mean of around −2.5 and nearly 100% of the density was negative. So, while in the first case zero could not be excluded at one of the usual levels of confidence (i.e., 95 or 99%) it could be excluded even at the 99.99% level in the second analysis, and overall both posterior densities imply that negative values are the most likely. The negative relationship implies that reduced rainfall levels in the central Mediterranean corresponded to lower levels of human activity in the Maltese Islands.

Establishing this correlation between regional precipitation and human activity in Malta casts a new light on the end of the Temple Period. The results suggest that the Tarxien phase at the end of the Temple Period saw intense activity, corresponding with higher regional rainfall. From around 4.5 ka there is a decline in both regional precipitation and archaeological activity in Malta. The following centuries saw a decline in both. There is little evidence for archaeological activity in Malta in the 4.2 to 4 ka period. It may be that Malta was abandoned, or nearly so, during

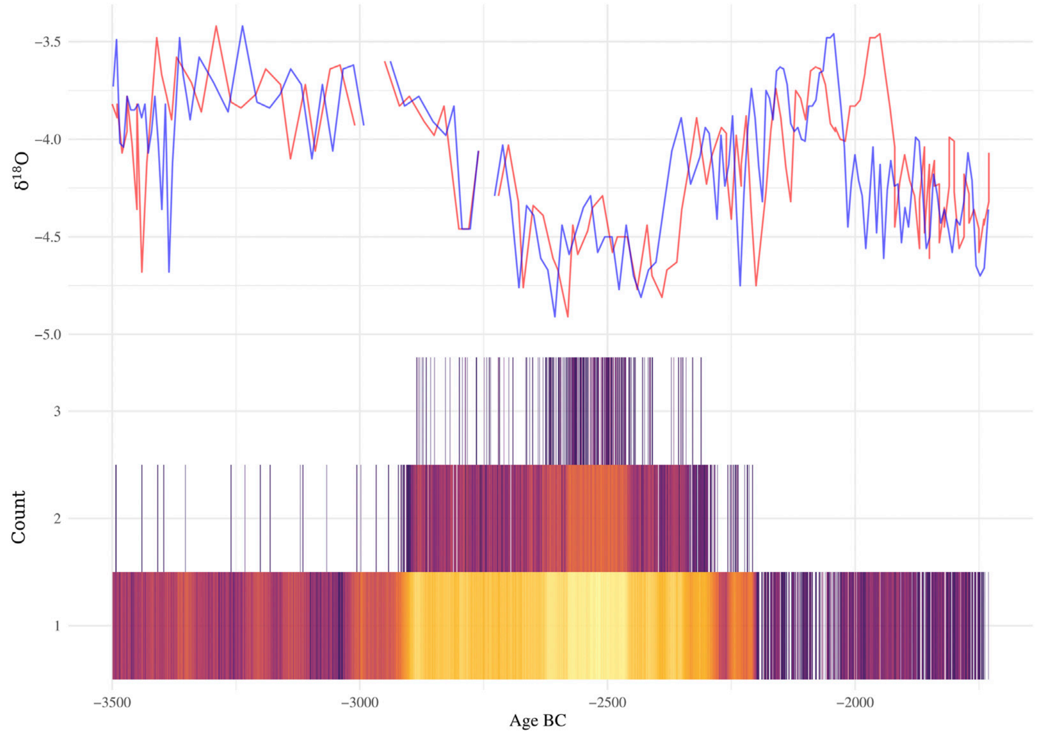

FIGURE 10 | As for **Figure 9**, but only including radiocarbon age estimates from the Xagħra Circle.

this time period. Crucially though, our results suggest that this occurred against a backdrop of centuries of decline. This is most clearly expressed with the Xagħra Circle data, while including all available dates from the islands produces weaker results. This is not surprising given the patchy nature of available samples for sites other than the Xagħra Circle. The varying frequencies of archaeological activity can be taken as indicating population decline and/or reduced ritual activity (such as burials). We hypothesise that it indicates both. This can be tested by future research, particularly as more data from non-ritual contexts is accumulated.

Agriculture and Water Management

By understanding how Temple Period society operated in terms of factors such as agriculture and water management, we will be in a better position to evaluate how it ended. It is also important to consider the several important aspects which are currently poorly understood. Even if climate change was key, there are diverse pathways from this to human societal changes.

Key Temple Period crops were wheat, barley, lentils, and peas, while for animals, sheep and goat were the most abundant, with cattle and pigs also relatively common (e.g., Trump, 1966; Bonanno, 1986; McLaughlin et al., 2020b; Malone et al., 2020c). This is both a classic Neolithic package, and one in many ways well suited to the conditions of the Maltese islands. The consistency of the taxa used for food production in the Temple Period, and preceding Neolithic, is noteworthy, and suggests an early and repeated recognition of the best ways to use the landscape of the islands (McLaughlin et al., 2020b).

The weakness of the Temple Period agricultural system was its reliance on presumably rainfall-fed annual crops which would have been vulnerable to drought. By storage and using livestock, a dry year need not have been catastrophic. It seems less likely, however, that extended periods of drought could be tolerated, as suggested by examples from the recent past. In the 1460s AD, for instance, there were three successive dry years when it is reported that all the livestock animals in Gozo died, the wheat crop failed, and there was widespread suffering (Wettinger 1982, 1985). Likewise, more recent examples from the Mediterranean highlight the frequency of crop failures (e.g., Garnsey, 1988). The Xagħra Circle human bones suggest a picture of generally good health in the Temple Period, yet there are indications of increasing stress from around 4.5 ka, with declining numbers of dental caries perhaps indicating reduction in cariogenic cereal consumption and increased enamel hypoplasia indicating childhood dietary stress (McLaughlin et al., 2020b). This may well indicate an agricultural system which generally still worked well, but was under stress.

Several sites have produced evidence for Temple Period water storage. The Ħal Saflieni hypogeum features a "vast cistern" (Trump, 2002, p. 131; see also Evans, 1971). This site also features basins positioned to catch water appearing from fissures, suggesting it may have acquired ritual significance (Grima, 2016). At temples such as Tas-Silġ and Tarxien,

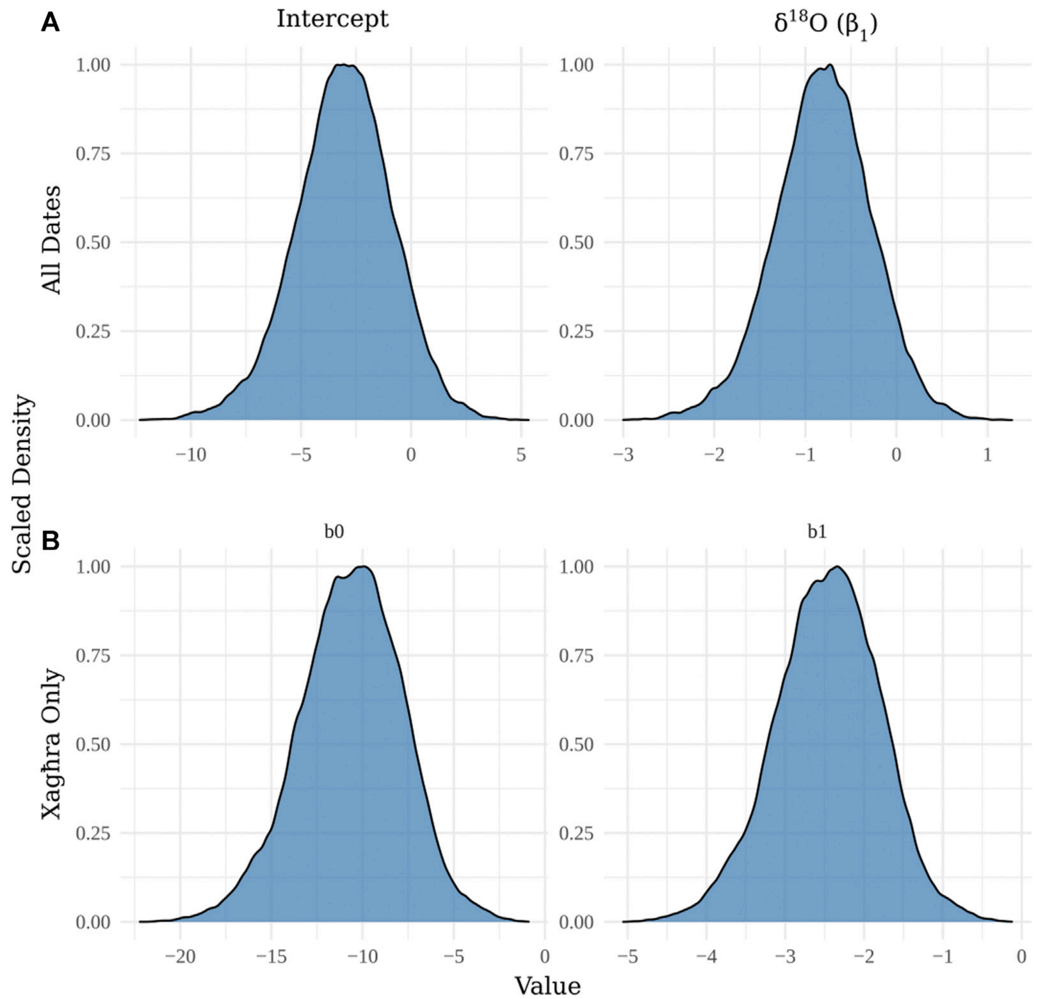

FIGURE 11 | Regression results for the REC models for all Maltese radiocarbon dates and climate **(A)**, and for only the Xagħra circle **(B)**. The left columns indicate the model intercept (i.e., the mean event counts, holding the $\delta^{18}O$ covariates constant at their study-period means) the columns on the right indicate the effects of climate (variation in $\delta^{18}O$) on the frequency of radiocarbon dated samples. The negative values indicate that drier conditions correlate with reduced numbers of radiocarbon dates.

multiple water storage facilities have been identified. However, given the multi-phase use of these sites, it is often hard to know how old these are. At Tarxien, however, a cistern was found by Ashby (1924) securely stratified beneath a *torba* (pounded rock powder) floor. This was located to catch water emerging from a fissure, again suggesting a ritual interest in this water (Grima, 2016). A much-discussed example is the Misqa Tanks (**Figure 12**). These are located very close to the Mnajdra and Ħaġar Qim temples, and a series of channels and cisterns have been cut in an outcrop of relatively impermeable rock. These are much larger than typical Bronze Age cisterns, and differently shaped to those built by Romans (Trump, 2002) and therefore quite possibly date from the Temple Period. Such water storage is important in thinking about Temple Period survival, yet it is also unlikely that water stored in such ways was sufficient for large-scale irrigation, and so crops and vegetation would have relied on precipitation and its vagaries.

A GIS-based study of variables that may have influenced temple location showed that proximity to springs was a very strong determining factor (Grima, 2004). More recently, further evidence of this relationship was found by a remote-sensing study of the immediate environs of Ġgantija, which identified the presence of a fault and springline running just east of the site (Ruffell et al., 2018).

After that brief summary of evidence for subsistence and water storage in the Temple Period, we now turn to consider the multiple areas of uncertainty which currently exist. Firstly, while multiple sites have produced evidence for wheat, barley, and legumes, were other kinds of crops absent? There are still relatively few Maltese sites at which extensive archaeobotanical studies have been conducted, and even fewer non-ritual sites where such evidence may be more abundant. Arboriculture, for

FIGURE 12 | Some of the channels and deep cisterns of the "Misqa Tanks." Located close to Mnajdra and Ħaġar Qim temples, they have been suggested to possibly represent Temple Period water storage.

instance, can offer a valuable way to manage annual variation in rainfall, as impacts will be less immediately devastating than with annual crops. A significant question then concerns whether Temple Period people in Malta made use of plants like olive trees and vines.

The earliest dates for olive domestication and cultivation come from the Levant, in the 7th millennium BC, while cultivation was occurring in the Aegean in the 6th millennium BC (Langutt et al., 2019). Yet it seems that by the third millennium BC, independent olive domestication occurred in areas including Iberia (Terral et al., 2004) and Italy (D'Auria et al., 2016) (for a summary see Besnard et al., 2018). In Sicily, olive oil residue dating to around 4 ka was recently identified (Tanasi et al., 2018). In the first millennium BC there was a Phoenician related spread of Levantine olives across the Mediterranean. Some analyses of olive genetic variation have found that Maltese olives occupy one side of the deepest split in the genetic tree (Di Rienzo et al., 2018), yet dating that split is currently challenging. Given these factors, the presence of domestic olive cultivation in Malta in the Temple Period seems possible. The limited number of systematic archaeobotanical studies in the islands should caution against the meaning of a current lack of on-site evidence for this. Pollen cores provide possible evidence for early cultivation in Malta. Olive pollen does not travel far (e.g., Florenzano et al., 2017), so high levels of olive pollen indicate extensive local cultivation. The complicating factor though is that wild non-domesticated olive is native to Malta, and it is not possible to separate this from the domesticated form by pollen (Farrell et al., 2020). The common approach to differentiate olive cultivation from wild olive changing in frequency due to natural climate change is to explore how olive changes in relation to other taxa in pollen records.

Different pollen records from Malta give different signals—for reasons discussed above, such as taphonomic biases, chronological uncertainty, and spatial variation within the islands. The record presented by Gambin et al., (2016) is particularly interesting, as it contains very high levels of olive pollen in the mid-third millennium BC, and this does not seem to be in sync with other Mediterranean arboreal taxa. Olive levels are higher than they were in the last two thousand years, when we know olive production was considerable in Malta. The interesting point though is that the high olive levels occur in the early to mid-third millennium BC, peaking ~4.6 ka at 19%. The proportion of olive pollen then declines so that it is low at ~4.2 ka (6%). A second peak occurs in the Roman era, but it reaches less than 10%. Different views have been expressed on whether available data suggests Temple Period olive cultivation (e.g., Fenech et al., 2020b) or not (Farrell et al., 2020). On face value, it could be argued that there was extensive olive cultivation in the peak of the Tarxien phase, but that this declined considerably, before 4.2 ka (Gambin et al., 2016).

With vine cultivation, the oldest known grape pips are from the Early Bronze Age at Tas Silġ (Fiontentio et al., 2012). Yet vine pollen has been identified in Malta as far back as ~6.7 ka (Djamali et al., 2012), and it may therefore have been a long-term part of the Neolithic and Temple Period diet. It was also identified in later setting, such as in the Wied Żembaq 1 core at ~4.7 to 4.3 ka (Farrell et al., 2020). Vines are also low producers of pollen, so its general paucity may be misleading. It has recently been argued that Sicily was a major centre for vine domestication, in the third or late fourth millennium BC (De Michele et al., 2019). There would therefore have been a long span of time for cultivation to spread to Malta.

A variety of other useful tree taxa such as fig (Trump, 2002) and carob (Trump, 1966; Farrell et al., 2020) are evident in the Temple Period. Some cores have high levels of *Pistacia* pollen, which may represent proximity to areas where these trees were being grown in a managed way, perhaps for food (for both people and animals) and firewood (McLaughlin et al., 2020b; Farrell et al., 2020). Likewise, French et al., (2020) suggested the coming and going of woodland indicators in different cores may indicate rotational land use. There are therefore fascinating hints at extensive arboriculture.

Another major area of uncertainty concerns the extent of landscape modification, which limits understanding on how climate changes would have manifested and impacted people. For instance, it remains unclear when the extensive artificial terracing which today characterises the Maltese landscape began. Some circumstantial evidence may come from the fact that Skorba and Ġgantija temples each have monumental artificial terracing, suggesting that the skills needed to create terracing for agricultural purposes were certainly available in theory. Likewise, the organisational and technological foundations were certainly in place for things like the artificial damming of steep sided valleys to create small reservoirs, yet there is currently no evidence that this was actually done.

Zammit (1928) argued that the numerous Maltese "cart ruts" were formed in the Temple Period, by people moving millions of cartloads of soil up slope to create terraces (see also McLaughlin et al., 2018). However, there remains a striking lack of consensus on the age and function of cart ruts, and most recent studies of cart ruts have suggested that they are much younger than the

Temple Period (e.g., Magro Conti and Saliba 2007; Trump and Cilia, 2008; Bonanno, 2017). Sagona (2004, 2015) argues that the cart ruts are actually "field furrows," and represent marginal areas being brought into cultivation at the end of Temple Period. While an interesting idea, there is currently little evidence to support this model.

Another aspect concerns soil modification, and how this could improve agricultural yields. Brogan et al. (2020) discussed evidence from Ġgantija that soil manuring was being practiced in the Temple Period, which appears sensible given long-term soil quality decline (e.g., French and Taylor, 2020). A variety of other methods may have been used to improve soils. For instance, adding seaweed could have been a powerful strategy (as it was in other parts of the world, e.g., Sagona, 2004). Often large volumes of seaweed wash up in Malta, and following some kind of simple processing to remove excess salt, this could have been added to the fields to improve yield. In this regard the discovery of seaweed at Għar Dalam may be significant (Despott, 1923). Another possibility would be the addition of phosphoritic nodules which occur between the Globigerina Limestone members to fields in order to boost phosphate levels. Grima (2004) discussed dark pebbles from Tarxien which may be from this phosphoritic layer, and which may, conceivably, hint at such movements. The nearest source to Tarxien is around 5 km east.

Finally, while the small number of sites with relatively good zooarchaeological samples are dominated by domesticated taxa, there are nevertheless hints of an interesting role for wild foods. For instance, multiple Temple Period sites have produced deer remains (e.g., Tagliaferro, 1911; Evans, 1971). Several sites, such as Skorba (Trump, 1966) and Santa Verna (Evans, 1971), have produced relatively large numbers of shells. However, the number of marine molluscs from such sites is seemingly too small to suggest that they were used as a regular food source. It can also not be excluded that many of the shells from Temple Period sites were collected when already dead. Might it, however, have been that there were cultural taboos about the consumption of wild species, which helped to ensure their survival, and allowed them to be used during periodic agricultural crises? Such possibilities can be evaluated by future studies of non-ritual sites.

Two small-scale isotopic studies have been conducted on human remains from the Xagħra Circle (Richards et al., 2001; Stoddart et al., 2009) and the FRAGSUS project has recently expanded upon this by sampling 224 teeth from Xagħra and five teeth from the Xemxija tombs, although this data is not yet fully available (Thompson, 2019). Still, the isotopic data available provide some provisional insights into the environments and diets of people in Malta. According to **Figure 11** of Thompson (2019), the carbon ($\delta^{13}C$) isotope values range from around -18.5‰ to -20.3‰, while the nitrogen ($\delta^{15}N$) isotope values range from around 7.3–13.6‰ with all but one sample falling above 8.3‰. Taken together, these values suggest a mainly terrestrial diet. The $\delta^{13}C$ values indicate that C4 plants and marine protein did not form a substantial part of these people's diets. The $\delta^{15}N$ values are consistent with high amounts of marine dietary protein, but given the $\delta^{13}C$ values this has instead been interpreted to reflect aridity. A decline in $\delta^{15}N$ values throughout the Tarxien phase may reflect a through-time decrease in meat and dairy consumption, given that the final centuries of this phase seem to have increasing rather than decreasing aridity, which could provide an alternative explanation for this observation. These interpretations are, however, currently hindered by a lack of faunal baseline data, although Malone et al. (2020a) suggest that yet-to-be-published isotope data from faunal remains supports a limited marine protein component in prehistoric Maltese diets. Interestingly, though, it has been shown that fish in the central Mediterranean have comparatively low $\delta^{13}C$ values (Craig et al., 2009). Another confounding factor relates to the possible use of marine biofertilisers (e.g., seaweed, fish), which have been shown to significantly enrich crop $\delta^{15}N$ and $\delta^{13}C$ values (Blanz et al., 2019; Gröcke et al., 2021). Key, then, for interpreting people's diets will be a strong marine and terrestrial faunal baseline data from prehistoric Malta.

Trade and Connectivity

As well as the "internal" aspects discussed above, understanding the functioning and end of the Temple Period is of course related to the external relations of the Maltese Islands. While the isolation and distinctive cultural developments of Malta have often been emphasised (e.g., Stoddart et al., 1993), others have suggested much stronger connection with areas such as Sicily (Robb (2001), p. 187). While material including obsidian and non-local chert were imported, the extent and implications of this are not clear. To [Robb (2001), p. 187], interaction with groups in Sicily was "necessary and regular" for people in Malta. He suggested that resources such as timber, groundstone axes, and ochre were all imported in large amounts. Such a perspective is also pertinent in terms of thinking about whether there could have been a conscious abandonment of the Maltese Islands at the end of Temple Period (e.g., Bonanno, 1993). If Maltese groups were as integrated and familiar with Sicilian landscapes as Robb (2001) suggests, the possibility for emigration appears stronger.

While the strengths and weaknesses of Robb (2001) paper can be discussed, it is important to point out the several significant changes which have developed in our understanding of the Maltese archaeological record in recent years. In some regards, such as the possible import of wood from Sicily, it is simply impossible with available evidence to say either way. However, when it comes to ochre, Attard Montalto et al. (2012) carried out analyses of various geological materials in the Maltese Islands and showed that actually Temple Period ochre was consistent with local sources, and so we need not posit import. Likewise, Robb (2001) saw the long development of temples from simpler structures in the pre-Temple Period Neolithic, yet it now appears that there was a long hiatus between this and the subsequent Temple Period (e.g., McLaughlin et al., 2020a). Rather than the protracted cultural self-definition imaged by Robb (2001), the evidence arguably points to a rapid emergence of key distinguishing traits in the Żebbuġ phase at the start of the Temple Period (Malone et al., 2020a).

Discussions and research continue on lithic raw material sources in the Temple Period, and what these suggest about movement and exchange. In terms of knapped lithics, local Maltese chert was commonly used. Imported obsidian was present, but never in large amounts, and it often occurs as very small flakes and chips, suggesting intense reworking of a relatively small amount of imported material. Imported chert, including that from Sicilian sources, is certainly present in fairly large numbers, but again, often as very small pieces (e.g., Malone et al., 2009b; Malone et al., 2020e). Yet debates continue on assigning chert to particular sources. Knowledge on the variability of Maltese chert sources remains limited. In recent fieldwork, for instance Chatzimpaloglou and others (Chatzimpaloglou 2019; 2020; Chatzimpaloglou et al., 2020a,b) identified a currently unique and previously unknown chert source near Dwejra, Gozo, with radically different characteristics to "typical" Maltese chert (i.e., transparent colour and higher quartz content). Likewise, the most commonly identified in the recent excavations in Gozo, Malone et al. (2020e) "Group 1" is ambiguous in terms of origin. It did not match any of their Sicilian comparative samples. Chatzimpaloglou (2019, p. 250) suggests the dominance of this chert at sites such as Ġgantija and the Xagħra Circle provides strong evidence of "constant seafaring activity" that connected Malta to areas like Sicily. Given the character of lithics in this material – indicating complete reduction sequences, and not giving the impression of being a prized imported commodity, i.e., it was treated in a very similar way to other chert that Chatzimpaloglou does consider to be local—the possibility that it is in fact from a local source must be considered.

Groundstone "axes" provide another somewhat confusing category of material culture in Malta. Made of hard rock, particularly igneous rock, these are definitely imported, and have been linked to sources from Sicily to the Alps (Skeates, 2002). The interesting point here though is that seemingly functional axes are extremely rare—for instance, Trump (1966) found just two at Skorba—but miniature axe-shaped forms with a hole pierced at one end, commonly described as pendants, are relatively common. They mostly come from the Ħal Saflieni hypogeum, with Tarxien and the Xagħra Circle also producing reasonably large numbers. What are we to make of these "axe pendants"? Given the widespread use of groundstone axes for woodworking in the Neolithic, the paucity of seemingly functional forms in Malta is puzzling. An obvious possibility is that the axe pendants were originally functional axes, and that over long use these were worked down, reflecting limited supply, and became decorative/symbolic objects (Skeates, 2002). In some cases, it is clear that two pendants were being prepared from a single larger parent object, perhaps explaining the diminutive size of the pendants. To Skeates (2002), groundstone axes were increasingly ritualised through the Temple Period (see also Barrowclough, 2007).

The consistent presence of imported materials in Malta demonstrates connections to the wider world, yet the available data can be interpreted in different ways. In some cases, the extent of this import is seemingly fairly limited, and therefore Robb (2001) point that the distinctive Temple Period culture was because of a "symbolic boundary" remains a matter of debate; the long sea crossing to Sicily or other localities in the region may have presented a considerable challenge. A more isolationist view might suggest that rather than very regular contact and exchange, it is also possible that a boat from a neighbouring society may have been driven off course to the Maltese Islands in a storm every few years, perhaps bringing with it a few groundstone axes and a small supply of obsidian or chert. Mitigating against this view, however, is the point made above about typical location of temples being near good landing points. While it is possible that this reflects intra-Maltese movements by boat instead of by land, we think it more likely that the positioning of temples reflects positioning to meet boats arriving from other areas, mediating contact with the outside world. In a highly ritualised setting though, these landings need not have been frequent to provide the ideological underpinnings to temple construction.

A Plague Epidemic?

As we have discussed, various aspects of environmental change, societal change, and the arrival of new people and ideas can all, to varying extents of specificity, be correlated with the end of the Temple Period. A further factor which is potentially important concerns the role of disease. Recent research in mainland western Eurasia now suggests a possible disease which could be involved: plague.

Plague is caused by *Yersinia pestis* bacteria, and recent genetic sequencing of human remains from western Eurasia has identified *Y. pestis* genomes at multiple sites. The earliest are around 5 ka in Sweden and Latvia, with third millennium BC examples from areas including Estonia, Croatia, Poland, and Germany (Rasmussen et al., 2015; Valtueña et al., 2017; Spyrou et al., 2018; Rascovan et al., 2019; Susat et al., 2021). It has been suggested that the Neolithic strains were less of a health risk than the Bronze Age strains (Spyrou et al., 2018). However, this has been contested (Rascovan et al., 2019), and either way, a more virulent and flea-borne version of plague originated at least 4,000 years ago (Spyrou et al., 2018). Crucially for our narrative, by the end of the third millennium BC, people had plague around the Black Sea, the Balkans, and just north of the Alps.

The timing for the spread of plague in Europe and the Mediterranean seems to correlate with the westward spread of "steppe ancestry." Some see this as a "massive migration" around 4.5 ka (e.g., Haak et al., 2015), others see it as a long process of genetic change (e.g., Furtwängler et al., 2020; Racimo et al., 2020). Limited information is available for how steppe ancestry and plague may have spread through the Mediterranean. One exception is Sardinia, where 70 ancient genomes ranging from the Neolithic to the Medieval period were published by Marcus et al. (2020). Interestingly, they found evidence of genetic continuity from the Neolithic until the 1st millennium BC, with no evidence for major gene flow into Sardinia during this period. At least biologically, Sardinia was isolated and cut off from the dominant processes in Europe and the Mediterranean.

In the Aegean, genomic studies suggest that the Minoan and Mycenaean civilizations were both the product of people primarily (at least 3/4) descending from local Neolithic people (Lazzaridis et al., 2017). However, there was a smaller scale input of ancestry from other areas, including steppe ancestry, which may have played a role in cultural change in the area. A recent study suggests a large input (~50%) of steppe ancestry in northern Greece at around 4.5 ka (Clemente et al., 2021).

FIGURE 13 | Unusual clay figurine from Tarxien temple, which has had small pieces of shell pushed into it before firing. The location of these in places associated with key points of the lymphatic system may suggest a link to diseases such as the plague (Image provided by Heritage Malta. Copyright image not to be reused without permission of Heritage Malta).

Fernandes et al. (2020) report genome wide data from Sicily and the Balearic Islands. They report that the oldest known skeleton from the Balearic Islands (~4.4 ka) has significant (more than 1/3) steppe ancestry. In Sicily, steppe ancestry was present by ~4.2 ka, possibly arriving from a westward direction due to the particular Y-chromosomes in the Sicilian samples otherwise only being known in Iberia.

So, did Malta follow the Sardinia path of biological isolation, or did it, like some other Mediterranean islands see the arrival of people with steppe ancestry at the end of the third millennium? As discussed earlier, the Thermi Ware phenomenon suggests the movement of people from the Adriatic/Aegean to Malta at this time, coming from an area where both steppe ancestry and plague existed. Evaluating such possibilities will require the screening of ancient genomes. There are, however, interesting grounds for speculation. Malone et al. (2020f) suggest that currently unpublished DNA evidence and skeletal anatomy demonstrate the existence of different ethnic groups, including "Africans." So along with the Thermi evidence, there may have been multidirectional migrations to and from Malta in the later Temple Period. A conference poster recently compared three genomes from the Xagħra Circle with other samples from Europe, and found that they showed high levels of inbreeding (Ariano et al., 2021). As well as supporting the isolation of Maltese people in the Temple Period, it is possible to imagine that this isolation and inbreeding increased vulnerability to plague.

As well as biological aspects, it is interesting to consider whether there is any cultural evidence which could relate to plague. A clay figurine from Tarxien (**Figure 13**) has been widely discussed in the literature. It shows a large-proportioned woman, with prominent vulva, stomach, and breasts as well as protruding spine and ribs on the back. Multiple small pieces of shell have been pushed into the figurine. To Zammit and Singer (1924) the figurine suggested a pathological condition; they suggested filariasis. Another common interpretation has been that the figurine depicts pregnancy (e.g., Vella Gregory, 2005, Vella Gregory, 2016; Rich, 2008). Trump (2002, p. 103) suggested that the figurine gave a "sinister impression of witchcraft." Monsarrat (2004) discusses the figurine, and suggests it could relate to either disease or pregnancy.

While acknowledging the possibility that the Tarxien figurine does relate to pregnancy and childbirth, we propose revisiting the alternative possibility that it may relate to disease. The suggestion of filariasis by Zammit and Singer (1924) is interesting. This is a group of conditions relating to roundworm infection, which commonly manifests through the lymphatic system.

The locations of the shell pierced into the Tarxien figurine—in the groin, armpits, shoulder, neck, back, etc.—are similar to the locations of prominent parts of the lymph system. Today, lymphatic filariasis, spread by mosquitos, affects some 120 million people (Fenwick, 2012). However, bubonic plague is also a lymphatic infection, with buboes appearing in places such as the groin and armpits a few days after infection (Prentice and Rahalison, 2007). Other symptoms of plague, such as headaches and joint pain, may relate to the other positions in which the Tarxien figurine shell fragments were placed.

While we emphasise that it remains a hypothesis to be tested, we consider the possibility of a plague epidemic at the end of the Temple Period as being plausible. In such a view, temples may have become nexuses for infection, perhaps explaining changes in how they were treated. If plague arrived after several centuries of deteriorating climate and social unrest, it may have provided a final blow to a vulnerable society.

DISCUSSION

In the later third millennium BC there were a variety of trajectories of climatic and societal change in and around the Mediterranean. Some of these involved arid phases and seemingly correlated societal crises. Yet this was by no means a universal response; some areas got wetter, and some societies prospered around 4.2 ka. Even within a small area, such as central Italy, records located close to each other disagree on the timing of aridity by several centuries (**Supplementary Material 1**). The meaning of this variation is currently unclear, and the ambiguity is further amplified by the dearth of high-resolution climate records in the Maltese Archipelago itself.

What can we say about the Maltese Islands? There seems to be a period of increased aridity broadly dating to ~4.5 to 3.8 ka (e.g., Gambin et al., 2016; Farrell et al., 2020). At this point we re-iterate the challenges of constructing accurate age-depth models, and the need for caution when extrapolating from a few dates to long sequences. With that caveat in mind, there appears to be a significant decline in cereal pollen ~4.3 ka (Carroll et al., 2012). Molluscs present a similar story, with signs of aridification from the mid third millennium BC, perhaps coming to a head ~4.3 to 4.2 ka (e.g., Fenech et al., 2020). Future work on sediment cores can continue to seek to improve chronology by using tephras (e.g., Zanchetta et al., 2019), and studies of more diverse types of climate archives can be conducted.

Significantly, major social changes are evident and occurred at the same time as these climatic changes. The Thermi phase, ~4.4–4.2 ka, suggests the arrival of new communities in the islands. There are hints of damage at several sites in the late Temple Period and Thermi phases. We have explored an example of this from the Xagħra Circle, where our chronological modelling suggests the deliberate smashing of the statue occurred before 4.4 ka, and our REC model approach found a negative correlation between archaeological indications of human activity and regional precipitation. It appears that from around 4.5 ka there was a decline in both rainfall and archaeological activity. The Thermi phase and 4.2 ka event, when the islands may have been abandoned between 4.2 and 4 ka (Carroll et al., 2012; McLaughlin et al., 2020a), therefore seemingly occurred after centuries of decline. The 4.2 ka event may therefore have provided the coup de grâce on an already declining and stressed population, but it did not strike a stable society out of the blue. The possibility of a plague epidemic may also crosscut these debates and suggest an alternative narrative, yet, once again, if there was a plague outbreak, it seemingly occurred in the context of a society in decline.

After a remarkably long period of apparent societal stability on a small and climatically unstable archipelago, the unique local phenomenon of the Temple Period expired by the end of the third millennium BC. It was followed by a Bronze Age reflecting the re-integration of the islands into the more dominant trends of the Mediterranean and increasing connectivity and trade. As [Broodbank, (2015), p. 343] discusses, in some regards Malta parallels developments in Cyprus, another remote Mediterranean island which developed distinctive and localised trajectories before being "normalised" relative to neighbouring areas in the late third millennium BC. This "victory for connectivity" in the emerging Bronze Age world saw the end of the fascinating local experiment that was the Temple Period. Despite now being one of the most intensely chronometrically dated areas in the Mediterranean, the causes of the end of the Temple Period in Malta remain unclear. As we have discussed, certain correlations are suggested by the evidence, but establishing causal pathways remains challenging.

DATA AVAILABILITY STATEMENT

The data analysed for this study can be found in the paper, **Supplementary Material**, and at (https://github.com/wccarleton/malta42) for R code and base data, and doi: 10.5281/zenodo.5354992 for additional large data files.

AUTHOR CONTRIBUTIONS

HG conceived of the paper and led the writing. WCC carried out the chronological modelling, and all authors wrote and edited the paper.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2021.771683/full#supplementary-material

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Suzdalevo Lake (Central Siberia, Russia)—A Tunguska Event-Related Impact Crater?

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In 1908, a massive explosion known as the Tunguska Event (TE) occurred in Central Siberia. However, its origin remains widely discussed and environmental impacts are not known in detail. We investigated evidence of the TE in sediments of Suzdalevo Lake, which is located near the explosion epicenter. According to local nomads (Evenkis), Suzdalevo Lake did not exist before the TE and was considered as a possible impact-origin water body. However, apart from oral testimony, there is no evidence of the lake formation process. Two short sediment cores (SUZ1 and SUZ3) were retrieved from the lake and dated using ^{210}Pb and ^{137}Cs. The sedimentary record was characterized using magnetic susceptibility, X-ray fluorescence, and the screening for melted magnetic microspherules. To study possible effects of the TE on the lake ecosystem, we performed diatom and freshwater fauna remains analyses. Results indicate that the lake contains sediments that originated before the TE and thus its formation was not related to the impact. Also, the depth to diameter ratio of the lake basin is too low (<1/100) for a young impact crater. In one of the two cores (SUZ1), we documented distinct changes in the lake-catchment ecosystem that occurred within a 5-cm-thick depth interval calculated for the best fit depths for the year 1908 using three alternative age-depth models (CRS, CIC, CFCS), namely, increases in terrestrial matter input (abundant fine plant macroremains, peaks in magnetic susceptibility and the Sr to Rb ratio) and taxonomic diversity and relative abundance of benthic taxa. The shifts in aquatic biota assemblages were likely caused by nutrient supply and improved water column mixing following a catchment disturbance. Nevertheless, precise timing of the observed abrupt changes in relation to the TE is not clear due to uncertainty of the ^{210}Pb dating method and absence of melted magnetic microspherules or an event layer. The disturbance signals in the proxy data may postdate the TE. Our results demonstrate potential usefulness of the paleolimnological approach to understand the possible environmental consequences of the TE and similar events elsewhere.

Keywords: impact structure, airburst, Tunguska cosmic body, forest disturbance, aquatic ecosystems, ^{210}Pb dating, diatoms, chironomids

1 INTRODUCTION

Impact and impact-like events are considered potential triggers of abrupt climatic and environmental changes, as their direct destructive power influences atmospheric and geochemical processes on local as well as global levels (Covey et al., 1994). Their potential consequences include not only earthquakes, tsunami, and fires, but also processes such as dust loading, ozone depletion, sulfate aerosol formation, disturbances of Earth's magnetic field, and nitric acid rain (Turco et al., 1981; Kolesnikov et al., 1997; Toon et al., 1997; Shishkin 2007; Wünnemann and Weiss 2015; Artemieva and Shuvalov 2016). On the morning of 30th June 1908, a massive explosion occurred in Central Siberia, near the Podkamennaya Tunguska River, in the Evenkiysky District, Russia (e.g., Gladysheva, 2020a; Gladysheva, 2020b and references therein). The explosion affected an area of about 2,000 km^2 of continental taiga and uprooted more than 80 million trees with an estimated power equivalent to 20–30 million tons (Mt) of TNT (Rosanna et al., 2015; Artemieva and Shuvalov 2016; Robertson and Mathias 2019). It was likely the most destructive impact-like event witnessed in the modern history of humankind. Fortunately, the Tunguska Event (TE) epicenter was located in a very remote and sparsely populated region. At least three people (local Evenki nomads) died as a direct consequence of the TE, and an unknown number of people were injured from the effects of the shockwave, thermal radiation, or glass damage (Jenniskens et al., 2019). A much smaller explosion (~0.5 Mt of TNT) from a meteorite about 19 m in diameter caused injuries of ~1,600 people on 15th February 2013 in a more populated area in the Chelyabinsk Oblast, Russia (Brown et al., 2013; Kletetschka et al., 2015; Kartashova et al., 2018), documenting the destructive potential of such extreme events. TE-related glass damage was reported over a wide area, especially around the Angara River, even 400 km away from the explosion epicenter (Jenniskens et al., 2019). The night sky shone brightly for a few days over an even larger area, including Europe. The origin of this phenomenon was explained by the same mechanism as the formation of noctilucent clouds, with water and dust creating ice crystals at heights from 70 to 300 km in the atmosphere. The reflective surface of these TE noctilucent clouds was $10^4\times$ greater than usual, probably caused by a two to three orders of magnitude larger crystal size (Gladysheva 2012).

The TE is considered to have been caused by the impact of a cosmic body, but neither an impact crater nor any stony fragments have been found (Artemieva and Shuvalov 2016). An exotic quarzitic boulder, known as John's Stone, was hypothesized by some authors as a potential meteorite, possibly of Martian origin, but research by Bonatti et al. (2015) suggested its relation to the local Permian-Triassic Trap magmatism-hydrothermalism. In recent years, several lines of evidence have been published in support of the hypothesis that Cheko Lake (~10 km NW of the inferred TE epicenter) fills an impact crater created by a fragment of the parent TE cosmic body. These include geophysical data (e.g., Gasperini et al., 2007; Gasperini 2015), the presence of tree trunks and branches below lake sediments (Gasperini et al., 2014), and physical modelling (Foschini et al., 2019). However, this hypothesis was questioned by Collins et al. (2008) and Rogozin et al. (2017) based on theoretical models and sediment dating, respectively. According to local Evenki reindeer-herding nomads (Evgeniya Karnouchova, pers. comm.), a TE-related origin is also assumed for Suzdalevo Lake, a small water body located in the southern part of the tree fall area, as it was first mapped by expeditions after the TE (Vasilyev 1998; Jenniskens et al., 2019, and references therein). Today, more than 110 years after the explosion, many doubts and uncertainties persist about the TE. As the original asteroid hypothesis was called into question due to the absence of a meteorite fragment, a cometary origin of TE has been suggested by some authors (e.g., Kresák 1978; Gladysheva, 2020a; Gladysheva, 2020b). However, other causes (e.g., the volcanic ejection of natural gas, a dark matter collision, solar activity) have been discussed as well (Kundt 2001; Froggatt and Nielsen 2015; German 2019). In a recent paper, Khrennikov et al. (2020) argue that the TE was caused by an iron asteroid body, which passed through the atmosphere at a minimum altitude of 10–15 km with trajectory length about 3,000 km and continued to the near-solar orbit.

Overall knowledge of the TE is limited due to the lack of scientific observations at the time of the explosion and almost no research on the epicenter performed in the following two decades. Moreover, most of the later investigations were conducted to determine what phenomenon caused the TE, with much less attention paid to the topic of environmental damage. Natural archives, such as tree rings, peat, and especially lake sediments, have the great potential to provide important new evidence of this kind.

Only a few studies on these natural archives in the Tunguska region have been performed so far. Tree-ring research by Kletetschka et al. (2017) revealed a directional chemical response in the xylem of larch (*Larix*) trees that survived the TE inside the tree fall area. Badyukov et al. (2011) described the presence of metal microspherules consisting of Ni(Cr) bearing wüstite and magnetite with Ni-rich metal inclusions and glassy silicate microspherules in soils above the floodplain of the Chunya River, which may indicate the possible presence of cosmic body material in various sedimentary natural archives. Similar findings of microspherules were reported much earlier by Zaslavskaya et al. (1964). Lake sediments have been rarely studied, as the location is very remote, and lakes are not common in the area. An important contribution was provided by investigations of the Zapovednoe Lake sedimentary record. Despite its location outside of the tree fall area and the radiant burn area (60 km from the TE epicenter; Johnston and Stern 2019 and references therein), the lake sediment contained a characteristic yellowish (clayey) TE layer possibly caused by an earthquake and likely related catchment erosion (Kletetschka et al., 2019a; Darin et al., 2020). A considerable increase in magnetic susceptibility followed immediately after the deposition of this TE layer, pointing to intense fires near the TE epicenter. These fires (e.g., Svetsov 2002; Jenniskens et al., 2019) could converted non-magnetic iron in organic material into magnetite particles with high magnetic susceptibility that

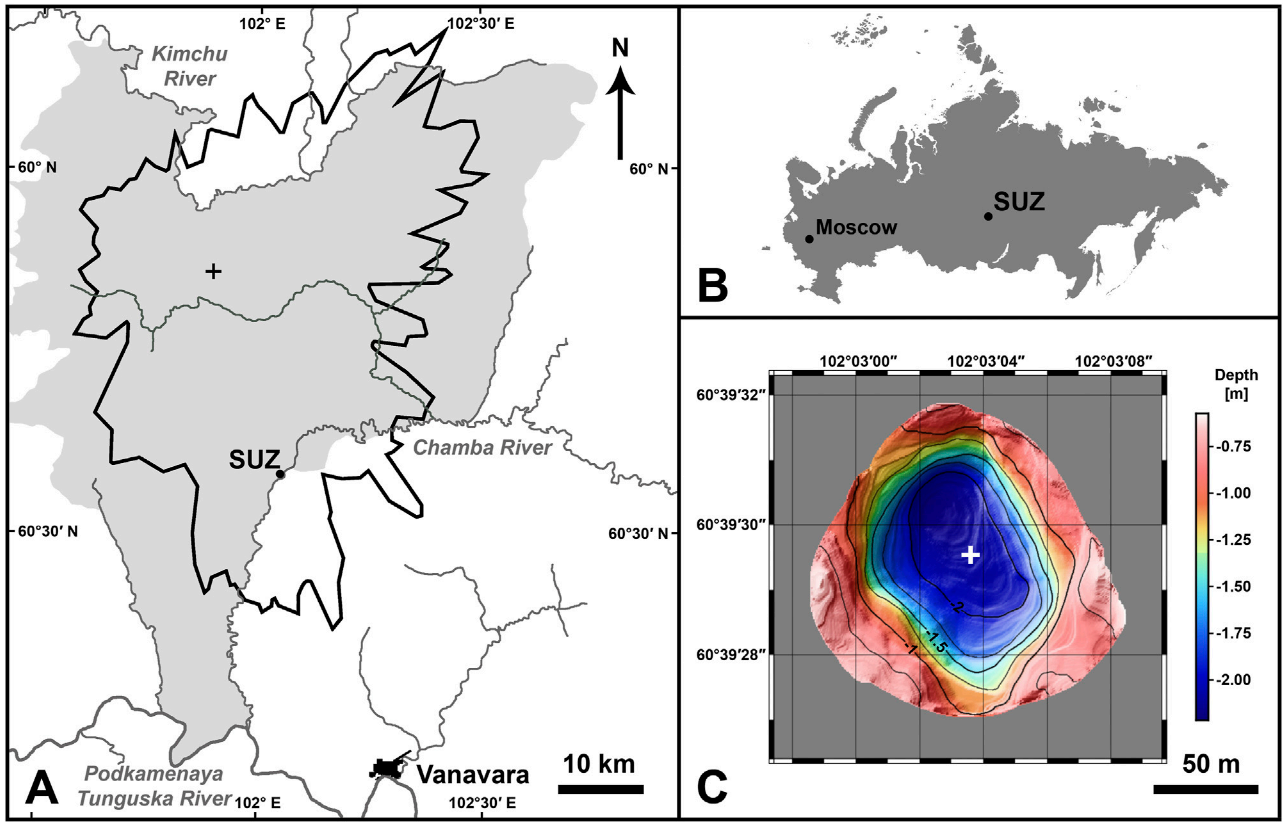

FIGURE 1 | (A) The Tunguska region and the study site—Suzdalevo Lake (SUZ). The bold black line shows the border of the TE tree fall area the black cross shows the TE epicenter. The area of the Tunguska State Reserve is shown in grey. **(B)** Geographical location of Suzdalevo Lake within Russia. **(C)** Bathymetric map of Suzdalevo Lake. The white cross indicates the position where two sediment cores (SUZ1 and SUZ3) were taken.

were then incorporated into ash and deposited in soils and various sediments (Kletetschka and Banerjee 1995; Kletetschka et al., 2019a). Therefore, such a characteristic signal should also be present in other lake sediment records and peat sequences in the region. A similar clayey layer of TE age has already been found in Cheko Lake sediments (Gasperini et al., 2009). If combined with a paleoecological approach, the presence of characteristic TE layers should enable studies on the effects of the event on related ecosystems. The potential of such paleoecological methods has already been demonstrated by Tositti et al. (2006) who discovered TE-related anomalies in tree pollen productivity and the onset of a phase of more humid conditions at the Raketka peat bog site (8 km from the TE epicenter). Other peat profiles (sites located 6–65 km from the TE epicenter; plant material of *Sphagnum fuscum*) have revealed probable traces of acid rains as a reaction to the TE, as evidenced by a positive anomaly in $\delta^{15}N$ (Kolesnikov et al., 1998).

In this study, we present a paleoenvironmental record of Suzdalevo Lake sediments. As Suzdalevo Lake has been reported by local Evenki people to have appeared just after the TE, we assumed that the lake could be a TE impact crater and/or an important natural archive to investigate the disturbance of the taiga forest and related changes in the aquatic environment. Reconstructing local environmental changes caused by the TE is crucial to understanding the processes triggered by this unique phenomenon.

2 REGIONAL GEOLOGICAL SETTING AND THE STUDY SITE

The TE tree fall area of butterfly shape (axis along the 115° azimuth; **Figure 1A**) is located in the Tunguska Basin, which is in the western part of the Siberian craton that is composed of high-grade Archeanic metamorphic complexes and granites (Gladkochub et al., 2006; Artemieva and Shuvalov 2016). At the Permian-Triassic boundary (~251 Ma), the area was affected by the extensive eruption of Siberian flood-volcanic rocks, the largest subaerial volcanic event known (~7×10^6 km^2 buried by basalts) (Kamo et al., 2003). Recent local river basins are filled with Quaternary sediments (fluvial and aeolian deposits) and soils, which also applies to the surroundings of the study site. Permafrost is discontinuous in this area with thickness up to 25 m (Gasperini et al., 2007; Ponomarev et al., 2019). Distinct climatic changes have been observed in overall central Siberia over the last century. The climate has become much warmer, and in some regions dry summer conditions have prolonged the "no-rain" period. This increases the likelihood of extremely dry periods and the risk of extreme fire events (Tchebakova et al., 2011). At the nearest meteorological station, that is placed in Vanavara (60°20′45″N 102°16′54″E; **Figure 1A**), the current (period 2000–2020) mean annual temperature is −4.5°C, the mean January temperature −27.7°C, and the mean July temperature 17.8°C. The "normal" mean annual precipitation (period 1933–2020) is 421 mm, however, the minimum mean annual precipitation of 271 mm was observed in 2016 (Weather and Climate 2021).

Suzdalevo Lake is a shallow water body located very close to the Chamba River (60°39′29.05″N, 102°3′3.36″E) a tributary of the Podkamennaya Tunguska River, 20 km SW from the TE epicenter (i.e., inside the tree fall area; **Figure 1A**). The lake is separated from the Chamba River by a natural dike ≥45 m wide and ≥4 m high. No bathymetric measurements or limnological characterizations of this site have been previously published. The lake was allegedly named after K. I. Suzdalev, a merchant from Vanavara, who visited the site shortly after the TE (Evgeniya Karnouchova, pers. comm.). Vegetation in the lake catchment is characterized by mixed taiga consisting mostly of pine (*Pinus*), birch (*Betula*), spruce (*Picea*), willow (*Salix*), and Dahurian larch (*Larix gmelini*) trees, with undergrowth of blueberries (*Vaccinium myrtillus*), cranberries (*Vaccinium vitis-idaea*), mosses and lichens. No historical logging at this site is known.

3 METHODS

3.1 Morphobathymetric Characterization of the Study Site

In May 2019, we surveyed the lake with a close-spaced grid of echosounding lines, with the aim to compile a morphobathymetric map of its floor and identify a suitable position for sediment coring. We used techniques and instruments like those employed by Gasperini et al. (2007) at Cheko Lake. The bathymetric measurements were performed with a 200 kHz echosounder tied to a wooden stick aside of a boat while a transducer was located at about 30 cm below the water surface. Instead of acquiring only the depth value provided by the echosounder through the serial port, we collected the entire echogram by means of a 16 bit A/D converter driven by SwanPRO acquisition software. The acquisition parameters of the echosounder signal were as follows: sample rate 0.856 µs, trace length 25 ms, and 2,140 trace samples (seven traces per second). The collected data were stored in XTF format, converted to SEGY format, consistency was checked using the Segy-change preprocessing software program (Stanghellini and Carrara 2017), and processed using SeisPrho software program (Gasperini and Stanghellini 2009) to display echograms and semi-automatically digitize the sediment-water interface. The lake-floor profiles were subsequently corrected for the vertical offset between the water surface and the transducer vertical position, and then exported in ASCII (lon, lat, z) format. The file was then processed with GMT to produce both a regular grid file and the final map. The original data were affected by spatial noise due to GPS precision being limited to about 1 m. To reduce this spatial noise, the final morphobathymetric map was compiled using a 2D median filter with a searching radius of 10 m.

3.2 Core Retrieval, Sediment Lithology

During the same field survey, two short lake sediment cores, SUZ1 and SUZ3, were collected using a Kajak gravity corer (sampling tube diameter of 5.8 cm and length of 50 cm) from the deepest middle part of Suzdalevo Lake. The lengths of the obtained cores SUZ1 and SUZ3 were 42 and 46 cm, respectively. Both cores were immediately sliced in steps of 1 cm, with the uppermost 1 cm (0–1 cm) divided into two layers—0–0.5 cm and 0.5–1 cm. The color, grain size, and amount of plant macroremains (qualitative data) were recorded during slicing and during analyses of aquatic biota remains.

3.3 Short-Lived Isotope Dating

Both sediment cores were measured using gamma spectroscopy for the specific activity of ^{210}Pb, ^{137}Cs, and ^{226}Ra isotopes in the Radiometry Laboratory (Institute of Geochemistry, Mineralogy and Mineral Resources Charles University, Prague, Czechia). Individual samples (1-cm-thick layers; the two uppermost layer were merged) were measured by well-in-well geometry in a SILAR® low-background anti-Compton-anti-coincidence gamma spectrometer with a specially designed 40 × 40 mm Na(Tl) well-type LEADMETER® detector with a total efficiency of 46.2% (for ^{210}Pb line of 47 keV) placed in a well-type guard NaI(Tl) detector 160 × 125 mm in 10-cm-low-background lead shielding (Hamrová et al., 2010). A Canberra DSA 2000 multichannel analyzer controlled by GENIE 2000 software was used to determine the specific activities of the above-mentioned isotopes. The measuring time for individual samples was 2 days, and 6 days for background. Special in-house standards with a light matrix were used for radionuclide quantification in the same geometry of the 8 ml vials. The IAEA-447 standard (moss-soil) was used as ^{210}Pb reference material with a result of 340 ± 6 Bq kg^{-1} for the recommended value of 338 Bq kg^{-1} and corrected for decay from the reference date (15/11/2009). Due to low weights of the SUZ1 samples affecting the results, we decided to measure isotope activities also for the SUZ3 core by merging four adjacent 1-cm-thick layers in a row. The output from the heavier 4-cm-merged samples (~4 g of dry sediment) was expected to be more accurate. The age of individual layers was obtained using the Constant Rate of Supply (CRS), the Constant Initial Concentration (CIC), and the Constant Flux Constant Sedimentation rate (CFCS) age-depth models that are implemented in an R package "serac" (Bruel and Sabatier 2020 and references therein). These alternative models were used because none of them can be considered as a universal method of age-depth model construction.

3.4 Sediment Magnetism and Geochemistry

All sediment samples from both cores were placed into plastic cups and magnetic susceptibility was measured using a SM30 magnetic susceptibility meter (ZHinstruments Inc., Czechia) at an oscillation frequency of 8 kHz and generated magnetic field amplitude of 40 A/m. The magnetic susceptibility values [X (SI), average of three measurements] were mass normalized.

The total content of selected elements was determined by means of X-ray fluorescence (XRF) spectrometry using a handheld ED-XRF analyzer VANTA VMR with a Silicon Drift Detector (Olympus, United States). The ED-XRF analyzer was coupled with a programmable moving core holder and autonomously run by a computer (for details Kletetschka et al., 2018; Kletetschka et al., 2019b). National Institute of Standards and Technology (NIST) standard reference materials 2711a Montana II Soil and 2710a Montana I Soil were used for quality control. Finally, we focused on an interpretation of concentrations and ratios of individual elements that are likely relevant to tracking the history of the lake's productivity as well as the erosional activity in the lake catchment. The strontium to rubidium ratio (Sr/Rb) and titanium (Ti) concentration were selected as proxies characterizing the input of material from the catchment (Cuven et al., 2010; Xu et al., 2010), phosphorus (P) and the silicon to zirconium ratio (Si/Zr) as proxies of lake productivity (Cuven et al., 2011), and the iron to manganese ratio (Fe/Mn) with iron (Fe) concentration control as proxy of near bottom redox conditions (Mackereth 1966; Davison 1993).

3.5 Separation and Analyses of Magnetic Microspherules

For separation of magnetic microspherules from the sediment samples (all SUZ1 layers), we performed a standard separation technique described by Israde-Alcántara et al. (2012). The separated material was analyzed under a dissecting optical microscope at 25–70× magnification. Suspected spheric objects (diameter >3 μm) were manually placed on aluminum stubs with nonmagnetic tools (sharpened wooden sticks). Finally, the spheric objects were identified with a scanning electron microscope (SEM) TESCAN Vega in back-scattered electron (BSE) and secondary electron (SE) modes, and subsequent elemental microanalysis was conducted using an energy dispersive X-ray spectroscope (EDS, detector X-Max 50; Oxford Instruments, United Kingdom) at the Laboratory of Scanning Electron Microscopy (Institute of Petrology and Structural Geology, Faculty of Science, Charles University, Prague, Czechia).

3.6 Diatoms and Freshwater Fauna Remains

Diatom analysis and the analysis of freshwater fauna remains were conducted at 1 cm resolution throughout the SUZ1 sediment core. Diatom samples were prepared following the method described by van der Werff (1955). The material was cleaned by adding 37% H_2O_2 and heating to 80°C for about 1 h, then by the addition of $KMnO_4$. Following digestion and centrifugation, the resulting clean material was diluted with distilled water to avoid excessive concentrations of diatom valves, which may hinder reliable observations. Known quantities of *Lycopodium* spores were added to estimate diatom concentrations. Cleaned diatom valves were mounted in Naphrax®, a high-refractive index medium. In each sample, 400 diatom valves were identified and enumerated on random transects at 1,000× magnification (oil-immersion), using an Olympus BX53 microscope equipped with Differential Interference Contrast (Nomarski) optics and an Olympus UC30 Imaging System. Diatoms were categorized into five ecological groups according to their life form (modified according to Buczkó et al., 2013): 1) aerophyton (living in subaerial and terrestrial habitats), 2) benthos (living at the bottom and near shore, mainly in soft sediments), 3) periphyton (attached to submerged substrata or organisms; more sessile than benthic diatoms), 4) plankton (living in the water column), and 5) tychoplankton (taxa frequently encountered both in the water column and in surface sediments). In addition, the category of benthos was further subdivided into three subcategories: epipsamon (living attached to sand grains), benthos sensu stricto (lake benthos besides epipsamon), and river benthos. Furthermore, the D to C ratio of diatom valves to chrysophyte cysts was calculated. The chrysophyte cyst sums are expressed relative to the number of diatom frustules (two valves = one frustule) plus chrysophyte cysts, with the following formula: D:C = [number of diatom frustules/(number of chrysophyte cysts + number of diatom frustules)] × 100 (Douglas and Smol 1995).

Samples for zoological indicators were washed with distilled water through a 100 μm sieve and transferred into a modified plastic Sedgewick-Rafter counting cell. All identified animal remains, mainly chironomid (non-biting midge) head capsules (HCs), were picked with either fine forceps or a steel needle using a dissecting optical microscope (15× magnification). Samples were then dehydrated in ethyl alcohol (~96%) and mounted on glass microscope slides in Euparal® mounting medium. For taxa identification, we used an optical microscope (100–400× magnification) and followed several identification keys—mainly Wiederholm (1983), Rieradevall and Brooks (2001), Brooks et al. (2007), and Szeroczyńska and Sarmaja-Korjonen (2007). Due to low abundances of all zoological indicators, including chironomid HCs, in most of the samples, we show only concentrations of individual taxa (i.e., fossils per 1 g of dry sediment).

Statistically significant changes in the diatom record were determined using the optimum sum of squares partitioning on percentage data implementing the ZONE program (Birks and Gordon 1985; Lotter and Juggins 1991). The results from optimum sum of squares partitioning on percentage data were tested for significance using a broken-stick model to derive a stratigraphical zonation (Bennett 1996). Due to the presence of zero values in the chironomid record in some of the analyzed layers (which do not allow independent zonation), we use the diatom zonation when the zoological indicator data and other proxies are discussed.

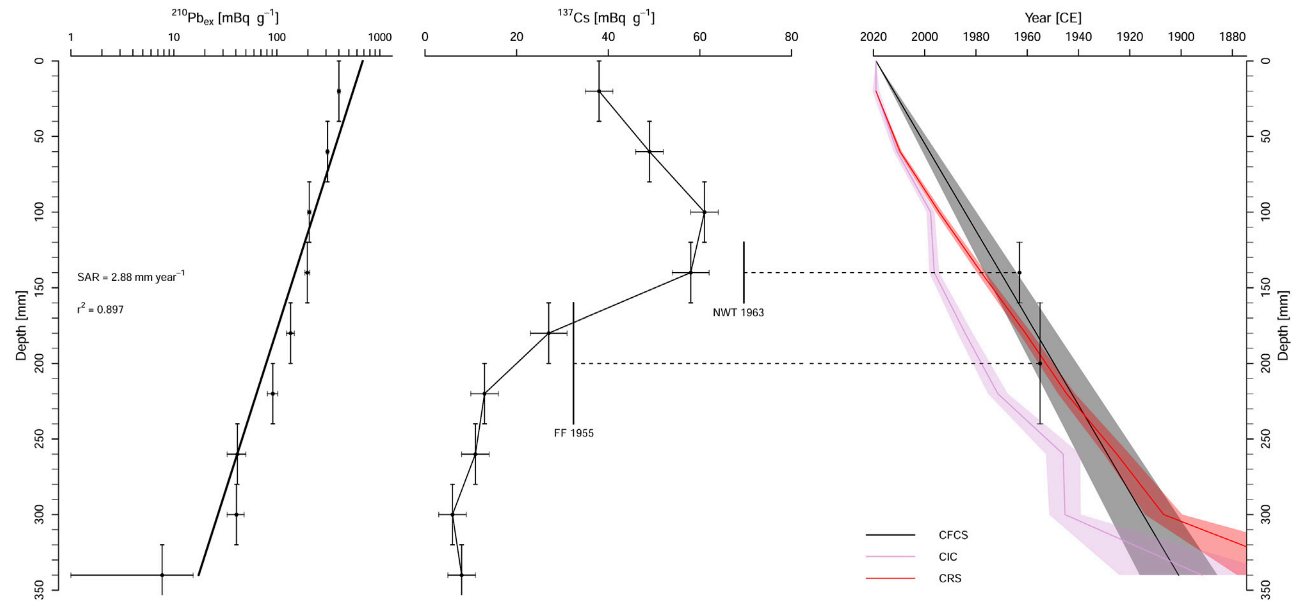

FIGURE 2 | Short-lived radionuclide activities and age-depth models for the SUZ3 core. From left to right: $^{210}Pb_{ex}$ activity (semilogarithmic plot), ^{137}Cs activity, and the Constant Flux Constant Sedimentation rate (CFCS), Constant Initial Concentration (CIC), and Constant Rate of Supply (CRS) age-depth models. SAR—sediment accumulation rate, NWT 1963—nuclear weapon tests fallout, FF 1955—first fallout period. The vertical error bars refer to analyzed sediment sample thickness (4 cm), while the horizontal bars depict 2-sigma uncertainty.

4 RESULTS

4.1 Lake Bathymetry and Sediment Lithology

Figure 1C displays the morphobathymetric map of Suzdalevo Lake obtained after data processing and compilation, while **Supplementary Figure S2** shows echographic (depth) profiles with the depth magnified by a factor of 10. The lake is very shallow, with a maximum depth of about 2.3 m and a surface area of ~1.8 ha. The depth-to-diameter ratio is about 0.015, and its irregular inverted-cone morphology is slightly elongated in the N-S direction. The depocenter is located close to the N shore, while the E and W shores show morphological irregularities. Both sediment cores (SUZ1 and SUZ3) were recovered from the depocenter (**Figure 1C**) and consisted of homogeneous dark brown gyttja with no distinct lamination or a clayey layer.

4.2 Sediment Age Determination

In the SUZ1 core, ^{210}Pb, ^{226}Ra, and ^{137}Cs activities were measured only for the upper 26 cm. Due to their low values and large error bars (**Supplementary Figure S3**, **Supplementary Table S1**), the same measurements were not performed for the deeper layers. Excess ("unsupported") ^{210}Pb ($^{210}Pb_{ex}$) was detected even in the deepest analyzed sample (depth of 25–26 cm), therefore the $^{210}Pb_{ex}$ inventory could not be calculated. The ^{137}Cs specific activities are relatively low and irregular at depths below 16 cm. The maximum ^{137}Cs activity of 93 Bq kg^{-1} was detected at the depth of 9.5 cm. Weights of some SUZ1 samples were <1 g of dry sediment (average 0.9 g).

The problem of low sample weights in the SUZ1 core was resolved using the parallel core SUZ3, where four adjacent layers were merged to produce larger samples (3.1–5.6 g of dry sediment). In nine merged (4-cm-thick) layers, the specific activities of ^{210}Pb decrease exponentially from the topmost layers to background ("supported") activities in the lower part of the core, showing a relatively smooth decreasing curve (**Supplementary Figure S3**). $^{210}Pb_{ex}$ was successfully detected in upper eight merged samples (**Figure 2**, **Supplementary Table S1**). The trend in the SUZ3 relation between $^{210}Pb_{ex}$ and depth in core is similar to the SUZ1 record, but the curve is smoother and shows lower error bars (**Supplementary Figure S4**). The ^{137}Cs specific activities are relatively low (maximum activity of 61 Bq kg^{-1}), demonstrating low contamination by radioactive fallout. An increase in ^{137}Cs activity, that should be equivalent with the global fallout due to nuclear weapon tests before its maximum in 1963 CE, was found between depths of 14 and 18 cm (**Figure 2**), with corresponding calculated ages of 1958–1963 years. CE (CRS model), 1988–1993 years. CE (CIC model), and 1963–1971 years. CE (CFCS model) for the average depth of 16 cm (**Supplementary Table S2**). However, this ^{137}Cs peak is flat and low ^{137}Cs activities are dispersed in all samples of the upper part of the core, probably due to continuous flushing out from the surrounding contaminated area, occasional sediment-water interface mixing (redeposition), and younger atmospheric fallout (later nuclear tests and power plant accidents).

Calculated sediment accumulation rates for the SUZ3 core differ among the age-depth models (**Supplementary Table S2**). Based on the CRS model, the accumulation rates decrease

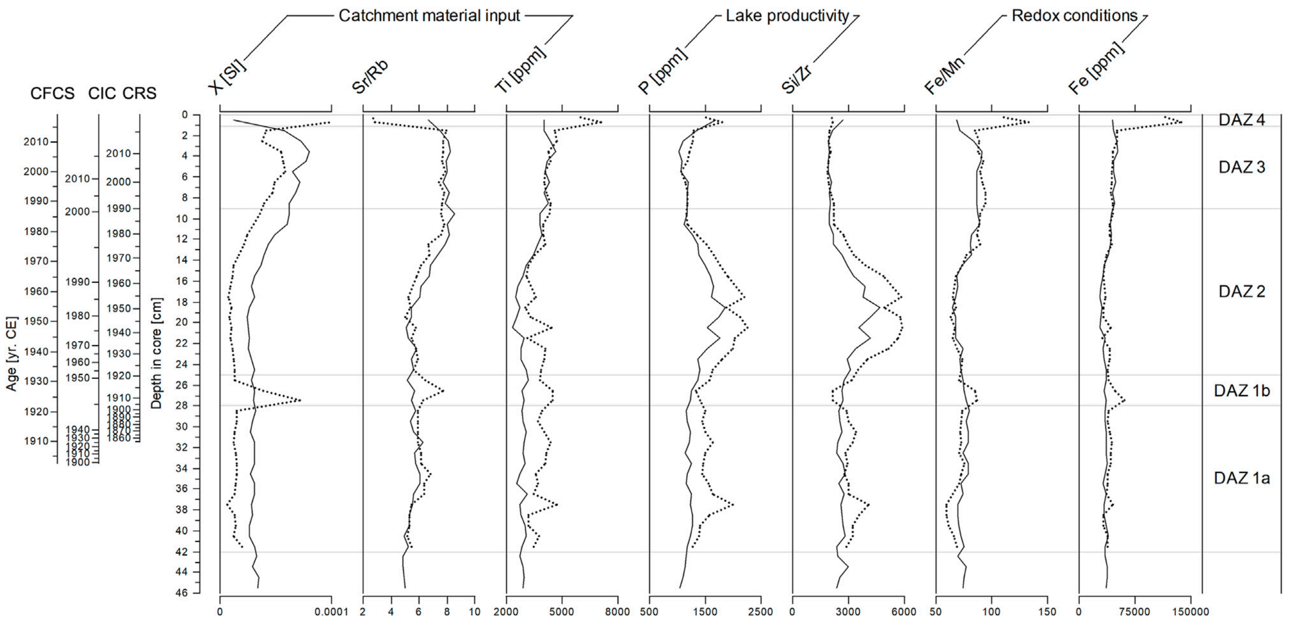

FIGURE 3 | Down-core variations of selected geophysical (mass dependent magnetic susceptibility) and geochemical proxies (Ti, P, and Fe concentrations; Sr/Rb, Si/Zr, and Fe/Mn ratios) in the cores SUZ1 (dotted line) and SUZ3 (solid line).

downwards from 3.27 (depth of 4 cm) to 1.24 (depth of 32 cm) mm year^{-1}. The uppermost samples between 0 and 3 cm show intermediate accumulation rates increasing from 2.44 to 3.10 mm year^{-1}. The CIC model shows two periods of high accumulation rate around 14 and 30 cm, and the CFCS model expects stable accumulation rate of 2.88 mm year^{-1}. The age of 1908 CE (best fit) is placed to depths of 27.75, 32.84, and 32.00 cm according to the CRS, CIC, and CFCS models, respectively.

4.3 The Magnetic and Geochemical Record

Mass normalized magnetic susceptibility values [X (SI)] in the SUZ1 core show a peak at the depth of 27.5 cm and an increasing trend between the depths 15 and 0 cm (**Figure 3**). For the same core, the concentrations of selected elements (ppm) and their ratios are plotted with depth and the diatom zonation (see details in **Section 3.5** and **Figure 3**) to better interpret the lake sedimentation history. Two proxies characterizing catchment material input to the lake are used. The Sr to Rb ratio has a similar trend as magnetic susceptibility (a peak at the depth of 26.5 cm and an increasing trend from 16 cm), except for a drop in the two uppermost layers that correspond to an increased concentration of Ti. Ti concentrations are otherwise relatively stable in the profile. Both proxies of primary productivity in the lake environment, P concentration and the Si to Zr ratio, show peaks at 37.5 cm, low values around 26.5 cm, and increased values between 24 and 12 cm (max. P concentration of ~2,250 ppm and max. Si/Zr of ~5,800) followed by low values (min. P concentration of ~1,070 ppm and max. Si/Zr of ~1850). Trends of the Fe to Mn ratio curve correspond well with Fe concentrations, showing increased values around 27.5 cm and a sharp increase with maxima in the two uppermost layers (shifts from 85 to 133 for Fe/Mn and from ~50,500 to ~137,200 ppm for the Fe concentration). The Fe to Mn ratio, a potential proxy for changes in the near-bottom redox conditions, was therefore determined by fluctuations in the Fe concentration.

A similar magnetic susceptibility and geochemical record was found for the SUZ3 core (**Figure 3**). Nevertheless, it shows two noticeable differences: 1) absence of the magnetic susceptibility peak at the depth of 27.5 cm followed by the Sr/Rb peak at the depth of 26.5 cm, and 2) absence of the magnetic susceptibility, Ti, Fe/Mn, and Fe peaks in the two uppermost layers. Based on this comparison, the SUZ1 core provided more dynamic records and was selected for extraction of iron-rich microspherules and analyses of biological indicator remains.

4.4 Iron-Rich Microspherule Presence

During the SEM observation of the magnetic extract from the Suzdalevo Lake sediment, we found reduced (oxygen content <50%) titanomagnetite (TM) grains in the depth interval of 26–30 cm (**Supplementary Figure S5**). However, their concentration is very low, not exceeding three grains per 1 g of dry sediment. Only one magnetic microspherule larger than 3 μm in diameter was found in the same samples with an original wet volume of 28 cm^3 (14 cm^3 for the two youngest layers). This iron oxide microspherule (10 μm in diameter; Fe 67.6%, O 30.4%, Cr <1%, Cu <1%) was separated from the sample 3–4 cm (~2011 CE). Its outer surface exhibits a distinctive skeletal texture characteristic of rapid melting-quenching processes (**Supplementary Figure S6**).

4.5 Biological Indicators

Altogether, 156 diatom taxa representing 55 genera were identified in the sediment studied. The most abundant taxa include *Staurosira costruens* var. *venter* (Ehrenberg) P. B.

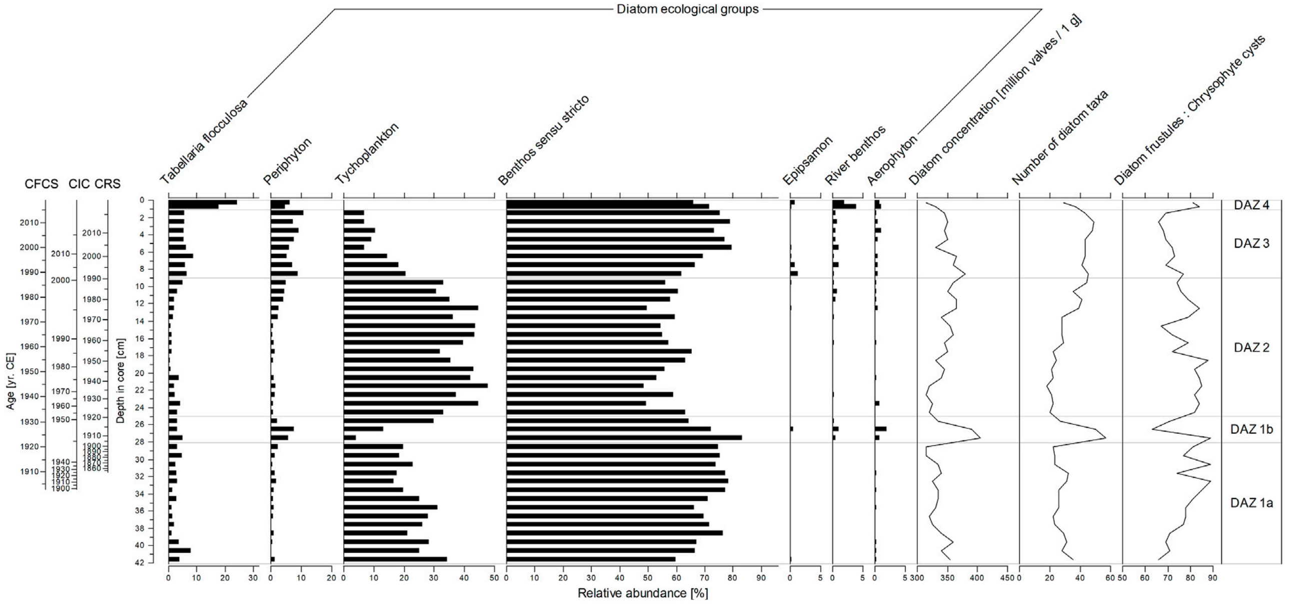

FIGURE 4 | Summary diatom stratigraphy diagram (core SUZ1), showing the proportion of ecological groups, diatom valve concentration and taxonomic diversity, and the D to C ratio. *Tabellaria flocculosa* is listed alone as it can be present in both tychoplankton and periphyton categories. For information about taxa included into particular ecological groups see the Supplementary Material (**Supplementary Figure S7**).

Hamilton, *Aulacoseira laevissima* (Grunow) Krammer, *Pseudostaurosira brevistriata* (Grunow) D. M. Williams and Round, *Aulacoseira alpigena* (Grunow) Krammer, and *Tabellaria flocculosa* (Roth) Kützing (**Supplementary Figure S7**). Most of the taxa belong to benthos sensu stricto, tychoplankton, and periphyton, whereas the epipsamon, river benthos, and aerophyton ecological groups are rare (**Figure 4**). Although *Tabellaria flocculosa* is usually considered to be a planktonic diatom, periphytic forms can be also common. Therefore, we decided to keep this taxon as a separate category.

The diatom record was divided into four significant diatom assemblage zones (DAZ 1–4) based on the relative abundances. DAZ 1 was further divided into two subzones (DAZ 1a, DAZ 1b), because of striking changes in the diatom valve concentration per 1 g and diversity (number of species per 400 valves) at the depth of 28 cm (**Figure 4**).

The average concentration of chironomid head capsules (HCs) is 9.5 HCs per 1 g of dry sediment. While HCs in nine samples are absent, the maximum concentration of HCs in a single sample reaches 131 per 1 g of dry sediment. Altogether 33 chironomid taxa were identified (poorly preserved HCs identified to subfamily level were not counted). The most common components of the chironomid assemblages (at least 5 HCs per 1 g in one sample) are *Chironomus anthracinus*-type, *Cladotanytarsus mancus*-type, *Cricotopus intersectus*-type, *Dicrotendipes nervosus*-type, *Endochironomus impar*-type, *Psectrocladius sordidellus*-type, *Tanytarsus lugens*-type, and *T. mendax*-type (**Supplementary Figure S8**). In addition to chironomids (Diptera: Chironomidae), we also observed head capsules of biting midges (Diptera: Ceratopogonidae); mayfly (Ephemeroptera) mandibles; ephippia (genus *Ceriodaphnia* and *Daphnia*), shells, and head shields (genus *Bosmina*) of planktonic cladocerans; bryozoan statoblasts (*Cristatella mucedo* and genus *Plumatella*); and microturbelarian (Turbellaria: Rhabdocoela) resting-egg capsules (**Figure 5**). However, these other zoological indicators are rather complementary to the chironomid record.

4.5.1 DAZ 1a (42–28 cm)

This (sub)zone is characterized by high abundances of benthic and tychoplanktonic diatom taxa, together with lower diversity and diatom valve concentration values. The zone is further characterized by fluctuation in the relative abundances of tychoplanktonic *A. laevissima* and *Aulacoseira italica* (Ehrenberg) Simonsen. Typical for those lowermost layers are high abundances of benthic colonial Fragilariaceae taxa including *S. construens* var. *venter* and *P. brevistriata*. Notable is the presence of acidophilous *Eunotia* species (*Eunotia glacialis* Meister, *Eunotia tenella* (Grunow) Hustedt or *Eunotia minor* (Kützing) Grunow) and a gradual increase in the D to C ratio. Chironomids, dominated by taxa associated with water macrophytes (e.g., *Dicrotendipes nervosus*-type and *Psecrocladius sordidellus*-type) and lake bottom sediment (*Chironomus anthracinus*-type and *Tanytarsus lugens*-type), reach their highest abundance and highest taxonomic diversity (number of taxa per samples), especially at the depth interval of 39–32 cm, peaking at 35.5 cm (131 HCs per 1 g of dry sediment). On the other hand, outside this depth interval, findings of chironomid HCs are rare (0–4 HCs per 1 g of dry sediment). The same trends were observed in abundances of bryozoan statoblasts and microturbelarian resting-egg capsules. Findings of ceratopogonid HCs and remains of planktonic cladocerans

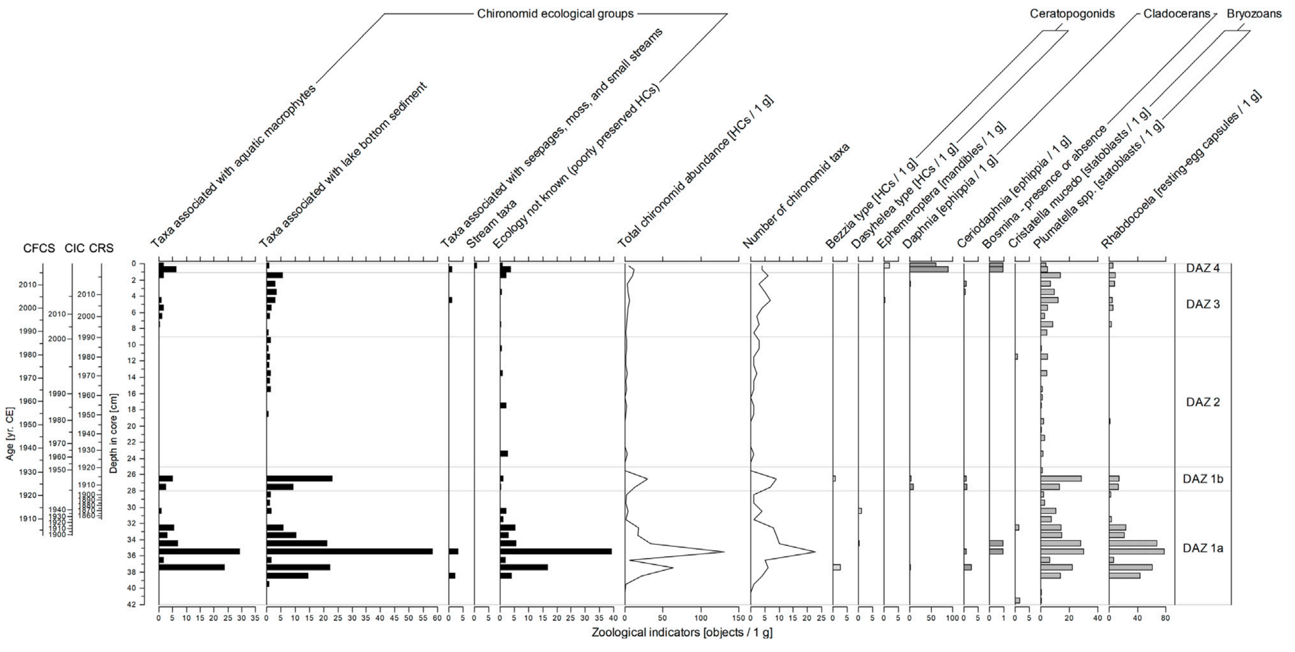

FIGURE 5 | Summary freshwater invertebrate stratigraphy diagram (core SUZ1). For information about taxa included into particular chironomid ecological groups see the Supplementary Material (**Supplementary Figure S8**).

(mainly *Bosmina*) are rare and occur in samples with increased abundances of chironomids.

4.5.2 DAZ 1b (28–25 cm)

The onset of this (sub)zone is characterized by a sharp decrease of tychoplankton, whereas the abundances of benthos, periphyton and aerophyton increase markedly. Furthermore, remarkable changes in the diatom valve concentration and diversity occur in this section, with a significant peak of diversity and valve concentration at 27.5 cm, followed by a peak in chrysophyte cyst concentration (low D:C ratio) at 26.5 cm. The significant increase in periphyton is most apparent in the higher abundances of taxa indicative of greater habitat availability, such as *Cocconeis placentula* Ehrenberg, *Gomphonema parvulum* Kützing, and *Epithemia adnata* (Kützing) Brébisson. This zone is further characterized by the first occurrence of species of the genus *Psammothidium*, typically bound to sand grains (epipsamon), and river benthic taxa. In addition, several aerophilous diatoms, indicative of inwash from the lake catchment, such as *Hantzschia amphioxys* (Ehrenberg) Grunow, *Pinnularia borealis* Ehrenberg, and *Luticola acidoclinata* Lange-Bertalot are present. Chironomid abundance and taxonomic diversity as well as abundances of bryozoan statoblasts and microturbelarian resting-egg capsules reach the second highest peaks in DAZ 1b (up to 30 chironomid HCs per 1 g of dry sediment). The most dominant taxon, *Chironomus anthracinus*-type, is accompanied mainly by other eurytopic taxa living in bottom sediments (e.g., *Cladotanytarsus mancus*-type and *Microtendipes pedellus*-type). *Tanytarsus lugens*-type, an inhabitant of well-oxygenated cold lakes, is not present in the assemblages. Within the planktonic cladocerans, *Bosmina* is replaced by *Daphnia* and *Ceriodaphnia*. In DAZ 1b, we also observed fine plant macroremains (length 1–5 mm) that were more abundant than in the other zones (**Supplementary Figure S9**).

4.5.3 DAZ 2 (25–9 cm)

The relative abundances of tychoplanktonic taxa markedly increase (up to 48%), with a gradual increase of *A. laevissima* from 15 to 33% at the onset of this zone, accompanied by a decrease in benthic taxa, diatom valve concentration, and diversity. Valve concentration and diversity are low at first, then rise gradually till the top of the zone. DAZ 2 is also characteristic by a rise and a subsequent steep decline in abundances of *A. italica*, and by extremely low abundances of chironomids HCs (0–3 HCs per 1 g of dry sediment). Chironomids associated with water macrophytes and remains of planktonic cladocerans disappear. In addition to bottom sediment associated chironomids, only bryozoan statoblasts of the genus *Plumatella* document the continuous presence of benthic invertebrates in DAZ 2.

4.5.4 DAZ 3 (9–1 cm)

A marked decrease in the abundance of diatom tychoplankton occur at the base of this section and benthic *S. construens* var. *venter* become the most dominant taxon. A gradual decrease of tychoplanktonic *A. alpigena* and *A. laevissima* is accompanied by a complete disappearance of *A. italica.* On the other hand, benthos, periphyton, aerophyton, and epipsamon increase, leading to relatively high taxonomic diversity of the assemblages. *Sellaphora saugerressi* (Desmazières) C.E.Wetzel and D.G.Mann, *Pseudostaurosira trainorii* E.A.Morales, *P. brevistriata*, and *Achnanthidium minutissimum* (Kützing)

Czarnecki form minor but characteristic elements of this zone, and the relative abundance of *Tabellaria flocculosa* increase markedly. Water macrophyte chironomids appear again, but total abundances of chironomid HCs increase only slightly (1–10 HCs per 1 g of dry sediment). This increase is more pronounced in bryozoan statoblasts and microturbelarian resting-egg capsules. The dominant chironomid taxa are similar to DAZ 1b—*Chironomus anthracinus*-type, *Dicrotendipes nervosus*-type, and *Microtendipes pedellus*-type; however, several *Tanytarsus lugens*-type specimens were also detected. Findings of *Daphnia* and *Ceriodaphnia* ephippia are rare and situated in the younger half of the zone. *Bosmina* remains are absent.

4.5.5 DAZ 4 (1–0 cm)

A distinct shift in diatom assemblages occur in the two top layers of the core, showing a decrease in valve concentration and diversity with a simultaneous increase in chrysophyte cyst concentrations (high D:C ratio). The most prominent change in this zone is a gradual increase in abundances of *T. flocculosa* and a sudden disappearance of diatom tychoplankton, together with high abundances of river benthic (*Planothidium frequentissimum* (Lange-Bertalot) Lange-Bertalot) and aerophytic taxa (*Microcostatus krasskei* (Hustedt) J. R. Johansen and J. C. Sray, *H. amphioxys*). High abundances of *Aulacoseira* species are replaced by an increase in the abundance of species that inhabit shallow water environments. The benthic diatom *Staurosirella pinnata* (Ehrenberg) D. M. Williams and Round, first occurring in the lowermost layers of the core, suddenly becomes the dominant taxon. Apparent changes were also observed in the zoological indicators. The proportion of water macrophyte chironomids increases due to the first occurrence of *Endochironomus impar*-type in the assemblages, and a single finding of *Eukiefferiella claripennis*-type, a rheophilic taxa, was observed. However, chironomid abundances remain low, similarly to in DAZ 3 (5–12 HCs per 1 g of dry sediment). The taxonomic composition of planktonic cladocerans also changes, with ephippia of the genus *Ceriodaphnia* replaced by *Bosmina* remains and abundant ephippia of g. *Daphnia* (63–92 ephippia per 1 g of dry sediment).

5 DISCUSSION

5.1 The Origin of Suzdalevo Lake in Relation to the Tunguska Event

The cores SUZ1 and SUZ3 were collected at the same location within the Suzdalevo Lake basin and show relatively similar geochemical, magnetic, and short-lived isotope activity records (**Figure 3**, **Supplementary Figure S3**). Due to this similarity, although partial differences are apparent, we used the ^{210}Pb dating of the SUZ3 core for interpretation of SUZ1 proxy data. In both cores, the observed peaks in ^{137}Cs (onset of the peaks at the depth of ~16 cm; **Figure 2**, **Supplementary Figure S4**) were interpreted as signals of the global fallout from atmospheric nuclear weapons with the ^{137}Cs maximum in 1963 CE (e.g., Appleby 2008; Bruel and Sabatier 2020), including the tests carried out by the Soviet Union at Novaya Zemlya from 1957 to 1962 (Khalturin et al., 2004), which is in good agreement with the results of the CRS age-depth model (1958–1963 CE at the depth of 16 cm) for the SUZ3 core. This model is likely the most relevant one for dating of the younger half of the sedimentary record as it reflects well sediment compaction in middle parts of the cores. The signal of the Chernobyl accident in 1986, that was reported from many regions of the Northern Hemisphere, is not known from lake sediments investigated in the area of the TE (Rogozin et al., 2017; Darin et al., 2020). However, the maximum ^{137}Cs peaks in Suzdalevo Lake cores are not very prominent. In SUZ1, low ^{137}Cs activities were detectable also below the depth of 16 cm, likely due to partial mixing and/or remobilization and downward diffusion within the sediments (Matisoff 2017). Despite the fact that the "no sediment mixing" assumption for construction of the ^{210}Pb-based age-depth models is not fully met, all three models (CRS, CIC, CFCS) show that the base samples of the studied sediment cores are older than 1908 CE (**Figure 2**, **Supplementary Table S2**). Since even the oldest layers contain valves of lake diatoms and remains of lake invertebrates, sedimentation in a lake environment is apparent throughout the whole record (**Figures 4**, **5**). Moreover, the diatom and zoological indicator assemblages below the first layer with no $^{210}Pb_{ex}$ activity (>36 cm, calculated ages >1908 CE) are not uniform (**Figures 4**, **5**, **Supplementary Figures S7, S8**) which contradicts potential very high accumulation rate in a lake formed by the TE. Therefore, Suzdalevo Lake was evidently formed before the TE. Due to the nature of the studied material (short cores sampled by a gravity corer) it is not possible to determine the time or the process of lake formation. It can only be speculated that it may have been associated with the selective melting of permafrost that is still present in the region (Gasperini et al., 2007; Ponomarev et al., 2019). Despite the oral testimony of the Evenki people, Suzdalevo Lake is not a TE impact crater filled with water, as has been proposed for the basin of Cheko Lake (Collins et al., 2008; Rogozin et al., 2017). Note that this conclusion is supported by the depth to diameter ratio being lower than 1/100 (**Figure 1C** and **Supplementary Figure S2**), while typical simple impact craters have values between 1/5 and 1/7 (Melosh 1989; Włodarski et al., 2017).

On the other hand, the existence of the lake before the TE is not supported by identification of a specific "TE layer". No distinct clayey TE layer was observed, in contrast to those documented in the sediments of Cheko Lake and Zapovednoe Lake (thickness from 2 to 8 mm) by Kletetschka et al. (2019a) and Darin et al. (2020), respectively (**Supplementary Figure S10**). This is probably due to the fact that Zapovednoe and Cheko lakes are deep riverine lakes with large catchments, while Suzdalevo is a small shallow water body separated from the Chamba River (**Figure 1C**, **Supplementary Figures S1, S2**). Sediments of riverine lakes and lakes with large tributaries are often very sensitive to erosion in a wider area compared to lakes with small catchments (e.g., Xu et al., 2010; Wilhelm et al., 2017). The most conspicuous, but not strong, clastic material input event in Suzdalevo Lake occurred in DAZ 4, based on the simultaneously increased values of mass normalized magnetic susceptibility, the Sr to Rb ratio, and Ti concentration in the SUZ1 core (Rapuc et al., 2020). However, DAZ 4 represents the youngest part of the sedimentary record and no similar erosion signal was found in the SUZ3 core. Another evidence of disturbance to the lake catchment was observed between the depths 25 and 28 cm (DAZ 1b), i.e., 14 cm above the base of the SUZ1 core (**Figure 3**). The DAZ 1b (SUZ1 core) contains abundant fine plant remains (**Supplementary Figure S9**), and its onset is characterized by increases in mass normalized magnetic susceptibility and the Sr to Rb ratio. The mass normalized magnetic susceptibility values reflect the concentration of potential magnetic carriers in the sediment (magnetite, pyrrhotite, maghemite, titanomagnetite, titanomaghemite, greigite); therefore, their enhancement in DAZ 1b reflects the presence of higher concentrations of at least one of these carriers. Since the area was exposed to fires due to the explosion and extreme radiation from the sky (Svetsov 2002; Jenniskens et al., 2019; Johnston and Stern 2019), the burning of organic material (e.g., grass, herbs, tree leaves and branches) has been associated with the conversion of iron-bearing organic matter to magnetite (Kletetschka and Banerjee 1995). The increase in the Sr to Rb ratio also reflects the higher content of plant remains in the sediment samples rather than a decline in terrigenous clastic input (Xu et al., 2010). This is supported by the relatively stable Ti concentration values, indicating no distinct change in the proportion or grain size of clastic material (Cuven et al., 2010). The above mentioned geochemical and magnetic anomalies in DAZ 1b were, however, observed only in the SUZ1 core (**Figure 3**). The absence of similar shifts in the core SUZ3 implies variability of the disturbance signal strength within the lake basin. The DAZ 1b onset at the depth of 28 cm is in agreement with the CRS-model-calculated depth for 1908 CE (27.75 cm), however, this "TE-depth" is placed ca. 5 and 4.3 cm deeper according to the CIC and CFCS models, respectively. It is important to notice that the time of the TE (i.e., 111 years before the sediment coring) is close to the limit of the ^{210}Pb dating method and the related models' applicability. Moreover, when the CRS model is applied, a "too-old" age error is always present for the deeper core layers due to underestimation of $^{210}Pb_{ex}$ (Binford 1990).

We found no increase in concentration of melted magnetic microspherules in layers of potential TE age. Possible existence of a layer containing these objects would have been used for validating the age-depth models. The lack of melted magnetic microspherules in the SUZ1 sediments means that the TE explosion produced less than 354 magnetic microspherules per 1 m^2, assuming the diameter of our gravity corer. This agrees with the known maximum concentration of these objects near the TE epicenter (90 magnetic microspherules per 1 m^2, when objects with diameter from 10 to several hundred μm were counted) as reported by Badyukov et al. (2011). They studied material collected in the early 1960s by an expedition led by K. P. Florenskii, and distinguished magnetic iron-oxide microspherules and magnetic silicate microspherules with metallic droplets, both subdivided based on the presence/absence of a Ni admixture. The single microspherule we found in the SUZ1 core (**Supplementary Figure S6**) corresponds to the category of iron-rich spherules without a Ni admixture that was, according to Badyukov et al. (2011), likely created by a high-temperature process from terrestrial rocks (i.e., melted and evaporated due to sudden heat pulse, and later nucleated and/or quenched due to subsequent cooling). The same type of microspherules can be, however, of anthropogenic origin and transported for long distances if sufficiently small (<150 μm in diameter) (Zhang et al., 2011). The maximum calculated age of the extracted microspherule of 2003 CE (CFCS model, depth of 4 cm; **Supplementary Table S2**) indicates that it likely originated from the background micrometeorite flux, redeposition of an older TE sediment or soil, or anthropogenic activities. It seems that, due to their low concentration, these objects (diameter >3 μm) cannot be effectively used as markers of the TE in lake sediment cores from the Tunguska region. Also, the somewhat reduced TM grains that were found at depths of 30–26 cm (**Supplementary Figure S5**) cannot be interpreted as clear evidence of the TE explosion. The concentration of these grains is low (<3 grains per 1 g of dry sediment) and could have originated from the erosion of local volcanic rocks (Kamo et al., 2003). Such erosion in the lake catchment and subsequent inwash of the TM grains to the lake depocenter could have rather been associated with the TE-related forest disturbance. In future studies focused on lake sediments in the Tunguska region, the detection of increased concentrations of Ir and other Pt group elements may be more promising as follows from the "Northern" peat bog record presented by Hou et al. (2004).

5.2 Lake Ecosystem Changes at the Time of the Tunguska Event

In this study, we present the first diatom and freshwater zoological indicator records from the area exposed to the TE explosion in 1908 CE (**Figures 4**, **5**). Throughout its recent history, Suzdalevo Lake lacked a significant planktonic diatom community and was dominated by tychoplanktonic *Aulacoseira* species together with small benthic alkaliphilic species of the Fragilariaceae family, commonly found in nutrient limited lakes with long periods of ice cover in alpine (Lotter et al., 1997; Karst-Riddoch et al., 2005), arctic (Douglas and Smol 1999; Laing and Smol 2000), and tundra regions (Westover et al., 2006). Similarly, the remains of planktonic cladocerans are rare in the sediments, demonstrating a greater suitability of the shallow lake habitats for benthic and littoral taxa (Szeroczyńska and Sarmaja-Korjonen 2007). This is supported by frequent findings of various benthic zoological indicators, such as chironomids, ceratopogonids, mayflies, bryozoans, or microturbelarians. All invertebrate taxa that were identified are known from the lakes in southern Siberia (42–65°N) or have a Holarctic distribution (e.g., Massard and Geimer 2008; Nazarova et al., 2008; Kotov 2016; Biskaborn et al., 2019).

According to the alternative age-depth models (**Figure 2**, **Supplementary Table S2**), the "TE-layer" and related signals of ecosystem changes should be located in DAZ 1a around the depth interval of 32–33 cm (CIC and CFCS models) or at the DAZ 1a/DAZ 1b transition, i.e., near the depth of 28 cm (CRS model). The first scenario is more likely in the case of the underestimation sediment accumulation rate in deeper layers mentioned by Binford (1990), however, the second scenario is also realistic when considering the error bars and thickness of the sediment layers used for the dating (4 cm). Moreover, only the second scenario corresponds to a distinct abrupt shift in lake biota (**Figures 4**, **5**). The reality of the first scenario would imply an absence of a unique signal in the diatom and zoological indicator records. Such a conclusion would, for example, be consistent to the observations from sediments of Lake Strzeszyńskie (W Poland) that experienced the Morasko iron meteorite shower 4.9–5.3 kyr.cal. BP (Pleskot et al., 2018). The estimated entry mass of the Morasko meteoroid was between 600 and 1,100 tons and fragments of this cosmic body formed seven impact craters with diameters ranging from 20 to 90 m (Bronikowska et al., 2017).

If the age of the DAZ 1b onset is ~1908 CE as suggested by the CRS model, the pre-TE status of Suzdalevo Lake is represented by the bottom zone (DAZ 1a) that is dominated by benthic colonial Fragilariaceae taxa (**Figure 4**, **Supplementary Figure S7**). These ecological generalists are common in lakes at high elevations and high latitudes, where ice-free intervals are short and nutrient supplies are low, although they also occur across a wide ecological gradient (Wolfe 2003). Furthermore, they inhabit the littoral zone, which is the first area to become ice-free (Westover et al., 2006). Thus, these taxa may quickly form blooms and outcompete larger diatoms during the short growing season (Smol 1988; Lotter et al., 1999; Grönlund and Kaupilla 2002). Fluctuations in abundances of all benthic zoological indicators (**Figure 5** and **Supplementary Figure S8**) imply the alternating presence of at least one adverse factor. Such severe suppression of benthic fauna in lakes is often caused by oxygen depletion (hypoxia) or even anoxia (e.g., Moravcová et al., 2021). Also, the presence of *Ceriodaphnia* ephippia and *Plumatella* and *Cristatella mucedo* statoblasts indicates limiting near-bottom oxygen concentrations caused by the intensive decomposition of organic matter accompanied by pronounced thermal stratification, limiting oxygen replenishment (Ursenbacher et al., 2020). However, the stratification and oxygen depletion were not permanent, as documented by the high abundance and high taxonomic diversity of chironomid HCs at depths from 39 to 32 cm, where both taxa that are tolerant (e.g., *Chironomus anthracinus*-type) and sensitive (*Tanytarsus lugens*-type) to low oxygen concentrations (Brooks et al., 2007; Tichá et al., 2019) were observed. Short periods of more intense water column mixing (affecting the sediment-water interface) could have occurred during the recent lake history as suggested by detectable low ^{137}Cs activities bellow the depth of 16 cm in both cores (**Figure 2**, **Supplementary Figure S3**), but such short-term changes cannot be reconstructed due to the time resolution of our records. The hypothesized changes in the mixing regime during DAZ 1a were likely triggered by an external factor, such as a climate change or a forest disturbance. A potential impact of floods is not supported by any erosion proxies (**Figure 3**) or presence of taxa indicative of running water environment (**Figures 4**, **5**). Therefore, if a flood occurred, it did not have an erosive effect on the lake shore. Another possible explanation comes from the alternative age-depth models. If the "TE-depth" calculation using CIC and CFCS models is more realistic then in the case of the CRS model, an effect of the TE explosion cannot be ruled out as well.

As mentioned above, the assemblages in DAZ 1b could represent a direct response of the lake-catchment ecosystem to the TE (**Figures 4**, **5**). In diatoms, the occurrence of aerophyton indicates the influence of the substantial transport of terrestrial material from the lake catchment, whereas the high abundances of periphyton and benthos suggest greater substrate variability. These changes therefore correspond to the observed increase in the amount of fine plant remains and the peak in mass normalized magnetic susceptibility (SUZ1 core), documenting a disturbance of the surrounding taiga. Diatom assemblages are known to also be structured by organic matter content and/or availability (Grimes et al., 1980), which significantly increased during this period. The diversified conditions, together with the input of organic matter, most probably led to increased diatom diversity and valve concentration (Adrian et al., 1999). Our data do not imply any conditions promoting the growth of acidophilous taxa, possibly connected with acidification or acid rains, as previously suggested by Kolesnikov et al. (1998). This also applies to the diatom assemblages in DAZ 1a. However, the peak in diatom valve concentration in DAZ 1b could have been supported by mild eutrophication after the increased deposition of nitrogen (N), estimated by Kolesnikov et al. (2003) to 200,000 tons across the 2,000 km^2 of tree fall area. This extra N supply was interpreted as a result of the high-temperature oxidation of nitrogen in the atmosphere with formation of nitrogen oxides during the impact (Kolesnikov et al., 1998, 2003); however, it could also have arisen from another unconventional process. Boslough and Crawford (2008) modelled the TE explosion in the atmosphere and calculated an overpressure reaching 1 GPa at 6–8 km above the Earth's surface. Such a pressure wave allows the compression of N in air to reach near the liquid phase (Alkhaldi and Kroll 2019), and thus may have allowed the oxidation and creation of N species over the impacted area. The deposition value published by Kolesnikov et al. (2003) (1 ton per 1 ha) may be overestimated or apply only to sites located close the TE epicenter (distance <10 km); however, even a smaller deposition could have affected Suzdalevo Lake, as by shown by Bergström and Jansson (2006). Moreover, an input of P-rich dust after the TE explosion-related thermal radiation and shockwave could be expected, transporting this key limiting nutrient to the studied lake and its catchment. No increase in P concentration was observed in the studied cores near the DAZ 1b onset or around the depth interval 32–32.84 cm (**Figure 3**), but trends in total P concentration sometimes differ from trends in biologically available P as shown by Norton et al. (2011). The taxonomic diversity and abundance of zoological indicators increase in DAZ 1b, with the dominance of *Chironomus anthracinus*-type and the absence of *Tanytarsus lugens*-type (**Supplementary Figure S8**) suggesting an improvement in near-bottom oxygen conditions but to a lesser extent than in the case of the period around the chironomid abundance and diversity peak at 35.5 cm (Johnson and Wiederholm 1989; Gąsiorowski and Sienkiewicz 2010). The potential destruction of the shoreline forest by the TE explosion could have caused increased wind speeds and shortened the periods of thermal stratification *via* wind mixing of the water column, resulting in improved dissolved oxygen concentrations (Klaus et al., 2021). On the other hand, the concurrent inwash of organic material could have accelerated respiration and oxygen consumption rates, which had the opposite effect and prevented the reappearance of the sensitive *Tanytarsus lugens*-type (Luoto 2013). In any case, the observed changes in DAZ 1b do not indicate any major disturbance or lake ecosystem collapse.

After the DAZ 1b, the ecosystem did not return to the pre-TE state. A new equilibrium, represented by DAZ 2, was established, and lasted until the 1990s (i.e., ca. 50–70 years) (**Figure 4**). We interpret this zone as a period of low water transparency and pronounced oxygen depletion, indicated by the substantial increase in the tychoplanktonic diatom taxa and extremely low abundances of all benthic zoological indicators, respectively. We assume that both processes were driven by the presence of additional dead plant biomass in the catchment after the TE. This led to a subsequent increase in dissolved organic carbon (DOC) production, and later to DOC leaching, DOC transport to the lake, and lake water brownification (Kopáček et al., 2018). The DOC leaching may have been amplified by reduced evapotranspiration in the disturbed forest, leading to increased soil moisture (Brothers et al., 2014; Kopáček et al., 2018). Brownification is a fundamental factor influencing lake ecosystem structure and function through more stable thermal stratification caused by increased absorption of solar radiation and limited light availability to benthic primary producers due to decreased water column transparency (Brothers et al., 2014; Solomon et al., 2015; Vasconcelos et al., 2016). These conditions likely caused the decline in benthic diatoms and especially in all benthic invertebrates, such as chironomids, ceratopogonids, bryozoans, and microturbelarians (**Figures 4**, **5**). The chironomid abundances are so low in DAZ 2 (0–3 HCs per 1 g of dry sediment) that even episodic near-bottom anoxic conditions at the deepest part in the lake cannot be ruled out (Johnson and Wiederholm 1989; Houfková et al., 2017; Ursenbacher et al., 2020). These conditions would have supported *Aulacoseira* species (**Supplementary Figure S7**), which are adapted to low light availability (Kilham 1990; Bradbury et al., 1994), but most of them also indicate turbulent, unstable environments, likely caused by mixing of the water column. Such ecological characteristics are related to the production of heavy resting cells during the *Aulacoseira* life cycle that requires resuspension from the sediments into the lake water to establish (tycho)planktonic populations (Round et al., 1990). In addition, *Aulacoseira* species also create heavy silicified vegetative cells and therefore require an increased degree of turbulence to prevent their sedimentation (Saunders et al., 2009; Buczkó et al., 2013). In view of these facts, the stratification could not be long-term, but occurred frequently enough to disadvantage the benthic fauna. A similar record showing a long-term *Aulacoseira* presence in a shallow lake affected by anoxia was published by Houfková et al. (2017). We can speculate that a severe winter stratification due to long ice cover period was the key factor that suppressed the benthic invertebrates but enabled a summer bloom of *Aulacoseira*.

While the highest diatom valve concentration per 1 g of dry sediment was observed in DAZ 1b, the highest P concentrations and the highest values of the Si to Zr ratio, the other two potential proxies for algal primary production (e.g., Cuven et al., 2011), were observed in DAZ 2 (**Figure 3**). We explain this discrepancy by the above-mentioned presence of large and heavy silicified *Aulacoseira* valves in DAZ 2, which could have increased the total diatom biomass and the concentration of biogenic silica (i.e., the Si to Zr ratio) in the sediment samples. Alternatively, the increased P content in DAZ 2 could be explained by an increase in P immobilization in the sediments caused by a higher aluminum hydroxide to iron hydroxide ratio in highly organic sediments during the brownwater phase, as shown by Kopáček et al. (2007). In the latter case, P concentration values would not reflect the availability of this limiting nutrient for aquatic organisms.

Since about the 1990s (DAZ 3), the lake biota in Suzdalevo Lake began to resemble those of the DAZ 1a (**Figures 4**, **5**). The overall dominance of benthic diatoms (around 70% of the total diatom assemblage) may be attributed to processes linked to increased water transparency and with more stable conditions after recovery of the taiga forest, when DOC concentration in the lake water decreased and mature trees on the lake shore started to attenuate water mixing by wind (Kilham, 1990; Westover et al., 2006). The higher diatom diversity could be explained by the decreased dominance of *Aulacoseira* taxa, leading to more even diatom communities. These new conditions were also more favorable for benthic invertebrates, including taxa associated with aquatic macrophytes, that were absent in DAZ 2.

We also attempted to document changes in oxygen availability and related redox conditions in the sedimentary record using the Fe to Mn ratio (**Figure 3**). This proxy is based on the fact that Mn is more easily mobilized and passes into solution more readily than Fe under reducing conditions (Davison, 1993). However, in Suzdalevo Lake, trends in the Fe to Mn ratio coincide with the Fe concentrations, indicating that the ratio was mainly affected by changes in Fe supply from the lake catchment (Mackereth 1966), and thus could not be used to reconstruct changes in redox conditions.

5.3 Recent Environmental Changes in the Suzdalevo Lake Sedimentary Record

The SUZ1 core provided an anomalous multi-proxy record for the uppermost two layers (DAZ 4), representing approximately the years 2016–2019 CE. In spite of the absence of these anomalies in the SUZ3 core that indicates variability of the signal strength within the lake basin or partial loss of the surface layer during the coring, the shifts observed in most of the proxies in the SUZ1 core are conspicuous and deserve a separate comment (**Figure 3**). The low Sr to Rb ratio and the sharp increase in Ti concentrations in DAZ 4 document an increased input of clastic material (Cuven et al., 2010; Xu et al., 2010), which was not observed in the other zones, including the depth interval where “TE-depth” is expected according to the age-depth models. Such a change in the proportion of inorganic particles could have been caused by increased erosion in the catchment or by flood activity of the nearby Chamba River (**Supplementary Figure S1**). Also, river benthic diatom taxa, such as *P. frequentissimum* (**Figure 4**, **Supplementary Figure S7**), reach their maximum abundance in DAZ 4, indicating a possible riverine influx and, together with higher abundances of aerophyton, may reflect the increased input of allochthonous material. In addition, the low diatom diversity and valve concentration and the dominance of *S. pinnata* and *T. flocculosa* suggest the persistence of relatively unproductive conditions throughout this period (Dam et al., 1994; Hofmann et al., 2011).

The same zone is characterized by the presence of abundant remains of two planktonic cladocerans, *Daphnia* and *Bosmina*, while the abundances of the benthic zoological indicators remain rather low (**Figure 5**). Among these benthic invertebrates, the only exception is the slight increase in chironomids associated with aquatic macrophytes and the solitary finding of the rheophilic chironomid *Eukiefferiella claripennis*-type (Brooks et al., 2007) (**Supplementary Figure S8**). Thus, the zoological record also suggests the influence of an external factor that changed conditions in the lake. DOC concentrations in boreal streams are often the lowest after high discharge events arising from snowmelt (e.g., Jonsson et al., 2007). If the factor responsible for the observed changes in lake biota was a snowmelt flood (or several floods during the period 2016–2019 CE) on the Chamba River, a drop in DOC accompanied with an increase in water transparency, along with other changes in water chemistry, could have occurred in Suzdalevo Lake. Such a shift would, for example, support the growth of aquatic plants and increase the abundances of the associated chironomid taxa (**Figure 5**). Due to the presence of *Bosmina*, a cladoceran well adapted to fish predation, short-time colonization of the lake by fish after a flood event cannot be ruled out either (Johnsen and Raddum 1987); however, we did not observe any fish during our field survey.

We do not have data on floods on the Chamba River and we do not know of any observations of changes in the connectivity between Suzdalevo Lake and the river, as the site is very remote. Nevertheless, based on available data from the nearest meteorological station in Vanavara (Weather and Climate 2021), severe floods caused by rapid snowmelt or an ice jam near the study site could have occurred during the given period. At this station, the average annual temperature and precipitation between the years 1933 and 2020 were -5.5°C and 421 mm, respectively, while between the years 2016 and 2019 the average annual temperature increased to −4.1°C and average annual precipitation increased to 625 mm. This change in the local climate would have been favorable for stronger snowmelt floods and corresponds to trends observed in the wider area of Central Siberia (e.g., Tchebakova et al., 2011).

6 CONCLUSION

The TE in 1908 CE was an unusual extreme event that became part of the Evenki oral heritage. We performed this study to assess the potential for a TE-related origin of Suzdalevo Lake, a shallow water body located in the TE tree fall area, and to understand the effects of the catastrophic explosion on the lake-catchment ecosystem. Our data show that the lake basin did not originate from the impact, but lake sediments from the site provide a multi-proxy record of a disturbance that occurred within a 5-cm-thick depth interval calculated using three alternative age-depth models for the position of the year 1908 CE. However, a clear link between this disturbance and the TE was not proven as the Suzdalevo Lake sediments do not contain an erosional clayey TE-layer, that was observed in the Zapovednoe and Cheko riverine lakes, or any melted magnetic microspherules produced by the TE explosion. We interpret the observed abrupt changes in the proxy records as the consequences of the inwash of dead plant biomass to the lake, increased wind mixing of the water column possibly caused by deforestation of the shoreline, and mild eutrophication by elevated nutrient input. After the phase of higher productivity (i.e., increased concentrations and taxonomic diversity of diatom valves and zoological indicator remains), the lake did not return to its original state for about 50–70 years, likely due to the increased DOC supply from its catchment and associated truncation of the photic zone and near-bottom hypoxia. Such changes in a lake environment that may be related to the TE are reported here for the first time, however, more lakes in the TE tree fall area should be studied to reveal the real impact of the TE on ecosystems.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in the **Supplementary Material** and the PANGAEA online repository. The accession link can be found in the **Supplementary Material**.

AUTHOR CONTRIBUTIONS

DV, RK and GK designed the research. RK, GK, MT and CS organized and performed the coring and morphobathymetric measurements. RK, DV, VG, ES, BC and RŠ performed the lab research. RK, DV, BC, VG, CS and GK analyzed the data. DV, RK, BC, and GK wrote the paper with final contributions from ES, MT, VG, RŠ and CS.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.777631/full#supplementary-material

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Extreme events in biological, societal, and earth sciences: A systematic review of the literature

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The term "extreme event" is commonly used to describe high-impact, unanticipated natural events, like floods, tsunamis, earthquakes, and volcanic eruptions. It first appeared in the scientific literature in the 1950s and has since spread to disciplines as diverse as economics, psychology, medicine, and engineering. The term is increasingly being applied to the study of historical, prehistorical, and deep-time events across a broad range of scales, and it is widely acknowledged that such events have had profound impacts on the Earth's biodiversity and cultures. Understandably, then, how people think about, define, and study extreme events varies considerably. With extreme events expected to become more frequent, longer lasting, and more intense in the coming decades as a result of global warming, the differing extreme event definitions—both across and within disciplines—is likely to lead to confusion among researchers and pose significant challenges for predicting and preparing for extreme events and their impacts on natural and social systems. With this in mind, we conducted a systematic quantitative review of 200 randomly selected, peer-reviewed "extreme event" research papers (sourced from Web of Science, accessed January 2020) from the biological, societal, and earth sciences literature with the aim of quantifying several pertinent features of the research sample. On the one hand, our analysis found a great deal of variability among extreme event papers with respect to research interests, themes, concepts, and definitions. On the other hand, we found a number of key similarities in how researchers think about and study extreme events. One similarity we encountered was that researchers tend to view extreme events within a particular temporal context and quite often in terms of rates of change. Another similarity we encountered was that researchers often think of and study extreme events in terms of risks, vulnerabilities, and impacts. The similarities identified here may be useful in developing a common and comprehensive definition of what constitutes an extreme event, and should allow for more comparative research into extreme events at all spatio-temporal scales which, we predict, will provide important new insights into the nature of extreme events.

KEYWORDS

climate change, natural hazard, human health, prehistory, vulnerability, risk, resilience, abrupt

Introduction

Extreme events are expected to become more frequent, longer lasting, and more intense through the 21st century as a result of human-induced climate change (IPCC 2021). These changes will almost certainly have devastating societal, environmental, and economic consequences. Already we are witnessing an uptick in the number of extreme heat and precipitation events as a result of climate change (IPCC 2021). Take for instance the 2003 European heat wave. This record-breaking event put a tremendous strain on health, resource, and energy systems. The loss to the agricultural sector was estimated at around €13 billion (IPCC 2021) and the event claimed upwards of 30,000 lives (Kosatsky, 2005). Data suggest that human-induced climate change contributed significantly to the 2003 European summer warming (Stott et al., 2004), and climate model simulations suggest that late 21st century summers may see average temperatures that resemble the extreme temperatures of this devastating heat wave (Beniston, 2004). These expectations have put extreme events and extreme event attribution at the center of a growing body of scientific research and spotlighted them with respect to planning and policy (Kraas, 2008; IPCC 2021).

Human populations are also experiencing changes in their risk, vulnerability, and exposure to extreme events due to non-climatic factors (for definitions of key terms *see* Table 1). For instance, urbanization and population growth concentrate people and activities into small areas, increasing vulnerability and exposure of people and populations to extreme events (Kraas, 2008; IPCC 2021). Moreover, human activities such as "soil sealing" and extensive cover of urban areas with impermeable materials increases flood risks (e.g., Pistocchi et al., 2015). There are also other societal changes such as rapidly aging populations in developed nations (e.g., Li et al., 2016). Variables such as these, all of which may be overlapping and compounding, make clarifying the meaning and character of extreme events a pertinent research topic (e.g., McPhillips et al., 2018; Broska et al., 2020).

Analyzing extreme events and planning for them, however, is challenging because events considered "extreme" can be decidedly different (Albeverio et al., 2006). Environmental hazards, for instance, can include extreme events like volcanic eruptions, earthquakes, asteroid impacts, heat waves, floods, and firestorms. Economic events can also be considered extreme, like recession, depression, and investment bubbles (e.g., Longin, 2000; Pagan and Sossounov, 2003). Events of a more sociological character, like crime waves, riots, demonstrations, and mass migration can be extreme, and so can political events like regime changes, state failure, acts of terrorism, and warfare (e.g., Comfort, 2002; Andrade et al., 2019). Finally, medical and epidemiological events can justifiably be called extreme as well, with examples like seizures, cardiac events, historical plagues, and the ongoing COVID-19 crisis (e.g., Lehnertz, 2006; Wang and Su, 2020). The variety of events that can and have been labelled "extreme" is surprisingly vast, making it hard to see the forest for the trees.

Even among events of a kind, there can be important differences. Flooding, for example, is an event commonly labelled "extreme," but floods can differ dramatically despite the fact that they all involve relatively large increases in the volume of water. In the summer of 2021, 15 cm of rain fell over parts of Germany and Belgium in as little as 24 h, leading to at least 196 deaths and millions of Euros in immediate damage to property and infrastructure. Compare that relatively localized extreme event with the expected scale and extent of global coastal flooding caused by sea level rise over the next century (e.g., Goddard et al., 2015; Frederikse et al., 2020). Scientists expect mean sea level to rise by as much as 2.5 m by 2100 with as many

TABLE 1 Some definitions of terms commonly used in extreme events literature as provided in the IPCC (2022).

Term	Definition
Vulnerability	"the propensity or predisposition to be adversely affected"
Risk	"the potential for adverse consequences for human or ecological systems, recognizing the diversity of values and objectives associated with such systems"
Exposure	"the presence of people, livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affects."
Hazard	"the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss of property, infrastructure, livelihoods, service provision, ecosystems and environmental resources."
Adaptation	In human systems, as "the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities." In natural systems, as "the process of adjustment to actual climate and its effects; human intervention may facilitate this."
Resilience	"the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation."

as 1.4 billion people directly affected by increasingly severe storm surges, flooding, saltwater intrusion, and coastal erosion. The economic costs could be astronomical and there will almost certainly be a grim human toll. These two extreme events are related by the involvement of climate change and flood water, but they are in many ways very different from each other in terms of causal chains, scale, time horizons, and the magnitude of costs, both economic and human.

Crucially, differences in temporal scale occur as well, and these have not been adequately discussed in the literature as far as we are aware. The timescales over which extreme events are thought to occur can sit at opposite ends of a long continuum. At one end are events occurring over seconds to minutes, like epileptic seizures within the brain (Lehnertz, 2006). At the other end, events may unfold over millennia or even millions of years, with classic examples being the "big five" mass extinction events (Raup and Sepkoski, 1982). These timescale differences highlight an understudied aspect of extreme events, namely the degree to which they are "event-like." English speakers usually only refer to an occurrence as an "event" if it (whatever is observed) is bounded in time and of some significance (Collins English Dictionary, 2018)—events have to be temporally discrete in some way in order for the label to make much sense in contrast to a common state of affairs or general condition. They also tend to recur—floods and heatwaves, for instance, happen every year somewhere in the world. Consequently, an event considered extreme when viewed on one timescale may be humdrum when viewed on another. Take for example the greatest mass extinction event, the end-Permian Extinction. Around 252 million years ago, ~60% of all biological families went extinct (Benton, 1995), an event sometimes called "The Great Dying." It was extreme by any sensible standard, but it occurred over a period of roughly 200,000 years. So, while all events have to be temporally bounded in order to be an "event" (in contrast to some standing reference condition), the ones we know about tend to only *appear* bounded at some temporal scales while being continuous at others.

Furthermore, scientists studying extreme events do so from perspectives that differ in important ways. In a recent review, McPhillips et al. (2018, pp. 443–445) state that climate scientists are primarily concerned with "mapping, characterizing, and modeling [natural] hazards," whereas social scientists are mostly concerned with understanding the "underlying social conditions that influence and/or are influenced by extreme events." These different motivations and natural/physical domains of interest give rise to different conceptions of what an "event" is and what makes one "extreme." They also lead researchers to emphasize different aspects of events and their effects. Some, for instance, emphasize "vulnerability" as a core component of extreme event research. As Brooks (2003) notes, social scientists typically think of vulnerability in terms of the "set of socio-economic factors that determine people's ability to cope with stress or change," whereas climate scientists tend to view vulnerability as the "likelihood of occurrence and impacts of weather and climate related events." These differences in terms of research interest and natural/physical domains make one wonder whether scholars from these separate fields are studying specific subtypes of a more general phenomena (i.e., extreme events) or phenomena that are altogether different.

Differences regarding research perspectives have led to a variety of conceptual and operational definitions for extreme events. Again, according to McPhillips et al. (2018), a variety of concepts related to extreme events have been used in the academic literature and, importantly, that different fields of research seem to employ different terms. They found, for instance, that "disturbance" was most common in ecological research, "hazard" more common in the Earth sciences, and "disaster" was most common in the social sciences. While it is easy to see how these terms are related to "extreme events" more broadly, they are not exact synonyms. Each term emphasizes a different perspective of extreme events and implies a slightly different conceptual definition—e.g., a given event may be "extreme" to a social scientist only if it results in a "disaster." McPhillips et al. also found distinctly different operational definitions—that is, definitions that determine how events are identified and measured. In some cases, events were identified by exceedances of absolute thresholds, while in other cases researchers determined a given event was extreme because it was considered statistically unlikely within a set of observations. The definitions identified by McPhillips' et al. were so variable that no normative definition(s) could be identified even within a given academic discipline.

Another key difference relates to whether extreme events should be defined by their impacts (realized or projected) or not. Sarewitz and Piekle (2001), for example, define extreme events as "an occurrence that, with respect to some class of occurrences, is either notable, rare, unique, profound, or otherwise significant in terms of its impacts, effects or outcomes." Similarly, from an ecological sciences perspective, Smith (2011, p. 656) defines extreme climatic events as "an episode or occurrence in which a statistically rare or unusual climatic period alters ecosystem structure and/or function well outside the bounds of what is considered typical or normal variability." In both these definitions, the impact (or response) is integral to the definition of extreme event. In other words, if a system's response falls within its natural range of variability—regardless of the natural properties of the event itself—then the system has not experienced an extreme event. In direct contrast to these definitions, McPhillips and others (2018) call for the separation of events and impacts when defining extreme events. Essentially, the authors argue that if the motivation for studying extreme events is ultimately to lessen their impacts, then it is important to distinguish between events on the one hand, and impacts on the other, so that successful management and mitigation strategies can be properly recognized and developed.

Based on these conflicting definitions, it is easy to see how an event could be classified as extreme or not depending on which definition one subscribes. Take for instance the Canterbury earthquake that struck the South Island of New Zealand in 2010. Despite having a magnitude of 7.1—and therefore being classified as "extreme" on the modified Mercalli intensity scale—this earthquake resulted in only two deaths. A definition based on the natural properties of the earthquake would describe this event as extreme, whereas a definition that incorporates the event's impacts may not. Now compare this event to the earthquake that hit Port-au-Prince, Haiti, in the same year (*see* Matthewman, 2016). This earthquake was of a similar magnitude, depth, and other characteristics, but saw some three million people affected and upwards of 100,000 casualties. That is to say, these events were similar in their natural characteristics but had profoundly different impacts. A definition that includes impacts would, therefore, describe the Canterbury earthquake as being much less extreme of an event (or not an extreme event at all) than the Port-au-Prince earthquake, whereas a definition based solely on the natural characteristics of the events would describe these events as being of similar "extremeness."

At first glance, the variability in extreme event research could be seen as a hinderance. The seemingly irreconcilable differences between research goals, scales, and definitions limit our ability to generalize and, therefore, to predict and prepare for extreme events. And yet, this variability also creates an opportunity for consilience. Here we mean "scientific consilience" whereby observations made in different fields with different tools and perspectives may all point to a single conclusion, indicating a convergence of knowledge. When knowledge convergence occurs, the differences among individual findings strengthen a given conclusion more than would a similar number of repeated, identical findings (Wilson, 1999). Consilience regarding extreme event phenomena, then, would allow us to better understand those phenomena individually and collectively. We could, in turn, better predict the occurrence of extreme events and their effects in the long-term. The costs of such events compounded by their increasing frequency and severity make it important to determine whether consilience is possible. This, in our view, is an urgent task.

With this in mind, we conducted a systematic review of 200 randomly selected scientific extreme events articles and book chapters in the biological, societal, and earth sciences as part of the special issue *Extreme Events in Human Evolution: From the Pliocene to the Anthropocene*. In essence, we wanted to capture extreme events literature that intersected these three disciplines, as well as provide a long-term perspective to extreme events to address the important issue of temporal scale we described above. To that end, this review had three main goals. The first was to synthesize how researchers across these disciplines defined and conceptualized extreme events. Importantly, we wanted to try and determine how "events" are being defined and what makes them "extreme" across disciplines, while at the same time avoiding imposing our own definition of these terms and the compound term "extreme event" on the literature. The second goal was to identify and scrutinize clusters in the literature based on the themes identified in our analysis. And finally, we aimed to determine whether a cohesive, multidisciplinary, multiscalar definition of extreme events could be developed and, if so, lay out a research trajectory to that end.

Materials and methods

To explore how researchers conceptualize and operationalize extreme events in biological, societal, and earth sciences, we conducted a review of academic literature using Web of Science (WoS; accessed January 2020) and following, where applicable, the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) statement (Moher et al., 2009). On beginning, we had to establish some search limits. In terms of time, we wanted to emphasize more recent research without excluding early studies. We also know from other reviews (e.g., McPhillips et al., 2018; Broska et al., 2020) that the publication of the first IPCC report in 1990 may have coincided with a marked increase in public and scholarly interest in human–environment interactions, including anthropogenic climate change and its impacts on society. So, as a compromise, we decided to limit our literature search to the three decades following 1990. Moreover, to reduce picking up articles outside of the scope of this review, we then further restricted our search to the following WoS categories: archaeology, anthropology, environmental sciences, ecology, geology, evolutionary biology, geography, and multidisciplinary studies.

In order to isolate papers focused on extreme events, we used a WoS topic query. Terms were searched for within the keywords, titles, and abstracts of papers indexed by WoS. As discussed above, different disciplines oftentimes emphasize different aspects of extreme events, sometimes explicitly using the term "extreme event," while other times using similar words with slightly different connotations (McPhillips et al., 2018). To bridge this divide we included additional search terms. On preliminary reading of the literature, it was clear that the terms "abrupt" and "rapid" were commonly used to describe extreme climatic events in history and prehistory, and so these terms were added to capture the long-term perspective mentioned above. Terms related to people, the climate, and the environment were also added to emphasize the disciplines of interest. The final WoS search query was: TS = (human or homin*) AND TS = (climat* OR environment*) AND TS = (extreme OR rapid OR disaster* OR abrupt OR catastroph*) AND event. Asterisks acted as wildcards to capture alternative endings like "environment-al," climat-ic, "catastroph-ic," and "homin-in."

The search returned 1,626 articles. Metadata for these articles were compiled into an Excel spreadsheet. The rows of the

TABLE 2 The 10 questions asked of each paper and examples.

Question	Tag example	Article example
What is the focus of the study?	Human-centred	Anderson and Bell (2011) studied the impact of heat-waves in the United states on mortality risk
How are extreme events defined?	Statistically	Bush et al. (2014) defined extreme precipitation as > 90th percentile based on daily precipitation data between 2004 and 2007
How are extreme events conceptualised?	Impact	Christidis et al. (2015) stated that severe heat waves in recent years have been characterized by their *impacts*
What data are being analysed?	Meteorological	Ghirardi et al. (2015) investigated the relationship between temperature and emergency department visits
How are the analyses conducted?	Quantitatively	Feng et al. (2019) conducted correlational analyses to investigate the relationship between trends in social variables on the one hand, and temperature and precipitation on the other
What themes are discussed?	Climate change	Bindi and Olesen (2011) discussed the potential consequences of climate change on agriculture in Europe
What is the period of interest?	Early Holocene (10,000 BC to 1500 AD)	Hong et al. (2014) investigated changes in summer rainfall in Central Asia over the past 8500 years
What is the objective clarity?	Hypothesis-driven	Pettay et al. (2015) tested the hypothesis that populations of the zooxanthella *Symbiodinium trenchii* in the Indo-Pacific Ocean represented a recent invasion
What is the geographical scope?	China	Hong et al. (2019) studied the impacts of climate change on future air quality and human health in China
What type of extreme event?	Flood	Gray and Mueller (2012) investigated the effects of flooding and crop failures on population mobility in Bangladesh

spreadsheet were then randomized and two of the authors (MS, WCC) independently analyzed the articles in the shuffled spreadsheet, one starting at the top and the other at the bottom. Articles outside the scope of the review were excluded—for example, a study on the effects of rearing methods on the post-release survival of southern sea otters mentioned the vulnerability of populations of this species to catastrophic oil spills, however, the study itself was not concerned with extreme events (Nicholson et al., 2007). Articles were analyzed until each analyst had reviewed 100 articles (for a total of 200).

The articles were analyzed with QSR International's Citavi reference manager version 6.3.0.0 (https://www.citavi.com). This program allows text in documents to be highlighted, tagged, and coded so that themes in the literature could be identified and explored. Using these functions, we coded text in each article to answer a series of questions designed to capture how extreme events are conceptualized and operationalized by scholars (Table 2). This included manually grouping each article into disciplines, similar to McPhillips et al. (2018). As our study was not concerned with research quality, no quality checks were performed. Once all relevant articles were tagged and coded, all authors consulted the data to check for instances where related tags might be placed under "senior" labels. As an example, "ecological management," "risk management," and "hazard management" were placed under "management." After tags were collated, the data was then exported using Citavi's "Export to Microsoft Excel" function and imported into R version 3.6.3 (R Core Team, 2013). The patterns in the data were then explored in R using *igraph* (Csardi and Nepusz, 2006), *gplots* (Warnes et al., 2009), *tidyverse* (Wickham et al., 2019), *tm4ss* (Wiedemann and Niekler, 2017), and their associated packages.

To assess how sufficiently the literature had been sampled, we constructed collector's plots (also known as species accumulation curves) for event types, data types, concepts, and themes. This approach charts the increase in some variable of interest—the number of species of beetles in a forest plot, for example—relative to sampling effort. Typically, the resulting curve rises rapidly at the start, and then more slowly in later samples (in this case articles) as increasingly rare occurrences (in this case tags) are added, before ultimately reaching a plateau (Gotelli and Colwell, 2001). The curve, therefore, reflects the diminishing returns of sampling effort and gives an idea as to how sufficiently a variable of interest has been sampled for—that is, if the curve reaches a stable plateau, it could be argued that the total sample is representative of the variable of interest.

We also assessed the through-time trend in research interest in extreme events. This required correcting for through-time increases in publication volume more generally. We therefore divided the number of articles published each year in our sample by the number of articles published each year in five of the most common journals in our dataset. Number of per year publications was sourced from Clavarites' InCites tool, which provides data going back to 1997, and we included only those journals with data available going back to this time. While this excludes newer journals like *PLOS One* (active since 2006), it likely captures the general through-time trends in publication volume.

Lastly, we ran a simple clustering analysis using the *heatmap.2* function (gplots) to explore co-occurring themes in the literature sample. This function first computes a distance (dissimilarity) matrix for the objects being clustered—in this case themes and articles—and then performs a hierarchical clustering analysis using the calculated distances. The output is then visualized as two dendrograms—one each for the rows and columns—and a heatmap. No specific dissimilarity cutoff value was used to define the clusters in our analysis. Instead, the heatmap was visually inspected to identify groups of papers that covered similar topics, which were in turn used to structure the discussion. And so, while the clusters are somewhat arbitrarily defined, we considered it to be an appropriate and useful approach for our purposes, and one that provided more objectivity to the analysis than more traditional reviews.

Results

The WoS search returned 1,626 articles. Of these, 124 were excluded as they did not fall within the scope of the literature review—that is, their focus was not on extreme events (for an example of such an article *see* Methods sections) (Supplementary Figure S1). A total of 200 articles were analyzed and the results of the systematic review are presented below. A full list of the articles can be found in Appendix 3.

Sampling adequacy

As expected, all five curves show a rapid rise at the start of the simulation as new tags were quickly added, followed by a deceleration in later articles with the addition of rarer tags (Supplementary Figure S2). The concepts curve appears to be approaching a plateau suggesting that a larger dataset would not result in significantly more concepts being added. The other three curves, however, still appear to have been increasing towards the end of the simulation. This is perhaps unsurprising given the broad scope of this review. Still, given that we focus on the most common concepts, themes, event types, and data types, it seems likely that we have adequately captured the structure of the data and that a significantly larger literature sample would show broadly the same patterns.

This is also supported by the almost exponential distribution of tags in each of these cases. For example, over half of the event types have only a single occurrence, whereas the top five occur in 29–62 articles (15–31% of articles). Similarly, around half of the concepts have three or fewer occurrences, whereas the top five concepts occur in 43–73 articles (22–37% of articles). It therefore seems unlikely that a significantly larger sample size would drastically alter the structure of the data with respect to the most common event types, data types, concepts, and themes.

Summary of the literature

It is clear from the data that interest in extreme events has been increasing in recent decades, with around one sixth of all papers in the literature sample being published in 2019 alone (Figure 1). Even when accounting for through-time increases in publication volume, the number of extreme event publications has been growing since at least the 1990's. Among the articles analyzed, a wide range of extreme events was covered including natural hazards (e.g., earthquakes, floods), ecological events (e.g., plagues, extinctions), societal events (e.g., conflicts, war), and existential threats (e.g., extraterrestrial impacts, nuclear fallout). The top five most common events were *1*) floods, *2*) heat waves, *3*) droughts, *4*) severe precipitation, and *5*) hurricanes (Figure 2).

Studies based in United States, China, and India were best represented, whereas those in countries in Africa, Oceania, eastern Europe, and western Asia were drastically underrepresented. Around one fifth of the world's countries were represented by at least one study (21%, or 41 out of 195 countries), and around one fifth of all studies in the literature sample were global in focus (Figure 3). Two thirds of the articles focused on humans and human populations, followed by the environment/climate (49%), policy (33%), plants/animals (11%), and finally infrastructure (2%). Unsurprisingly, there was a great deal of overlap in article focus as, for example, articles that were concerned with the role of climate change in altering the frequency and magnitude of extreme events were also often concerned with the impacts that these changes might have on contemporary and future human populations.

Studies of contemporary (>1900 AD) extreme events were most common, followed by events from the early Holocene to the start of the early modern period (10,000 BC to 1500 AD), future events, Modern Era historical events (1500–1900 AD), and lastly early prehistorical events (<10,000 BC) (Table 3). In terms of scale, contemporary and future studies were primarily concerned with natural hazards, their impacts, and the role of anthropogenic climate change in altering the nature of hazardous events. Studies of past events were also concerned with natural hazards, but also focused on longer-term climatic events driven by broad scale changes in the Earth's climate systems.

About half of all studies provided only a qualitative definition of extreme events, or no definition at all. In these instances, extreme events were described as simply being "rare" or "anomalous"; as an "abrupt," "sharp," or "rapid" change in some variable of interest like temperature; some peak in a time-series; or passing some vague threshold. Quantitative definitions of extreme events were the next most common (37% of papers) and included significant changes in some variable of interest, usually expressed as an absolute numerical value or ratio; passing some defined threshold such as daily precipitation; or the most extreme or some set of extreme values. Least common were statistical definitions of extreme events (22% of papers) which included exceeding some pre-defined statistical threshold (e.g., 95th percentile) or number of standard deviations, or were defined using more sophisticated analytical techniques (e.g., Peak-Over-Threshold). In terms of analyses,

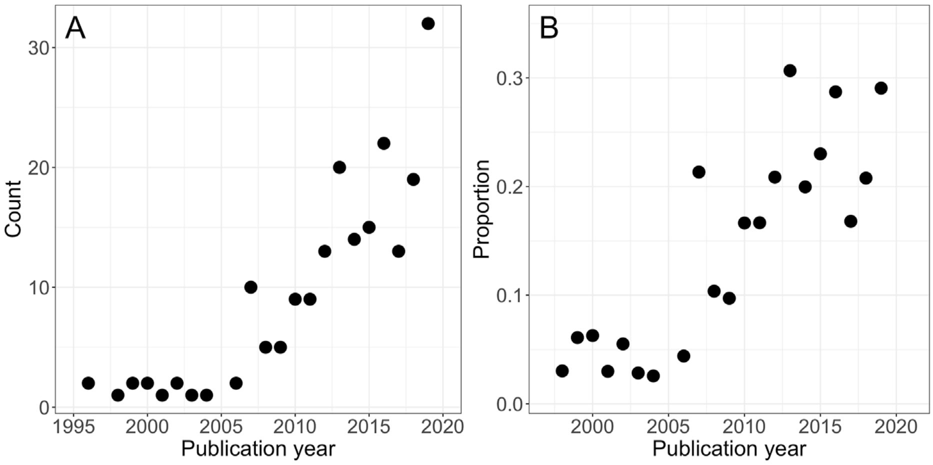

FIGURE 1
Number of publications per year **(A)** and adjusted for through-time increases in publication volume **(B)**. Note that the two graphs have different starting years (Graph A starts at 1996, whereas Graph B starts at 1997). This is because of the way by which we attempted to correct for through-time increases in publication volume (*see* Methods).

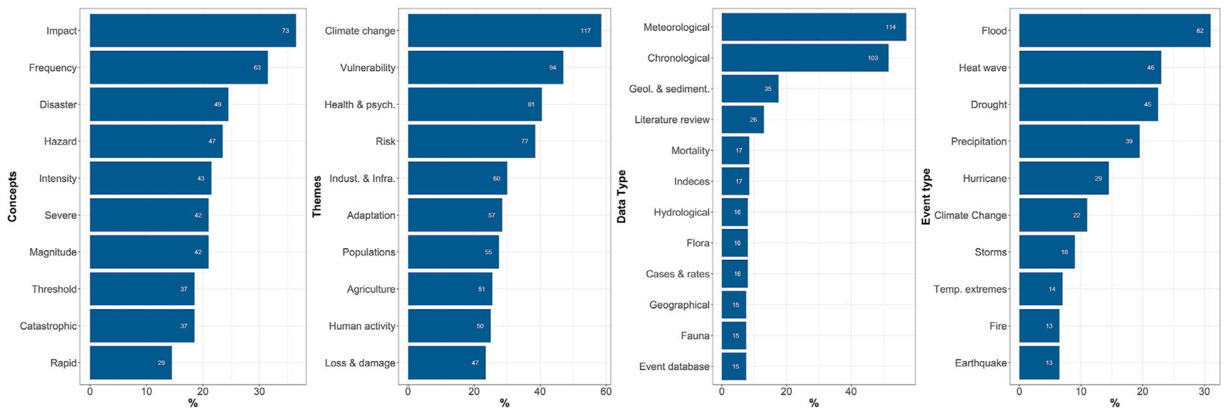

FIGURE 2
The top most common concepts, themes, data types, and event types in the literature sample (n = 200). Numbers within the bars denote the number of papers each occurred in.

most studies (87% of papers) presented some sort of numerical or statistical analysis. Around a third of articles were primarily qualitative, most of these being literature reviews.

A total of 50 data types were used in the study of extreme events. The top five most common were *1*) meteorological, *2*) chronological, *3*) geological and sedimentological, *4*) literature review, and *5*) mortality and indices data (tied) (Figure 2). Meteorological data consists of physical measures like temperature and wind velocity, as well as climate models. Chronological data comprises mostly time-series data, as well as radiocarbon data used in pre-Modern Era studies. Geological and sedimentological data includes a variety of measures related to the Earth's surface and sediments (e.g., slope, grain size, magnetic susceptibility). Literature review and mortality data are self-explanatory. And lastly, index data relates to a variety of indices often used in climate studies (e.g., heat index).

We identified 105 concepts related to extreme events (Supplementary Table S2). The top five most common were *1*) impact, *2*) frequency, *3*) disaster, *4*) hazard, and *5*) intensity (Figure 2). We also conducted a simple analysis of collocation strength (CS), collocations essentially being commonly co-occurring word pairs, such as "fast food." The results show

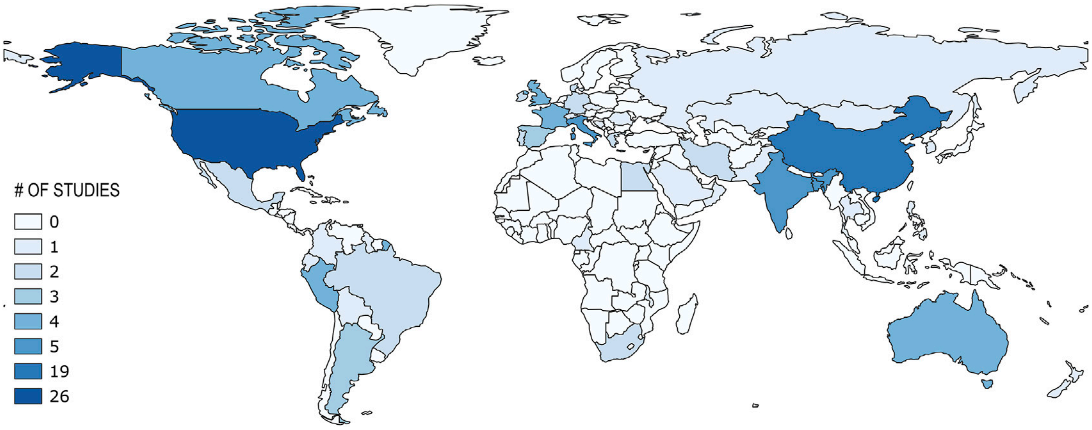

FIGURE 3
The number of extreme event studies by country. Note that 40 articles in our literature sample had a "global" focus and are included in the counts here, making the minimum count for any particular region 40. Studies of inter-country regions (e.g., the Mediterranean) were excluded.

TABLE 3 Number and percentage of papers by period.

Period	Number of papers	Percentage of papers (%)
Early prehistory (<10,000 BP)	14	7
Early Holocene (10,000 BP–1500 AD)	40	20
Historical (1500–1900 AD)	26	13
Contemporary (1900 AD–present)	163	82
Future	38	19

that impact is most strongly associated with the concepts magnitude (CS = 0.43), hazard (CS = 0.38), and disaster (CS = 0.38); frequency is most strongly associated with the concepts intensity (CS = 0.55), disaster (CS = 0.38), and impact (CS = 0.35); and disaster is most strongly associated with the concepts hazard (CS = 0.48), impact (CS = 0.38), and frequency (CS = 0.38).

A total of 90 themes related to extreme events were identified (Supplementary Table S3). The top five themes were *1)* climate change, *2)* vulnerability, *3)* health and psychology, *4)* risk, and *5)* industrialization and infrastructure (Figure 2). Climate change was most strongly associated with the themes vulnerability (CS = 0.55), risk (CS = 0.49), and health and psychology (CS = 0.45); vulnerability was most strongly associated with health and psychology (CS = 0.61), risk (CS = 0.58), and climate change (CS = 0.55); and health and psychology was most strongly associated with vulnerability (CS = 0.61), risk (CS = 0.57), and industrialization and infrastructure (CS = 0.54).

Lastly, we ran a simple clustering analysis to explore co-occurring themes in the literature sample (Figure 4 and Supplementary Figure S3). The clustering analysis revealed little in terms of structure, although this is perhaps unsurprising given the broad scope of the literature surveyed and the type of data being analyzed. Still, some clusters do stand out that are worth exploring. The most apparent is a cluster of 48 articles focused on climate change on the one hand, and human health, vulnerability, and risk on the other (hereafter *health, vulnerability, and risk*). Three other clusters can be made out but are narrower in focus with respects to our tags. These are 27 articles related to human activity (hereafter *human-environment interactions*), 44 articles concerned mainly with human health and well-being (hereafter *human health and well-being*), and 64 articles focused on climate change (hereafter *climate change dynamics*). These clusters are discussed in detail below.

Breaking down the most common concepts by discipline revealed some interesting differences in how extreme events are defined and conceptualized (Figure 5) (*see* McPhillips et al., 2018 for a similar analysis). Impact, and the related concept disaster, are commonly used to define extreme events in the social sciences but occur much less frequently across the other disciplines, although impact was still the most common concept in earth sciences. Thresholds are also commonly applied in the earth

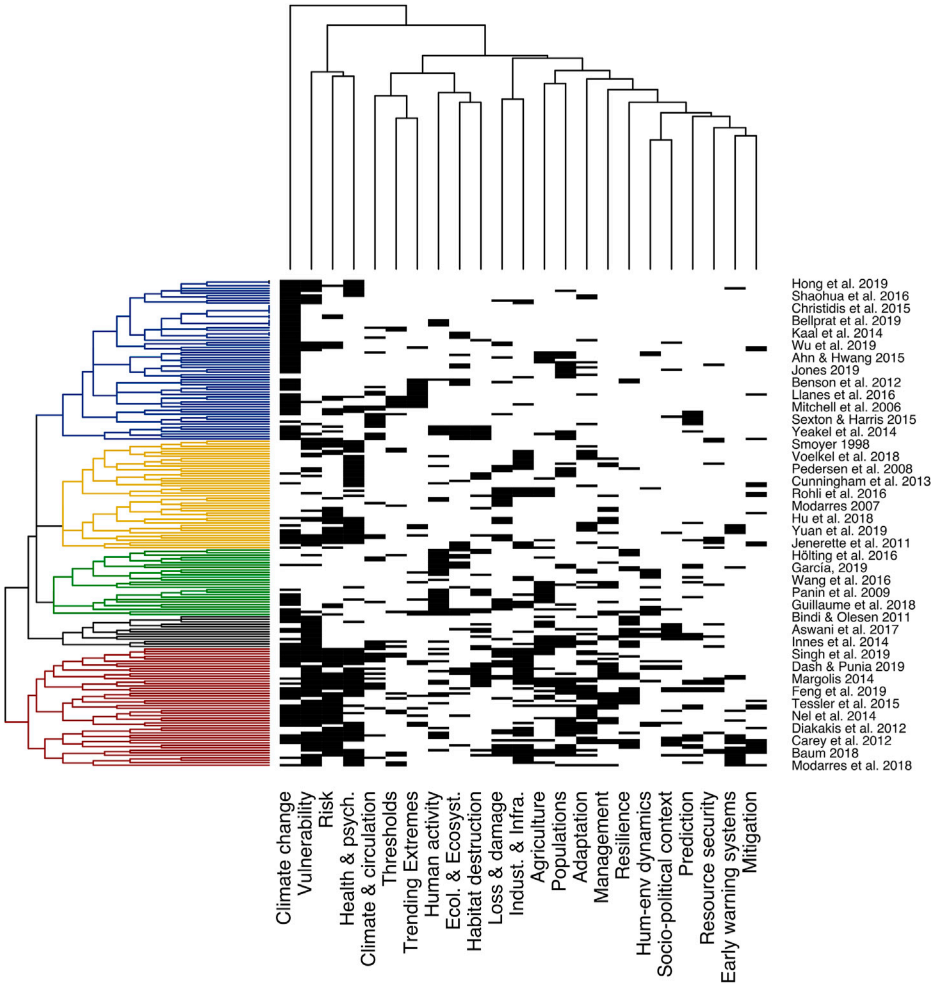

FIGURE 4
Heatmap showing paper likeness and theme clustering. Papers on the x-axis and themes on the y-axis. Only the top 20 themes were used in this clustering analysis. The clusters are color-coded as follows: *health, vulnerability, and risk* in red; *human-environment interactions* in green; *human health and well-being* in yellow; and *climate change dynamics* in blue. The full figure, with all 200 papers displayed, is presented in the Supplementary Material (Supplementary Figure S3). Please note that this figure was generated prior to some merging of themes and this dataset is provided as Appendix 4.

sciences. In the climate and ecological sciences, the frequency of an extreme event appears to be particularly pertinent. Whereas in the palaeo sciences, the abruptness, rapidity, and magnitude are key to defining extreme events.

Likewise, there were some evident differences when breaking down the most common themes by discipline (Figure 6). Social sciences were mostly concerned with the themes of human health and well-being, vulnerability, and risk. Earth sciences were also concerned with risk as well but also with the themes of human activity and loss and damage. Climate sciences were concerned with health and psychology and vulnerability, but also the themes of trending extremes and climate and circulation. Ecological sciences, understandably, had a strong focus on the theme ecology and ecosystems, as well as human activity and vulnerability. And lastly, the palaeo sciences had a strong focus on the themes of populations, agriculture, habitat destruction, and ecology and ecosystems. Climate change as a theme was common across all disciplines.

Discussion

Defining and conceptualizing extreme events

One of the primary goals of this review was to scrutinize how "extreme events" were being defined across biological, societal, and earth sciences. Concerningly, only half of all papers provided

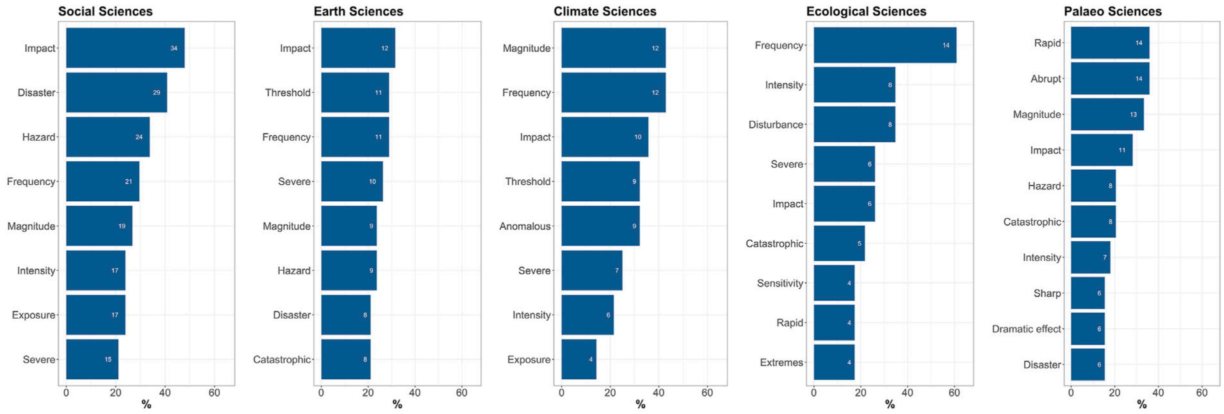

FIGURE 5
The common most concepts across the social, earth, climate, ecological, and palaeo sciences. Numbers within the bars denote the number of papers each concept occurred in.

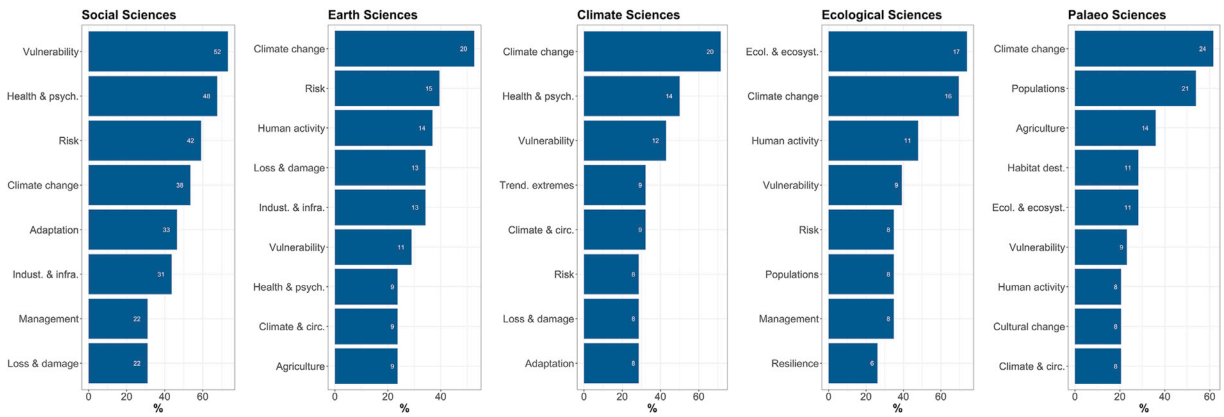

FIGURE 6
The common most themes across the social, earth, climate, ecological, and palaeo sciences. Numbers within the bars denote the number of papers each concept occurred in.

any sort of quantitative definition of what constitutes an extreme event, while the remainder gave only qualitative definitions or no definitions at all. Concerns over the lack of definitions in the extreme events literature have been raised elsewhere (McPhillips et al., 2018), and the present review suggests that the situation is even less clear when considering extreme events across an exceptionally broad range of spatial and temporal scales.

One key finding of this review was that studies of historical and prehistorical events rarely provide explicit, quantitative definitions of what constitutes an extreme event. This is perhaps unsurprising given the types of events commonly investigated and the resolution of the data available. Take for instance one commonly studied type of extreme event in history and prehistory—long-term climatic events. Such events are typically described as being an abrupt or rapid change in one or some set of climate parameters, and are often defined or discussed in relation to their magnitude and impacts (e.g., Innes et al., 2014; Crombé, 2018). These descriptions imply that some measure was used to determine magnitude and impact, and they further imply that comparisons must have been made to some baseline or reference period. However, rarely do scholars quantify what about a climate change event and/or its impacts qualify it as an extreme event and neither do they explicitly describe the baseline compared to which the given event is evidently extreme in some way. The same is often the case for more recent events. In our literature sample, observations about natural hazards like floods, hurricanes, and earthquakes were rarely accompanied by definitions for the relevant events. Only a handful of articles provided some sort of quantitative definition, which included metrics like total area affected, number of lives lost, and damage to property or income (e.g., Messerli et al., 2000; Gray and Mueller, 2012), and statistical definitions were even rarer. Again the baseline or reference condition is also rarely if ever explicitly described in the research.

Statistical definitions were far more common in studies of heat waves (e.g., Anderson and Bell, 2011; Baldwin et al., 2019) and severe precipitation (e.g., Coumou and Rahmstorf, 2012; Fischer and Knutti, 2015). The key reason for this being that these events are easy to measure on a continuum with simple metrics. Particularly common was the use of threshold values such as the 90th, 95th, or 99th percentile. In these instances, threshold values were typically based on the underlying statistical distribution derived from historic data relevant to the area of study—the previous 30 years temperature record from New York City, for example (e.g., Jegasothy et al., 2017; Matthews et al., 2017). Importantly, this considers the spatio-temporal dynamics of extreme events, as what is considered extreme in one place and/or time may not be considered extreme in another (Goodess, 2013). A few papers discussed other statistical approaches for identifying and modelling extreme events using Extreme Value Theory—such as the Peak Over Threshold method—although these were rarely applied in our sample (e.g., Evin et al., 2018; Singh et al., 2019). For a detailed discussion on statistical approaches for studying extreme events we refer readers to Ghil et al. (2011).

Indices were another common approach for describing and defining extreme events. Again, these were particularly common for climate-related events such as heat waves (e.g., Modarres et al., 2018; Sun et al., 2019), droughts (e.g., Modarres, 2007; Wu et al., 2015), and severe precipitation (e.g., Bartholy and Pongrácz, 2010; Gado et al., 2019). Most often, these indices combined two or more physical measures in an attempt to better capture the multivariate aspects of weather-related events and their impacts on human health and natural systems. The heat index (HI), for example, combines air temperature and relative humidity to provide an "apparent" or "feels like" temperature, with HI values >40.6°C considered to represent an extreme heat event with respects to human health and well-being (e.g., Matthews et al., 2017). Drought indices like the Palmer drought severity index (PDSI) and the Palmer hydrological drought index (PDHI), which combine various measures including temperature, soil moisture, and evapotranspiration, were popular tools for assessing drought exposure and damage in the agricultural sector (e.g., Rohli et al., 2016). Lastly, several studies defined extreme events using simple univariate thresholds, such as exceeding some daily rainfall amount or maximum temperature (e.g., Cunningham et al., 2013; Nel et al., 2014). As with the statistical distributions of single metrics (e.g., temperature or rainfall) described above, the studies involving indices must have employed a baseline or reference in order to judge when a given index reached some critical level. But in many cases the baseline was either not described in detail or seemed to have been defined arbitrarily or pragmatically given the data available (e.g., Sung et al., 2013; Wang et al., 2016).

It is clear from the above that the motivations for studying extreme events dictate how extreme events are defined, measured, and identified. This is made more apparent if we observe the most commonly used concepts across the various disciplines (Figure 5). As noted elsewhere (McPhillips et al., 2018), one of the key inter-disciplinary differences in the study of extreme events is the consideration of their impacts. In the social sciences, and to a lesser extent the earth sciences, the concepts of impact and disaster are key components of extreme events. Frequency appears to be a particularly important characteristic of extreme events in the climate and ecological sciences. Disturbance is unique to the latter and has a long history in the discipline (*see* McPhillips et al., 2018). Whereas rapidity, abruptness, and magnitude appear to be key concepts in the definition of extreme events in the palaeo sciences.

Thematic clusters in the literature

To further explore the thematic clusters in our literature sample we conducted a simple hierarchical clustering analysis using the top 20 themes only (*see* above). Although this clustering analysis is somewhat arbitrary, we believe that it captures well the extreme events themes in our literature sample. As mentioned above, we identified four broad thematic clusters: *Health, vulnerability, and risk*; *Human-environment interactions*; *Human health and well-being*; and *Climate change dynamics*.

Health, vulnerability, and risk

Papers in this cluster focus on the interaction between climate change on the one hand, and human health, vulnerability, and risk on the other. Climate change in these articles is typically discussed in relation to natural hazards. In fact, in many of these articles the authors make some reference to the role of climate change in increasing the frequency, duration, and intensity of natural hazards, now and into the future.

In at least 43 papers, the authors discussed the vulnerability of people, populations, and, to a lesser extent, systems, to extreme events. About half of these were concerned with the specific socioeconomic factors that make people particularly vulnerable to extreme events. This included vulnerable populations, such as those living in developing nations (e.g., Sena et al., 2014; Wang et al., 2019), as well as vulnerable individuals, typically the very young, the elderly, the poor, and people with underlying mental or physical health conditions (e.g., Baldwin et al., 2019; Smid et al., 2019). Some studies examined the specific link between natural hazards and human health (e.g., Green et al., 2010; Bush et al., 2014; Margolis, 2014), while others investigated the impacts of natural hazards on human livelihoods more generally (e.g., Gray and Mueller, 2012; Arias et al., 2016; Middleton et al., 2019).

Risk was the second most common theme in this cluster, occurring in at least 40 papers (e.g., Bush et al., 2014; Tessler et al., 2015). Several studies in this cluster were primarily concerned with determining the risks associated with present and future extreme events (e.g., Ameca y Juárez and Jiang, 2016; Abadie et al., 2019). Baldwin et al. (2019), for instance, argued that effective risk assessment of compound heat waves—which are predicted to become more frequent in the future—will require factoring in vulnerability from prior heat waves. In a similar vein, Coffel et al. (2018) modelled future wet bulb temperatures to assess which regions will be most at risk to extreme heat waves in the second half of the 21st century.

More common in this cluster, however, were studies focused on adaptive strategies for reducing risk. Included in these were a number of related concepts such as mitigation, risk management, climate change adaptation (CCA), disaster risk reduction (DRR), and early warning systems (EWS) (for reviews of these concepts we refer readers to Few, 2007; Birkmann and von Teichman, 2010). The approaches proposed in this cluster were understandably diverse and included various social, ecological, and infrastructural adaptive strategies. With regards to heat waves, Margolis (2014) lists a number of effective strategies for reducing heat wave risk. These included promoting good health, access to quality health care, acclimatizing to heat, reducing exposure to ambient heat and air pollution, formal emergency heat wave response plans, among other things, all of which have been shown to reduce risk and increase resilience to extreme heat events.

In at least 18 papers, the risks that climate change and natural hazards pose to agricultural activity was discussed (e.g., Feng et al., 2019; Middleton et al., 2019). This is perhaps unsurprising given *1*) the obvious effects that events like floods and droughts can have on agricultural productivity, *2*) the fact that data strongly suggests that such events are becoming more frequent and intense as a result of climate change, and *3*) the economic and societal importance of agriculture. In one review, Bindi and Olesen (2011) suggested that climate change and extreme weather events will have varying impacts on agriculture across Europe in the coming decades, with increases in crop yields in northern Europe and large reductions in southern Europe. Other studies investigated the impacts of abrupt climate change on agricultural productivity in the past (e.g., Messerli et al., 2000; Feng et al., 2019). One such study found that over the last two millennia in China's Hexi Corridor, abrupt cooling events have resulted in significant declines in grain yield which ultimately led to rises in socioeconomic crises and social disturbances (Feng et al., 2019). Several studies, including the one just mentioned, advocated for studying natural archives and palaeontological and archaeological records as models for examining how human populations and natural systems will respond to future climate change and extreme events (e.g., Riede, 2014; Hoffmann et al., 2015). We return to this point below.

Human-environment interactions

The second theme-group comprises papers focused primarily on the interactions between human activity and the environment. In at least 11 papers, the authors discussed the direct impacts that agricultural practices, such as land clearing, compaction, cropping, terrace construction, and so on, can have on the landscape (e.g., Giguet-Covex et al., 2012; Hölting et al., 2016). A clear message in these papers is that the impacts of such activities can be quite severe, for example, by promoting floods, erosion, dust storms, and denudation. Particularly problematic is when such activities coincide with significant climatic changes. In one study, Viglizzo and Frank (2006) discussed the role that land-clearing practices played in the late 20th century ecological and socio-economic collapse of the Argentine Pampas. Despite only being colonized by agriculturalists in the 19th century, intensive deforestation, over grazing, and over cropping, combined with particularly wet conditions starting in the 1970's, increased the frequency and severity of floods so much so as to disrupt farming practices and send the region into a socio-economic crisis. Along similar lines, Giguet-Covex et al. (2012) found that flood frequency in the French Alps increased during the warmer periods of the Iron Age and the Roman Period, which the authors attribute to increased rainfall on the one hand, and intensive land-clearing practices that reduced rainfall infiltration and increased surface runoff on the other.

Several papers in this cluster highlighted the challenges associated with studying and understanding compound events such as those just mentioned. The spatial and temporal interactions between drivers and/or hazards can make predicting extreme events and their impacts more difficult than if all the drivers and hazards were independent, oftentimes leading to drastic underestimations of risk. In one study, Cuenca Cambronero et al. (2018) tested the impacts of *1*) extreme temperature as a single stressor and *2*) extreme temperature combined with biotic (i.e., food) and abiotic (i.e., insecticide) stress on the mechanisms of thermal tolerance in the water flea *Daphnia magna*. Importantly, the physiological and molecular responses to the combined stress environment were not predictable from the response to warming alone, and, therefore, if we want to accurately predict how species will respond to rising temperatures, it will be necessary to understand how multiple stressors act synergistically. Other ecological studies investigated the compounding impacts of extreme climatic events on the one hand, and environmental and human disturbances on the other, on various animal communities (e.g., Oliveira et al., 2014; Hölting et al., 2016).

Human health and well-being

Similar to the first cluster, the cluster *human health and well-being* addressed human health, but rather than treating it as a dimension of vulnerability, the research in this cluster focused specifically on the biophysical and psychological impacts of extreme events. In at least 21 papers, for instance, extreme events as a cause of mortality were investigated. Several papers analyzed mortality data directly. This included deaths caused by temperature extremes (e.g., Kalkstein et al., 2011; Li et al., 2016; Smith and Sheridan, 2019), floods (Thieken et al., 2016), air pollution (Vanos et al., 2015), earthquakes (Pawson, 2011), and tsunamis (Vött et al., 2019). A number of studies investigated how mortality rates have changed, or will change, in response to climate change and more frequent and intense extreme events. Kalkstein et al. (2011, p. 126), for example, developed time-series of meteorological and mortality data to assess how heat-related mortalities changed between 1975 and 2004 across 40 major U.S. cities. Encouragingly, their findings showed a significant decrease in heat-related deaths since 1996 for most of the major cities investigated, which the authors suggest is the result of "improvements in [excessive heat event] forecasting/recognition combined with an increased interest and commitment of public and private resources to [excessive heat event] education, notification, and response measures."

Around 20 papers were concerned with human physical and mental health. Several studies investigated how extreme events might result in toxic levels of pollution and the possible impacts on human health (e.g., Pedersen et al., 2008; Li et al., 2010; Vanos et al., 2015). Through a combined literature review and geographic information systems (GIS) analysis, Plumlee et al. (2016) evaluated the impacts that an ARKStorm—a hypothetical but realistic "megastorm" scenario for California—could have on environmental contamination. Their results indicated that a number of anthropogenic and natural sources of contamination are vulnerable under an ARKStorm scenario including: numerous small (e.g., gas stations, dry cleaners) and large-scale (e.g., chemical manufacturing plants, agricultural operations) industrial and commercial facilities; livestock agricultural operations that, in addition to contaminants, have the potential to release deadly pathogens; urban centers and mining operations that have the potential to leach dangerous heavy metals and asbestos; and a number of other sources. Other studies were concerned with the psychological impacts that extreme events have on mental health (e.g., Pedersen et al., 2008; Thieken et al., 2016). In a study on the economic and psychological impacts of the 2003 European floods, survey respondents frequently reported feelings of "uncertainty about the future, worries with regard to family, existence and subsistence, and the future, fears of loss, panic, trauma, shock, crying fits or nervous breakdowns" (Thieken et al., 2016, p. 1527).

Lastly, a handful of studies were primarily concerned with the interaction between extreme events and disease (e.g., Andrade et al., 2019; Cheung et al., 2019). What is clear from these studies is that extreme events can, under the right circumstances, result in the proliferation of deadly diseases and other ailments. In one such study, Lara et al. (2009) investigated the impacts that cyclones and landslides have on counts of *Vibrio*—the genus of bacteria that causes cholera, among other illnesses—in an estuarine setting in Bangladesh. They found significantly higher abundances of *Vibrio* following both cyclones and landslides which the authors attribute to a higher amount of suspended particulate matter as a result of sediment disturbance.

Climate change dynamics

The final cluster comprises 64 articles intently focused on climate change, as defined by our tags. Around half of these articles were concerned with identifying trends in climate processes over the last century or so, or were aimed at predicting how these trends will change throughout the 21st century in response to climate change.

With respect to recent trends in extreme events, studies of precipitation were the most common (e.g., Cárdenas et al., 2016; Christy, 2019). In one study, Gado et al. (2019) analyzed precipitation data from 31 weather stations to examine the spatial and temporal changes in rainfall in Egypt between 1955 and 2016, showing that despite recent increases in extreme rainfall events in Egypt, rainfall trends have been on the whole decreasing since the 1950's. In another study, Räsänen et al. (2016) analyzed tree-ring based drought indices to assess long-term variations in ENSO over Mainland Southeast Asia between 1650 and 2004. A key finding of this study was that most extremely wet and dry seasons in the past 355 years occurred during ENSO events, but that there has been considerable spatial and temporal variability in ENSO teleconnection and that this variability may be increasing. Given the strong influence that ENSO has over precipitation, and the potential impacts on heavily agricultural-dependent regions like Mainland Southeast Asia, a better understanding of the relationships between ENSO and the hydroclimate—now and into the future—is paramount (Räsänen et al., 2016)

Future projections of climate change and weather events were central to around 12 papers in this cluster. These included projections of extreme temperature (e.g., Huguet et al., 2008; Matthews et al., 2017), precipitation (Bartholy and Pongrácz, 2010), storm surge (Gaslikova et al., 2013), and air pollution events (Hong et al., 2019). Matthews et al. (2017), for instance, used global climate models (GCMs) to assess the impacts that 1.5°C and 2.0°C warming will have on the hazards of extreme events in China. Presently, heat waves occur in approximately half of the country—mainly in southern, eastern, and the southern part of northern China—and impact around 20% of people. Under a 2°C warming scenario, Matthews et al. (2017) predicted that approximately 80% of the country would experience heats waves—excluding only mountainous regions like the Tibetan Plateau and Changbai Mountains—and would impact roughly 80% of China's population. In another study in China, Hong et al. (2019) combined climate, air quality, and epidemiological models to assess how China's air quality will change under a RCP 4.5 climate change scenario. Alarmingly, the study found that fine particulate matter and ozone concentrations are expected to rise drastically across much of the country, resulting in an estimated additional ~9,000–12,000 deaths. Despite focusing on different climate and hydrological phenomenon, all of these studies reached a similar conclusion—that is, as the climate continues to warm, extreme climatic events are going to become more frequent, more severe, longer lasting, and impact a greater number of people worldwide.

Precisely what is driving the uptick in extreme events was a theme in at least five papers in this cluster (e.g., Fischer and Knutti, 2015; Bellprat et al., 2019). In other words, to what degree, if at all, has human activity contributed to the rise in extreme events. In one analysis, Christidis et al. (2015) found that anthropogenic forcing has led to a considerable shift in the temperature distribution, indicating that human activity has had a strong influence on the frequency of extremely hot summers in Europe over the past 15 years. Moreover, and rather concerningly, the study suggested that summers like the 2003 European heat wave will become increasingly common by the mid-century and may even, under particularly severe climate and anthropogenic forcing scenarios, come to represent rather cold summers by the end of the century. Similarly, Fischer and Knutti (2015) found that 18% of moderate daily precipitation events are attributable to post-industrial anthropogenic warming.

Other studies instead emphasized the difficulties in detecting extreme events and linking a causal mechanism to them, which Coumou and Rahmstorf (2012) refer to as the "detection problem" and "attribution problem" (Coumou and Rahmstorf, 2012). Statistically speaking, detecting extreme events is difficult because extreme events are, by definition, rare occurrences, "living" in the tails of poorly constrained probability density functions. Even once detected, attributing an extreme event to a particular external forcing requires models to "get the unforced internal variability of extremes right as well as the spatiotemporal pattern of the forced response" (Coumou and Rahmstorf, 2012, p. 492). This typically requires multiple climate models/time series of sufficient length, as well as properly accounting for model errors in simulating the probabilities of extreme event occurrences, the latter often not being achieved in extreme event attribution studies (Bellprat et al., 2019). And lastly, there remain philosophical and epistemological questions surrounding extreme event attribution. These extend from what it means for something to be caused by something else in complex systems, and to what extent answers to such questions are influenced by politics and moral considerations (Hulme, 2014).

Lastly, around a third of all papers in this cluster focused on climate change and extreme events in history and prehistory. The reason for this cluster being so heavily dominated by these papers likely relates to themes common in these papers not being included in our hierarchical clustering analysis. Given the growing interest in past extreme events, for not only understanding human and ecosystem responses to climate change and extreme events in the past, but also as models for understanding how humans and ecosystems may react to climate change and extreme events now and into the future, we dedicate the following section to examining how extreme events are conceptualized and operationalized in the palaeo sciences.

Extreme events in history and prehistory

A total of 39 papers, or around one fifth of papers in our literature sample, were concerned with pre-Modern Era extreme events, which we define here as pre-dating 1500 AD. Progressively higher resolution pollen, sediment, ice core, and speleothem data mean that scientists are increasingly better positioned to identify and characterize past extreme climate events and natural hazards. Likewise, higher-resolution archaeological data and growing access to large online databases are providing archaeologists with new means by which to test the impacts that extreme events had on past human populations. The idea that past climate events and natural hazards can act as model systems for exploring how humans and ecosystems may respond to extreme events now and into the future is also gaining traction. In a recent review, not included as part of our literature sample, Burke et al. (2021) p. 1 make the case that studying the archaeological record and earth archives "offers opportunities to identify the factors that promoted human resilience in the past and apply the knowledge gained to the present, contributing a much-needed, long-term perspective to climate research." Important to such a goal will be a common language to ensure that ideas and concepts are communicated effectively between and within disciplines. It is clear from our analysis, however, that no common language has yet emerged. With that in mind, we review the 39 palaeo sciences papers in a similar way to the clusters above to see specifically how researchers in the palaeo sciences define, think about, and study extreme events.

As stated above, a key distinguishing trait of palaeo science extreme event research is an emphasis on long-term climatic events. Studies of these are typically concerned with two main objectives. The first is trying to identify these climate events in pollen, sediment, speleothem, ice core, and other proxy records, to determine if a particular region experienced the event in any meaningful way (e.g., Huang et al., 2013; Innes et al., 2014). And the second is identifying, if any, the impacts that these events had on ecosystems and human populations, the latter often regarding the possible role of abrupt climatic change in driving cultural change, settlement abandonment, societal conflict, and population collapse (e.g., Madsen et al., 2007; Yeakel et al., 2014).

Two climatic events that have received considerable attention in this respect are the Medieval Climate Anomaly (MCA; *c.* 950–1250 AD) and the Little Ice Age (LIA; *c.* 1300–1850 AD), not least because they appear to have had significant impacts on human populations around the globe (e.g., Panin et al., 2009;

Feng et al., 2019). Based on pollen assemblages from Anatolia, Bakker et al. (2013) argued that the MCA—which saw a rise in temperature across the North Atlantic region—played a key role in the resurgence of agriculture and revival of the Byzantine Empire around the 10th century AD. In contrast, the LIA—which saw a drop in temperatures following the MCA—has been linked to significant decreases in food production that resulted in "famines and plagues and, secondarily, conflicts and social disturbances" (Feng et al., 2019 p. 958).

Two other climatic events are the 8,200 BP and 4,200 BP events, both of which are thought to have played important roles in precipitating cultural change and population collapses around the globe (e.g., Ghilardi et al., 2012; Yeakel et al., 2014; Cheung et al., 2019). Broadly speaking, these events seemingly involved abrupt (i.e., within decades) transitions to much cooler and drier conditions and each had significant ecological and societal consequences, although detailed multidisciplinary studies often reveal the complex nature of these interactions (e.g., Groucutt et al., 2022, this issue). At the Tanjialing site in eastern China, for instance, pollen and biogeochemical data show that between *c.* 4,200–4,000 BP the region experienced a chronic drought which some have suggested reduced agricultural productivity and ultimately led to the collapse of the Shijiahe culture (Li et al., 2013). At the same time in central-western Korea, Ahn and Hwang (2015) found a significant decrease in archaeological radiocarbon dates, which the authors interpreted as a significant population decline or return to less sedentary lifeways in response to deteriorating climatic conditions.

The warm Bølling-Allerød (B-A; *c.* 14,700–12,900 BP) and the cold Younger Dryas (YD; *c.* 12,900–11,600 BP) are yet another two examples of extreme climatic events that had substantial and far reaching ecological and societal impacts (e.g., Wang et al., 2012; Mayewski et al., 2014). In one study, Wang et al. (2012) examined charcoal records from the Chinese Loess Plateau and found that the YD was associated with intense fire activity, possibly due to the expansion of grasslands, increased fuel loads, and longer fire seasons. Based on sediment marker and ice core data, the YD has been argued to have been triggered by an extraterrestrial impact that exploded over North America *c.* 12,900 BP, which, from the blast and ensuing climate cooling, caused the extinction of the vast majority of North America's megafauna, as well as significant population declines and cultural changes among Native American populations (Firestone et al., 2007).

Several studies warned about the difficulties in separating climatic and anthropogenic influences in the proxy records often used to identify extreme climatic events (e.g., Bakker et al., 2013; Azuara et al., 2015). By studying lake sediments, pollen, and chironomids—a family of insects also known as midges or lake flies—from the Inner Hebrides in Scotland, Edwards et al. (2007) found that the opening of woodlands at around 8,200 BP was likely caused by human activity (e.g., land clearing for grazing) and not by climatic deterioration, as is often suggested. In two similar studies, Wang et al. (2012) and Miao et al. (2017) studied sedimentary charcoal records in East Asia to investigate how fire frequencies changed throughout the late Pleistocene and Holocene, arguing that increased fire activity starting in the mid-Holocene was likely driven by intense land-use practices and not climate change. In another study, Bakker et al. (2013) argued, based on sediment, pollen, and archaeological data, that the mid 12th century decline in agricultural activity was linked to socio-political change and not to the onset of the Little Ice Age. Studies such as these caution against conclusions drawn from simple correlations between observed changes in proxy records and known climatic events.

Other studies warned about separating truly abrupt climate changes from more gradual ones. Similar to the 8,200 BP and 4,200 BP events, albeit less well-known, the 9,300 BP event is also considered to have been an abrupt cooling event that precipitated ecological and cultural changes. In northwestern Europe, this event is associated with the drying up of lake and river beds and more frequent wildfires, and, from an archaeological standpoint, significant changes in raw material use, site distribution, and hunting strategies (Crombé, 2018). Crombé (2018, p. 353) argued, however, that some of these changes may have been initiated by climate changes in the preceding millennia, stating that without a high resolution chronology "a serious problem of equifinality remains." Madsen et al. (2007) make a point about long-term climate cycles being the overall driver of the shift from the Paleolithic to the Neolithic, but that shorter-term centennial- to millennial-scale climate shifts acted as triggers for abrupt cultural and social change.

Lastly, as indicated at the start of this section, there appears to be a growing emphasis on drawing on past climate events and their impacts as a way for understanding how ecosystems and human populations may respond to extreme events in the future. Feng et al. (2019, p. 957), for instance, stated that to build "resilience against the impacts of climate change requires a deep understanding of social and environmental feedbacks to create a reliable buffer against future changes." In that study, the authors examined the relationship between climate change on the one hand, and food security and social stability on the other, over the past two millennia in China's Hexi Corridor. Based on their findings, the authors described a "domino effect" whereby society's failure to respond to climate change led to cascading feedbacks that ultimately resulted in socioeconomic crises such as famine, plague, migrations, and conflicts. Paulette (2012) made a similar case for Bronze Age Mesopotamia, stating that "it is possible that an examination of ancient forms of hazard management and mitigation could resurrect some forgotten techniques that could be directly applied to the modern world." And finally, by using historic and prehistoric volcanic eruptions as case studies, Riede (2014, p. 355) made that case that by studying the societal impacts of past natural disasters "we can derive historically informed evidence-based policy recommendations that can provide otherwise purely symbolic planning with operational and functional dimensions and that can be part of culturally sensitive social resilience strategies."

Consilience

In addition to the differences highlighted above, we also identified some regularities and highlighted clusters of themes and concepts that appeared in the sample. Both the variability and the regularities are important for the useful convergence of knowledge. As we argued in the introduction, having multiple distinct pieces of evidence pointing to a particular conclusion lends more weight to that conclusion than would a similarly-sized collection of identical pieces of evidence (Wilson, 1999). The differences among extreme events in terms of type, scale, cause, and effect(s) can be an advantage for research. That advantage, however, can only be realized if different extreme events can be made comparable somehow, and that requires at least some broad similarities. Essentially, consilience in the study of extreme events requires some common denominators.

One broad similarity apparent from the patterns we observed is that researchers view extreme events within a particular temporal context. The vast majority of extreme event research we encountered involved the identification of a "rapid" change over time—e.g., a major swing in climate conditions, increase in local temperature, change in species composition, or the breach of a key threshold. The presence of "time" in the event definition has not always been explicitly recognized, but it is almost always present. Relatedly, a baseline or reference period of some kind was always present or implied, and it was the rate of change in conditions from the baseline to some state considered extreme that defined extreme events. So, "time" provides a context to all extreme event research, and importantly it usually appears in the denominator of an explicit or implicit rate function. Some of the papers we read included an explicit mathematically defined rate of change in some variable of interest (e.g., Marriner et al., 2013; Zhang et al., 2015), while others included discussions and word choice that only implied authors were thinking about rates of change (e.g., Innes et al., 2014; Moreno et al., 2019). A climate swing, for example, is considered extreme not just because of the magnitude of the difference in climate parameters between one time and another, but because of the rapidity of the observed change. Therefore, most of the extreme event research we encountered contextualizes extreme events in terms of rates of change. Consequently, the differences we observed in terms of temporal scale between event types or research domains can be marginalized by focusing on the rates of change. It may, at least in-part, be the rate of change that makes an event "extreme." So, comparing events that appear to be incomparable because of vastly different temporal scales (e.g., mass extinctions and heatwaves) could be made possible by shifting the focus of extreme event research onto time-series analyses aimed at understanding rates of change.

The other broad similarity we observed is that many researchers discussed their particular events in terms of risk, vulnerability, and impact. To us, this broadly similar way of thinking indicates that extreme events may be "extreme" primarily because one or more observable phenomena are acutely sensitive to changes in another phenomenon. For example, humans have thermal tolerances, which means that changes in temperature matter for human health—and, crucially, an acute change in temperature can lead to an acute change in health status. This link between observable phenomena implies that extreme events might usefully be viewed as features of certain systems. Briefly, a system (vis. Systems Theory) is any collection of interrelated parts that make up a unitary whole—e.g., an ecosystem, a circulatory system, a computer system. Systems usually also exhibit the flow of materials, energy, or information between the interrelated components. Changes in one component can affect (cause changes in) another component. When isolating two components for study, the relationship between the components can be abstractly viewed like a mechanical device, say a circuit including a switch and bulb—flip the switch, turn on the bulb. And it may be the nature of the relationship between inputs and outputs in certain systems that gives rise to extreme events concerning the system. In fact, there is an extensive literature on taking a (dynamical) systems theory approach to climate change modelling that could serve as a jumping off point for building a unified theory of extreme events across domains (e.g., Scheffer, 2020). That research has indicated that environmental, ecological, and social systems can contain feedbacks between components, and that changes in one component can lead to cascades of changes in all inter-connected components. The measurements of components in these systems, we argue, can be scaled with respect to time—a change in health status per unit time, for example, compared to a change in temperature over the same interval—which would allow for potentially very different "extreme event systems" to be compared in terms of the nature of the relationship(s) between components in an abstract system. Essentially, the comparisons would take place between input and output rates (or changes therein) of measured variables. Exciting potential may lie in taking a time-series based approach to studying rate changes in dynamical systems across many domains—*see* for example recent work on predicting regime shifts in systems as varied as epileptic seizures and the Earth's climate (Bury et al., 2021), based largely on studying rates of change over time in one or more variables.

Together, these two broad similarities suggest there are common denominators that could be used in comparative research of extreme events. More research is needed, but it is encouraging to see that "extreme events" comprise a broad class of phenomena and that radically interdisciplinary research into them could be fruitful. Importantly, comparative extreme event research could potentially yield new insights into extreme events of all types, at all spatio-temporal scales. With better general insights in-hand, we expect that predictions concerning future extreme events will be more accurate and, thereby, more useful for planning and preparation. Better predictions are clearly needed if climate change continues to increase the magnitude and frequency of extreme events over the next century or longer.

Future directions

In our view, the present review identified several important lacunae and biases in the extreme events literature. The first of these relates to the fact that many studies do not provide an explicit definition of what constitutes an extreme event, an issue that has been raised recently by others (e.g., Smith, 2011; McPhillips et al., 2018; Broska et al., 2020). Moreover, even when provided, definitions of extreme events vary greatly between, and oftentimes within, disciplines. According to some, the growing interest in extreme events across a broadening range of disciplines makes a "common and comprehensive definition more crucial than ever" (Broska et al., 2020, p. 1). It may also be important to develop a common nomenclature in describing and studying extreme events to help bridge interdisciplinary divides. As we noted, we think there are key similarities that could support a general definition and bring consilience to the study of extreme events, but further research is going to be necessary. That research will have to include attempts to compare events from across a range of spatiotemporal scales and possibly from domains of research that may appear to be largely unrelated.

A key part of this research may involve taking a dynamical systems approach (*see* Scheffer, 2020), as we suggested earlier. Dynamical systems have been an active area of research across academic disciplines for decades and a branch of mathematics for a century. Its primary focus is on the study of change (usually over time) in the state of a system measured by one or more variables (Strogatz, 2018). It is abstract and, so, can be applied in a variety of contexts. Dynamical systems research is often concerned with the identification of certain system features like "tipping points," "regimes," and "attractors," which are now familiar terms in ecology and climate change literature (Lenton et al., 2008) and can be regularly found in popular media reports. A tipping point, for instance, is a parameter value (e.g., global temperature) at which a system will change states from one region of parameter space (set of potential values) to another. Different regions of potential parameter values are often called "regimes." And "attractors" are parameter values that a system will tend toward. These and other features of dynamical systems—indeed the theory and math of Dynamical Systems more generally—are becoming an integral part of climate change science (Ghil and Lucarini, 2020). The famous hypothesized collapse of the thermohaline circulation (Marotzke, 2000) is an example of a complex climate system reaching a tipping point that shifts the Earth's climate from one regime into another. A dynamical systems analysis is concerned with studying the long-term evolution and behavior of a system in abstract terms with a focus on understanding the qualitative features of potential trajectories the system might take. This sort of abstraction makes it an attractive approach for comparing extreme events in different domains with different time scales. To compare extreme events, we propose viewing them as features of dynamical systems and then abstractly defining a multicomponent system model to represent the relevant processes. For example, heatwaves could be compared to floods by considering each phenomenon as a two-component system. One component would represent the environment and the other humans in the environment. Changes in the first component (an increase in heat, or rainfall) affect changes in the second (hospital visits, or property damage respectively). Each component has traits that can be measured and quantified, and those quantifiable traits can be used to find parameters in a statistical or dynamical systems model. If the model is parameterized in terms of rates, as we explained earlier, then the two quite different systems can be compared directly. One possible outcome of this exercise is that the two systems, even when modelled with the same framework, share no similarities. In that case, the conclusion would be that the events are not part of a common class of "extreme event" phenomena, and perhaps no common class exists. Another outcome, however, might be that the two models share important features—like parameter values, attractors, and/or tipping points. In that case, we could conclude that these two distinct phenomena frequently labelled "extreme" in the literature do in fact belong to a common class. While we cannot, as yet, confidently define extreme events in an inclusive way, we see a clear path toward determining whether a single definition is useful and/or warranted. That way forward involves taking a systems approach and leveraging our observation that rates of change seem to be a common feature in the research on extreme events we examined.

Another area in need of attention relates to geographical biases. Studies based in United States, China, and India were best represented, whereas those in countries in Africa, Oceania, eastern Europe, and western Asia were drastically underrepresented (Figure 3). Around one fifth of the worlds countries were represented by at least one study (21%, or 41 out of 195 countries), and around one fifth of all studies in the literature sample were global in focus (Figure 3). What is particularly interesting about this bias is that it is at odds with the apparent interest in vulnerability, as expressed in the literature. That is to say, that for some of arguably the most vulnerable groups of people in the world, there has been very little research into how they might be impacted by climate change and extreme events, at least as far as our literature sample is concerned. The clearest example here is Africa. Only eight papers in our literature sample (4% of papers) focused specifically on Africa: two of these were concerned with events earlier in the Holocene (Marriner et al., 2013; Yeakel et al., 2014), and one examined the impacts of heat waves on birds (Cunningham et al., 2013). That is to say, the number of studies concerned with the impacts of extreme events on contemporary Africans can be counted on one hand. Another clear example here is islands. According to the IPCC (2021), small island states are some of the most vulnerable to climate change and extreme events, notably sea level rise, droughts, and tropical storms. And yet, only four studies in our literature sample focused specifically on small island states (Yamano et al., 2007; Green et al., 2010; Aswani et al., 2017; Smith and Dressler, 2019). Therefore, a greater focus on vulnerable regions is critical if we are to reduce the impacts of climate change and extreme events on some of the world's most vulnerable groups.

A third area in need of attention is causality. Most studies in our literature sample either explicitly or implicitly dealt with causality in some way—humans and their activities as drivers of climate change, for instance. However, very few studies tackled the epistemology of causality directly, and those that did tended to highlight the difficulties in identifying causal relationships in complex systems (e.g., Schneider and Root, 1996; Coumou and Rahmstorf, 2012; Lu et al., 2016). One of the key reasons for this is that extreme events are, by definition, rare, and most observational records relatively short, making detecting systematic changes in extreme event occurrence difficult (Stott et al., 2016). To this we would also add the sizable challenge of identifying causal relationships between extreme events given only very infrequent, sometimes isolated co-occurrences. Take for example research on societal collapses in the past thought to be triggered by climatic events, such as the abovementioned abrupt cooling episodes at 4,200 BP and 8,200 BP and dramatic societal upheavals that followed (e.g., Yeakel et al., 2014; Cheung et al., 2019). Dramatic societal collapses tend to be rare and so do major climate transitions or events—at least, rare on the scale of human generations as far as we know. Co-occurrences, then, between major climate events and societal collapses can be expected to be even rarer, assuming the two event types are not universally related. Their rarity, both individually and in combination, makes a causal relationship between them hard to demonstrate. Distinguishing potential casual factors from mere coincidence may, therefore, require special methodological, philosophical, and theoretical frameworks (e.g., Hulme, 2014; Stott et al., 2016). Some of the theoretical work may relate to extreme event prediction, which is an area of research that has included methodological attention to the challenges raised by event rarity in statistical analyses (e.g., "extreme value theory"). Future research could proceed from that work and recent work on extreme event attribution (Shepherd, 2016). In particular, the latter would be highly relevant for systems approaches seeking to explain ecological or societal responses to climatic or meteorological extreme events, but we must also highlight that there are important challenges and limitations related to event attribution methods (van Oldenborgh et al., 2021). Needless to say, though, understanding extreme events and planning for them will require a firm understanding of the relevant causal relationships and our review indicates there is a lot of room for methodological and theoretical development.

A fourth area in need of attention are compound extreme events. While only a handful of studies in our literature sample focused on compound events (e.g., Oliveira et al., 2014; Baldwin et al., 2019), a key takeaway from these studies was that their impacts oftentimes equate to more than the sum of their parts. In other words, the impacts of compound extreme events—successive flooding and droughts, for example—can have particularly devastating impacts on biological, societal, and earth systems. As argued recently (Raymond et al., 2020), successive events and events of different types that co-occur can rapidly overwhelm even well-prepared societies and, as with isolated events, will tend to affect most those communities with the highest baseline risk levels. Raymond and others (2020) urge deeper interdisciplinary research and collaboration among policy makers and other stakeholders in order to understand the potential impacts of compound extreme events on various societies at local, regional, and larger scales. Crucially, as extreme events become more frequent, longer lasting, and more intense, so too will compound extreme events, and there is now strong evidence to suggest that this is already the case (e.g., Baldwin et al., 2019). Critical, then, is a good understanding of how extreme events interact and compound with one another so that their impacts can be effectively mitigated. Achieving that understanding, we argue, may require not just interdisciplinary research, but comparative extreme events research based on some common framework.

Another area in need of attention relates to the use of past extreme events as models for contemporary and future extreme events (e.g., Mayewski et al., 2014; Feng et al., 2019). Looking to the past would expand the database for extreme events and human societal responses to those events. Having a bigger, more varied database would lead to a deeper understanding of extreme events and, thereby, better predictions for future events. Unfortunately, though, while there are now hundreds of scientific papers published every year on long-term human environment interaction based on palaeoclimatological and archaeological data (e.g., Carleton and Collard, 2020; Davis, 2020), most of these report conclusions that are not sufficiently rigorous or reliable to be used as a basis for policy or planning (Smith, 2021). The relevant measurement and chronological uncertainties are generally poorly handled, if at all, in typical case studies and systematic quantitative comparisons between palaeo climate records and archaeological records are uncommon. This problem, we think, has to do in part with the inherent and often irreducible uncertainties in palaeo datasets. But it also stems from a dearth of appropriate statistical models and accessible, user-friendly computational tools that do not require software development skills. Only recently have we seen a greater emphasis on methodological research concerned with all-source uncertainty quantification (e.g., Parnell et al., 2015; Boers et al., 2017). So, while we argue that past extreme events (and human responses to them) should be investigated in order to better understand extreme event phenomena in general, the scientific community needs to devote more time and resources to developing the necessary methodological and computational tools. Only then will we be able to use past events as models for future ones.

And lastly, from a review-oriented methodological standpoint, we recommend using collector's plots (also commonly known as species accumulation curves) when conducting systematic reviews of literature. These should be done regularly throughout the analysis and the plots inspected. This will *1*) ensure that sufficient sample sizes are reached and *2*) will reduce sampling redundancy—it may be a waste of time to analyze, say, 200 papers, when the data of interest is adequately captured with fewer papers.

Study limitations

We recognize a number of important limitations and biases that characterize our study. The first of these relates to the scope of the literature search and systematic review. Although our review was intentionally broad with respects to discipline and spatial and temporal scale, it did not include all the ways scholars consider extreme events. In addition to those discussed above, events that have been considered "extreme" in the literature include economic events like recession and depression and medical events like seizures and cardiac arrest (*see* Introduction). Expanding the scope to include economics and medical science—and any disciplines interested in extreme events for that matter—should provide a more comprehensive insight into how extreme events are conceptualized and operationalized across an even broader range of disciplines. To that end, future work should extend the literature search beyond Web of Science to literature databases like MEDLINE, Embase, PsycINFO, and JSTOR to better capture research across disciplines such as medicine, economics, and history.

A second limitation involves likely biases in the literature favoring sensational, trendy, or otherwise attentional grabbing research topics. Since our literature sample was randomly selected, we likely observed topics, themes, and event types that were most frequently investigated, which means our sample reflects the interests of the research community. In part, that was intentional because we aimed to discover how scientists thought about, identified, measured, and studied extreme events—i.e., in part we intended to understand the scholarly community, biases or not. As a result, any biases affecting what research was common in the literature would have no negative effect on our inferences. But, we also aimed to determine whether extreme events could be studied as a general class of phenomena. This second objective meant that our focus was also in part on extreme events rather than just what researchers thought about them. Thus, research biases could potentially have obscured our view of extreme event phenomena since our sample of event types would have been filtered by the researchers' biases. In future, it may be worthwhile scouring the literature for more rarely-discussed event types, themes, topics, regions, and time periods in order to investigate whether there are widespread relevant biases potentially skewing our understanding of extreme event phenomena more broadly.

The third limitation we recognize concerns the search terms used in our study. While we selected search terms to capture extreme events literature that intersect the biological, societal, and earth sciences, additional search terms may have improved our literature search and thereby our literature sample. For instance, McPhillips et al. (2018) found the terms "impact," "frequency," and "disturbance" to be key components of extreme events in the social, climate, and ecological sciences. To better capture these disciplines, these search terms, and likely others, should be considered in the future.

The final limitation we recognize concerns the lack of cross-validation during the coding and tagging of the articles. So, while the two authors (MS, WCC) that conducted the analysis of the papers worked closely and regularly consulted on the meaning of tags and how and when to apply them, no efforts were made to cross-validate the tags as a test for intra-observer variability. We see this as likely being less of an issue for the most common tags in our data set. For example, concepts such as climate change or vulnerability are fairly unambiguous and we suspect that the two authors would have tagged these similarly. So, while intra-observer variability was likely present, we suspect that it would have had little impact on the most common tags and therefore our results overall.

Conclusion

On the one hand, our systematic analysis revealed a great deal of variability among extreme event papers with respect to research interests, themes, concepts, and definitions. On the other hand, we found a number of key similarities in how people think about and study extreme events across a diverse range of disciplines. Namely, we found that scholars tend to view extreme events within a particular temporal context, and quite often in terms of rates of change. We also found that researchers often discuss their particular events in terms of risk, vulnerability, and impact. We believe that these "common denominators" may be useful in developing a universal and comprehensive definition of what constitutes an extreme event and should allow for more comparative research into extreme events at all spatio-temporal scales. Taken together, a common understanding of extreme events, a greater emphasis on comparative research across disciplines, and addressing the biases identified in this study, we think, will be key for better predicting, planning, and preparing for extreme events now and into the future.

Data availability statement

All code and data needed to run the analyses are provided as appendices with the article and can also be found at https://github.com/Stewie1302/ExtremeEvents-Review.

Author contributions

MS, CC, and HG conceived the idea. MS and CC analyzed the articles. MS conducted the data analysis. All authors contributed to the writing of the manuscript and approved the submitted version.

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Conflict of interest

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2022.786829/full#supplementary-material

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