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Integrating traditional ecological knowledge into US public land management: Knowledge gaps and research priorities

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Traditional Ecological Knowledge (TEK) is an understanding of natural systems acquired through long-term human interactions with particular landscapes. Traditional knowledge systems complement western scientific disciplines by providing a holistic assessment of ecosystem dynamics and extending the time horizon of ecological observations. Integration of TEK into land management is a key priority of numerous groups, including the United Nations and US public land management agencies; however, TEK principles have rarely been enshrined in national-level US policy or planning. We review over 20 years of TEK literature to describe key applications of TEK to ecological understanding, conservation, restoration and land management generally. By identifying knowledge gaps, we highlight research avenues to support the integration of TEK into US public land management, in order to enhance conservation approaches and participation of historically underrepresented groups, particularly American Indian Tribes, in the stewardship of ancestral lands critical to the practice of living cultural traditions.

KEYWORDS

TEK, Indigenous knowledge, federal land management, conservation, global change, restoration

1. Introduction

Traditional Ecological Knowledge (TEK) refers to an understanding of ecosystems acquired through long-term observations by people inhabiting a region. In contrast to western Scientific Ecological Knowledge (SEK), TEK is often encoded in rituals, beliefs, and cultural practices (Gadgil et al., 1993; Berkes et al., 1994; Berkes et al., 2000). Any group of people routinely interacting with the environment for extended time periods develop TEK, though the term often refers specifically to Indigenous Traditional Ecological Knowledge (ITEK). The term '*traditional ecological knowledge*' has been criticized, since the word '*traditional*' can be construed negatively to imply a regressive or static knowledge system. While TEK has been described using other terms, like '*Indigenous knowledge*' or '*local ecological knowledge*', these monikers are less broadly applied, in part because they do not fully capture the range of knowledge systems represented in contemporary, highly mobile, pluralistic societies and in part because '*traditional ecological knowledge*' quickly established after its use in several seminal publications. Some argue that no single term or definition can capture the plurality of local environmental knowledge, and instead suggest using the term 'TEK' as a working concept to drive inclusive collaborations aimed at achieving sustainable management of ecological systems (Whyte, 2013). In this spirit and given its widespread application, we continue to use TEK here, while acknowledging the drawbacks, limitations and history of the term.

While TEK has existed for millennia, formal description of the term in western scientific literature occurred in the late 1980s and early 1990s (Johannes, 1989; Berkes et al., 2000). Since that time, hundreds of papers have incorporated TEK, and described the value of including local knowledge in management and conservation planning (Gadgil et al., 1993; Berkes et al., 1994, 2000; Moller et al., 2004; Berkes and Turner, 2006). Limited, yet critical, inroads have been established to include TEK, and more broadly, ecocultural-related goals in US federal land management (Armatas et al., 2016; Ens et al., 2016). Simultaneously, frameworks for understanding human roles in ecosystems are evolving (Berkes and Turner, 2006; Liu et al., 2007), providing a springboard to incorporate TEK in management plans, improve protections for cultural natural resources, and identify novel methodology for evaluating the socio-ecological merits of management actions.

Building on this momentum, we review literature related to TEK, explain how and why TEK can inform management, enumerate challenges of incorporating TEK into land management, and address a core debate within this field that suggests that TEK and SEK are incompatible. Using this framework, we highlight best practices, knowledge gaps, and US policies that could be strengthened or expanded to enshrine protection of ecocultural resources in Federal land management. Finally, we support key concepts using a case study of the Emory oak Collaborative Tribal Restoration Initiative (EOCTRI), a collaboration between western Apache Tribal Nations, the US Forest Service, industry, and university researchers to conserve a cultural keystone species in the southwestern US. While numerous opinion pieces or case studies describe the benefits of TEK-integrated land management, to our knowledge, no review has examined the current body of literature to inform US federal land management and policy.

There is an urgent need for a clear strategy to manage ecocultural resources on US Federal land, and to co-develop management actions with local or Indigenous groups (Bach et al., 2019). Indigenous communities, relocated to reservations a fraction of the size of ancestral territories, rely on public lands to access sacred areas and harvest sites to supply natural products used in traditional foods, crafts, and ceremonies (Souther et al., 2021b). Mismanagement of public lands could trigger irrevocable cultural loss since language, traditions and spiritual practices are often tied to particular species and ecosystems (Ens et al., 2016). At the same time, global change has amplified risks of inappropriate management actions and necessitated large-scale restoration initiatives to prevent broad-scale habitat and diversity loss (Benito-Garzón et al., 2013). Rapid integration of TEK into US federal management plans could improve ecological outcomes of these restoration actions, support local communities and tribal sovereignty, and proactively prevent global change exacerbating historical injustices.

2. Methods

To identify literature related to TEK and land management, we conducted systematic searches in both the ISI Web of Science and the SCOPUS databases. We intentionally used broad search terms to retrieve a wide-range of manuscripts linked to this theme. Within both databases, we searched the terms "traditional ecological knowledge" OR "Indigenous knowledge" OR "local environmental knowledge" AND "land management" OR "natural resource management" for occurrence in the title, abstract, or keywords of manuscripts published from 1900 to 2022. This initial search yielded 432 primary research articles. Articles were then screened for relevance, excluding literature that described predominantly human-dominated systems, such as agricultural and urban areas, and literature focused on describing the knowledge system itself, without tangible ecological or management connections. Using this method, we culled the original body of literature by *ca.* 28%, resulting in a total of 284 articles with content that matched the theme of this review (Supplementary Data Sheet S1). We were unable to review a total of 27 publications, primarily because they were not published in English; however, publications excluded due to inaccessibility represented only 6% of the 432 articles from the original search. Finally, we used a snowball sampling technique, in which we followed citation chains associated with emergent themes, adding a further 37 citations. In total, we reviewed 321 manuscripts for this review.

We used an inductive-deductive approach, in which we iteratively developed and refined themes that emerged from the literature (Shamseer et al., 2015). In order to characterize the current TEK literature, we also categorized manuscripts according to manuscript type, which included the classifications, primary research (studies in which data were collected and reported by the authors), literature reviews, case studies and opinion pieces. The literature reviews, case studies, and opinion pieces reviewed here, by our definition, included no direct data collection or analysis. For primary research studies, we noted whether investigators collected social data, ecological data, or both data types. Finally, we classified primary research studies in terms of analytical data treatment. If data were collected, but simply summarized to characterize TEK or other response variables, we indicated that statistics were descriptive. Alternatively, if data were used in hypothesis-testing, studies were classified as employing inferential statistics.

3. Key informational gaps in TEK literature

Overall, the number of TEK-focused studies has increased since the term was initially introduced in the published literature (Figure 1A). Less than half of all studies we reviewed were primary research on TEK, while the remaining publications were classified as case studies, literature reviews, or opinion pieces (Figure 1B). For the majority of primary research publications, authors collected solely social data, with many fewer incorporating ecological data (Figure 1C). Twenty-five percent of primary research studies employed inferential statistics to analyze data, with most describing data patterns only (Figure 1C). Globally, Australia contributed the highest number of publications, followed by the United States, and Canada (Figure 2). Within the US, TEK-research was geographically skewed toward the west coast, with the highest number of publications occurring in California. Notable gaps in publication rates were observed in the central and eastern portion of the country (Figure 3).

Interpretation of the literature reviewed herein should be contextualized within geographic, topical, and quantitative gaps in this TEK literature. Lack of data precludes quantitative techniques, such as meta-analysis, to examine patterns among studies, reducing inferential strength and preventing description of the magnitude of social and ecological impacts of incorporating TEK into management. As an example, several studies stated that incorporating TEK into land management increased species diversity at these sites, but either did not provide quantities or did not compare with a reasonable control method. Like most literature, TEK-focused manuscripts suffer from positive publication bias – in other words, virtually all studies suggest that TEK

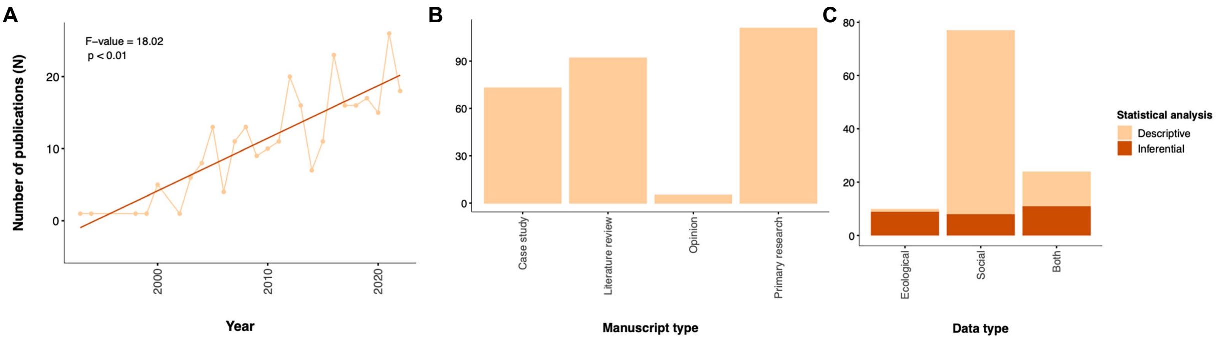

FIGURE 1
Summary information for literature reviewed within this manuscript. **(A)** Publication of TEK-themed manuscripts has increased through time since the year 2000. **(B)** Around half of the TEK-literature reviewed here was primary research and the remaining publications were divided among case studies, literature reviews, and opinion pieces. **(C)** Among the primary research papers, the majority collected social data only and applied only descriptive statistics.

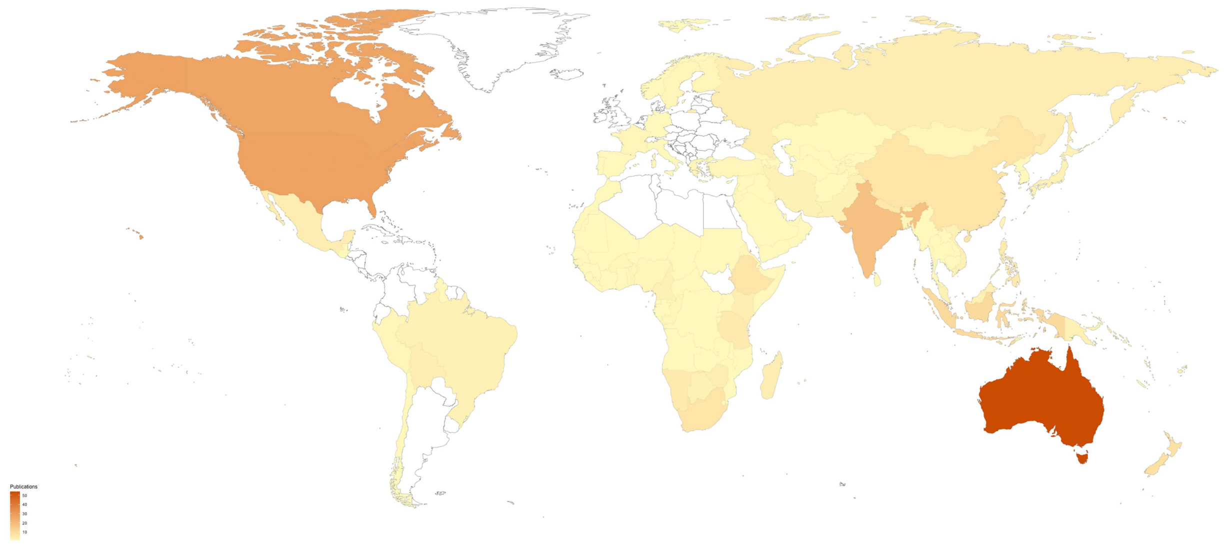

FIGURE 2
Global choropleth map of TEK-publications. The majority of studies have been conducted in the US, Canada, and Australia. South America, Africa, and much of Asia emerge as geographical gaps in TEK-focused studies.

has a positive effect on management outcomes. While we acknowledge these biases, this review revealed broad themes relevant to guide management actions as well as future research trajectories.

4. Traditional ecological knowledge (TEK) overview

4.1. TEK supports sustainable land management

Before modern supply chains introduced global commodities to local communities, human groups, particularly from non-agricultural societies, relied on nearby ecosystems for food, clothing, shelter, and other essentials. Irresponsible use of natural resources would therefore negatively impact reliant human communities. These feedback loops between ecological and social systems drove the development of cultural mechanisms that promoted sustainability (Gadgil et al., 1993; Berkes et al., 2000; Moller et al., 2004; Carpenter et al., 2009; Chapin et al., 2010; Camacho et al., 2012; Folke, 2015; Westley et al., 2021). For this reason, TEK emergent from coupled socio-ecological systems provides insight into sustainable land management practices. Viewing land management through a social-ecological lens can improve outcomes by identifying pathways and feedbacks structured by management decisions that shape ecosystem dynamics and dictates the nature of human-ecological interactions (Rai, 2007; Ruiz-Gutiérrez and Zipkin, 2011; Schultz et al., 2015; Cinner et al., 2016; Gill et al., 2017; Lyver and Tylianakis, 2017; Kobluk et al., 2021).

Traditional ecological knowledge improves understanding of contemporary ecosystems. While the past functional roles of Indigenous peoples have often been ignored or dismissed as insignificant, numerous studies demonstrate that the legacy of past social-ecological interactions manifests in current ecological systems. Humans, throughout time, have profoundly affected ecosystems, acting as ecosystem engineers that shape landscapes, (Smith, 2007), climate, and fire regimes (Kimmerer and Lake, 2001; Bond and Keeley, 2005; Raish et al., 2005; Bliege Bird

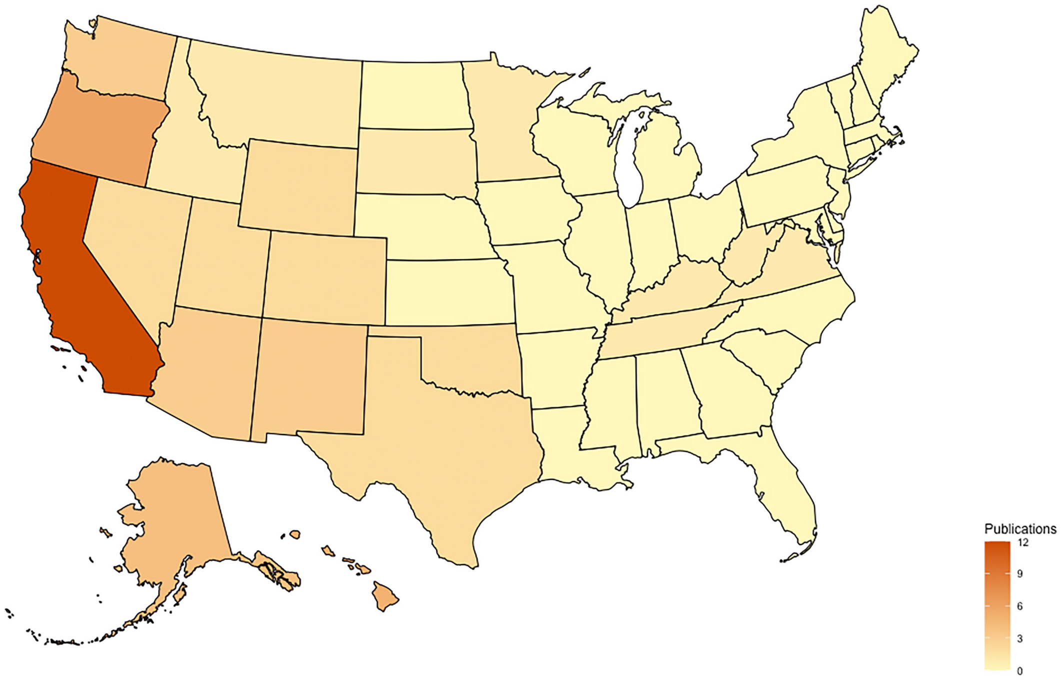

FIGURE 3
Distribution of TEK-focused publications within the US. The highest number of studies were conducted in California. Few studies were observed elsewhere in the US, with a notable gap in the central and eastern portions of the country.

et al., 2008, 2018; Rodenburg et al., 2012; Bird R. B. et al., 2013; Bird M. I. et al., 2013; McCune et al., 2013; Pellatt and Gedalof, 2014; Prober et al., 2016; Albuquerque et al., 2018; Bliege Bird and Nimmo, 2018; Power et al., 2018; Crabtree et al., 2019; Moura et al., 2019; Long et al., 2021; Halpern et al., 2022; O'gorman et al., 2022), as selective agents altering evolutionary trajectories (Rangan et al., 2015; Sullivan et al., 2017), as seed dispersers influencing gene flow patterns (Kondo et al., 2012; Auffret and Cousins, 2013), and as keystone species modifying trophic pathways (Lepofsky and Caldwell, 2013; Dunne et al., 2016; Suraci et al., 2016; Smith et al., 2017; Crabtree et al., 2019; Westley et al., 2021). For some ecosystems, removing traditional human communities has resulted in ecosystem degradation and loss of diversity (Bliege Bird and Nimmo, 2018; Knight et al., 2022).

In the US, new estimates suggest that human groups may have arrived from Asia to North America as much as 21 ka (Moreno-Mayar et al., 2018), indicating that human populations influenced ecosystems for thousands of years prior to the imposition of contemporary land management. The ecological impacts of these groups, particularly effects mediated through cultural burning practices, are thought to have been profound and persistant through time. (Devin and Doberstein, 2004; Kimmerer and Lake, 2001; Raish et al., 2005; Adlam et al., 2021; Halpern et al., 2022; Knight et al., 2022; O'gorman et al., 2022). Indigenous burning reinforced oak and chestnut dominance in the Appalachian forests of the eastern US, maintained the extent of the tallgrass prairie in the Midwest, and shaped the composition of western forests (Kimmerer and Lake, 2001). Cultural burning was widespread, implemented by numerous Indigenous groups, and practiced for myriad reasons; to clear home sites, to encourage the growth of desirable species such as food provisioning-species (i.e., oaks, chestnuts), to send long-distance signals, to foster habitat for important game species or to corral game, and to control pest populations (Kimmerer and Lake, 2001). Integrating TEK into prescribed burning to restore fire regimes has been largely successful (Bond and Keeley, 2005; Bliege Bird et al., 2008, 2018; Butz and Butz, 2009; Pellatt and Gedalof, 2014; Fache and Moizo, 2015; Clinchy et al., 2016; Bliege Bird and Nimmo, 2018; Adlam et al., 2021; Halpern et al., 2022). In addition to cultural burning, Indigenous communities likely shaped ecosystems through multiple pathways, including harvest, hunting, and transport of species, as has been shown for past human populations in other countries. Failure to acknowledge Indigenous functional roles within ecosystems on public lands will result in the omission of key ecological processes (Donlan, 2005; Alagona et al., 2012; Higgs et al., 2014). Engaging local and Indigenous communities for ecological insights may provide a more comprehensive understanding of these systems.

4.2. TEK developed over long time horizons

Traditional ecological knowledge develops *via* long-term interactions of human populations with ecosystems, and thus may contextualize contemporary ecological change, extending descriptions of baseline conditions to time periods preceding modern documentation (Homann et al., 2008; Gratani et al., 2011; Johnson et al., 2015; Armatas et al., 2016; Hopping et al., 2016; Bach et al., 2019). In response to changing climate, species are undergoing widespread changes in the timing of critical life events (i.e., phenology), traits, spatial distribution, and abundance (Thomas et al., 2004; Skelly et al., 2007; Kelly and Goulden, 2008; Lavergne et al., 2010; Walther, 2010; Parmesan and Hanley, 2015). System-level understanding of the timing of important ecological events can help identify phenological mismatches, disruptions of species interactions, and overall phenological shifts in response to climate change (Prober et al., 2011; Moura et al., 2013; Armatas et al., 2016;

Pyhälä et al., 2016; Wiseman and Bardsley, 2016). In North America, many tribes track cryptic seasonal events using the phenology of indicator species (Armatas et al., 2016). The Karuk, Hupa, and Yurok Tribes, for instance, track the migration of edible fish species by following the flowering schedule of dogwood trees (Armatas et al., 2016). Applying comprehensive phenological knowledge spotlights shifts in critical life events and mismatches among interacting species important for understanding ecological impacts of climate change that may not be identified by conventional short-term western scientific studies.

More broadly, long-term landscape perspectives may provide reference conditions for restoration targets and serve as an early warning of species extirpation, state transitions, or other changes from which recovery is challenging (Prober et al., 2011; Uprety et al., 2012; Vinyeta and Lynn, 2013; Johnson et al., 2015; Wiseman and Bardsley, 2016; Souther et al., 2021b). As an example, western Apache Tribes in Arizona, who consume Emory oak acorns as a traditional food, advised the US Forest Service that populations of this oak lacked smaller size trees and produced fewer acorns relative to populations in the past. Tribal members attributed decline in reproduction and recruitment to a variety of factors, including climate change, livestock grazing, and fire suppression (Coder et al., 2005). These observations initiated a landscape-scale Emory oak restoration project, the Emory oak Collaborative Tribal Restoration Initiative (EOCTRI), taking place on USFS and Tribal Lands in the Southwest (Figure 4; Souther et al., 2021a). Without this warning from western Apache people, land managers would likely not have identified Emory oak as a conservation concern, since the presence of long-lived adult trees masks risks to this species. Western Apache TEK drove implementation of conservation interventions for this species prior to irreversible decline (Souther et al., 2021a). Environmental change in response to anthropogenic disturbance of terrestrial and atmospheric systems is occurring at the local-level in complex and idiosyncratic ways (Pyhälä et al., 2016). By engaging local populations, land managers can broaden understanding of ecological change, and make management decisions in real-time as issues emerge (Pyhälä et al., 2016).

4.3. TEK is often holistic

In many cases, TEK is characterized by a comprehensive understanding of ecosystems, with humans situated within biotic communities, and landscapes representing not only ecological features, but also place-based sociocultural memories (Athayde and Silva-Lugo, 2018). Recognition of the complexities and interrelationships within biotic communities broadly supports scientific understanding of ecological systems. The model of coupled human and natural systems, or the concept of the eco-cultural landscape (i.e., the totality of ecological and cultural elements in a region) may improve management and conservation outcomes by appropriately recognizing human roles within ecosystems (Rai, 2007; Cullen-Unsworth et al., 2012; Johansson et al., 2019; Campbell, 2020; Pablo and Córdova, 2021).

Conservation failures due to lack of cultural understanding or engagement have increased recognition of the importance of collaborative planning in US and global resource management. A prime example is the establishment of biodiversity conservation reserves or carbon sequestration offset areas by wealthy countries in equatorial


Mr. Vincent Randall, Cultural Director for Yavapai-Apache Nation, advises Mr. Andrew Stevenson, USFS silviculturist.


Tribal monitors collecting data on soil stability at an Emory oak stand.

For several decades, Apache elders have voiced concern regarding the health of Emory oak ecosystems, specifically noting low levels of seedling recruitment and diminished acorn yields. In 2018, western Apache Tribes, the US Forest Service (USFS), industry groups, and researchers at Northern Arizona University convened to develop a conservation program centered on Emory oak restoration. The Emory Oak Collaborative Tribal Restoration Initiative (EOCTRI) serves as a regional model for co-produced science and conservation. Tribal members identified the management concern and steer research, restoration methodology, and communication activities. Tribal monitor field crews employed through the WestLand Resources, Inc. Tribal Monitor Program receive capacity in western scientific research methodology, and collect the majority of the ecological data that guides adaptive management of restoration activities. Restoration treatments focus on reducing biomass to reduce competition for dwindling water resources and to decrease the likelihood of stand replacing wildfires. Restoration sites will be used to host intergenerational events to support knowledge transfer and cultural activities related to acorn harvest. Novel ways of quantifying effects on human interactions with restored landscapes are being co-developed, in order to measure the socio-ecological objectives of this project. Student training merges SEK and TEK.

FIGURE 4
A model for co-produced science and management in the Southwest.

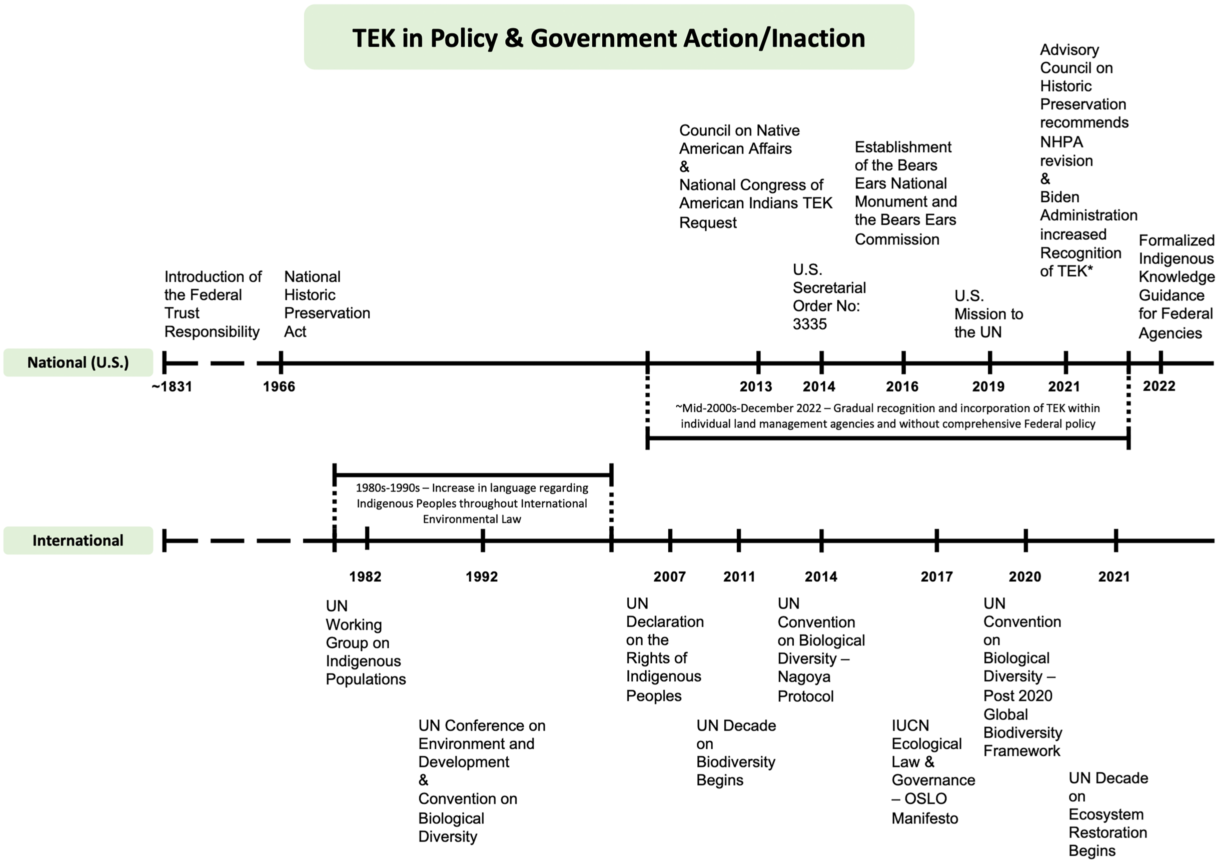

FIGURE 5
A timeline of TEK policy integration at both the national (upper timeline) and international (lower timeline) level. This timeline is not exhaustive but meant to highlight the overall progression of TEK acknowledgment within policy. *The Biden Administration's increased recognition of TEK is represented in policy such as: Memorandum for the Heads of Departments and Agencies, Indigenous Traditional Ecological Knowledge and Federal Decision Making, 2021, U.S. Joint Secretarial Order No. 3403: Fulfilling the Trust Responsibility to Indian Tribes in the Stewardship of Federal Lands and Waters, 2021, Executive Order #14072 Strengthening the Nation's Forests, Communities, and Local Economies, 2022, Executive Order #14049 White House Initiative on Advancing Educational Equity, Excellence, and Economic Opportunity for Native Americans and Strengthening Tribal Colleges and Universities, 2022, and Executive Order #13990 Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis.

regions where lack of consultation with local communities has resulted in ineffective programs (Michon et al., 2007; Dressler et al., 2012; Vaz and Agama, 2013; Albuquerque et al., 2019; Johansson et al., 2019). In Ethiopia, the creation of Reducing Emissions from Deforestation and forest Degradation (REDD) carbon conservation areas increased risk of large fires, reducing or potentially nullifying overall carbon sequestration gains (Johansson et al., 2019). More broadly, ignoring local traditions and use patterns has frequently resulted in conflict and non-compliance with imposed regulations; problems largely resolved by co-development of management plans with local communities (Rodriguez-Navarro, 2000; Anderson et al., 2005; Spak, 2005; Michon et al., 2007; Dressler et al., 2012; Uprety et al., 2012; Vaz and Agama, 2013; Indrawan et al., 2014; Albuquerque et al., 2019; Kiage, 2019; Nanlohy et al., 2019; Fabre et al., 2021). Inclusive land governance often results in increased engagement and stewardship behavior when local values and priorities are incorporated into land management practices, creating a shared vision for governance (Oettlé et al., 2004; McGetrick et al., 2015; Long and Lake, 2018; Pyke et al., 2018; Tsai, 2020; Skroblin et al., 2022). This is particularly important for reducing conflict when managing pooled or common resources (Kanwar et al., 2016). Applying a coupled human-natural system lens is critical to meet the multiuse missions of many US public land managers that must maintain ecological health, while supporting social uses of national forests, grasslands, and other areas.

4.4. Intrinsic value of TEK

Though this review focuses on improving ecological outcomes by integrating TEK into land management, we recognize the intrinsic value of ecocultural practices, traditions, and local ecological knowledge (Carino et al., 2009; Mackey and Claudie, 2015). For much of the 20th century, society broadly valued local knowledge of flora and fauna due to potential economic contributions of new foods, medicines or other products. While the benefit of TEK for identifying and managing these resources is still important (Turner et al., 2000; Chapman, 2008; McCallum and Carr, 2012; Rodenburg et al., 2012; Maroyi, 2017, 2022; Nalau et al., 2018; Strenchok et al., 2018; Guerrero-Gatica et al., 2020; Abbas et al., 2022), ecocultural resources have been more holistically valued within the framework of 'Cultural Ecosystem Services' (CESs). Cultural ecosystem services include intangible, yet invaluable, functions beyond supplying commodities, such as providing inspiration, aesthetically pleasing views, a sense of place, cultural vitality, and recreational, educational and fellowship opportunities

(Paudyal et al., 2016; Pascua et al., 2017). The CES categorization provides a strong foundation to better value human connections to ecosystems, yet may not fully capture the pivotal role of TEK in preserving culture, language and relationships. Cultural keystone species, a term coined by Nabhan and Carr (1994), describes species that feature so heavily in language, ceremonies, traditions and oral history to be necessary for cultural practices. The cultural keystone concept could be extended to describe ecosystems, places, and landscapes necessary to sustain culture.

Incorporating local and Indigenous perspectives into land management to support the continuation of cultural practices is increasingly valued, even when financial gains are not a primary driver (Kruger, 2005; Long and Lake, 2018; Lindsay et al., 2022; Skroblin et al., 2022), as exemplified by several recent court rulings requiring dam removal to support traditional fishing (Long and Lake, 2018). Support of bio-cultural sovereignty, the right of people to access landscapes and natural resources necessary for cultural practice, itself an important management goal (Cleary, 2005; Jackson et al., 2005; Spak, 2005; Alan et al., 2006; Jackson, 2006; Menzies, 2006; Christensen and Grant, 2007; Houde, 2007; Banjade et al., 2008; Grice et al., 2012; Uprety et al., 2012; Baldy, 2013; Brondízio et al., 2021; Fabre et al., 2021; Parsons et al., 2021; Lindsay et al., 2022). In addition to advancing favorable ecological outcomes, co-management of natural resources with local and Indigenous groups, protects cultural diversity, and power-sharing, a core value of democratic societies (Devin and Doberstein, 2004; Spak, 2005). As medical research increasingly demonstrates health benefits of interactions with nature (Driessnack, 2009; Hansen et al., 2017; Chaudhury and Banerjee, 2020), access to eco-cultural resources may be seen as a fundamental human right (Menzies, 2006). Given the reliance of local and Indigenous groups on nearby ecosystems for cultural practices and subsistence, mismanagement of natural resources disproportionally affects these often marginalized groups. Inclusive governance is particularly important to avoid exacerbating historical injustices and inequities as climate change drives shifts in ecosystems and natural resources (Pollino et al., 2007; Banjade et al., 2008; Blanch, 2008; Vinyeta and Lynn, 2013; Maldonado et al., 2014; McGetrick et al., 2015; Schick et al., 2018). Valuation of alternative knowledge systems is important in modern pluralistic societies and may drive novel insights of complex coupled human and ecological systems (Colchester, 2004; Houde, 2007; Bohensky and Maru, 2011). Integration of TEK and goals related to eco-cultural protections in to land management strategic planning is generally supported by local communities and should be prioritized by US land management agencies (Nanlohy et al., 2019; Fabre et al., 2021; Skroblin et al., 2022).

5. Applying TEK to improve land management

5.1. Harvest practices and single species conservation

Ecological constraints and human reliance on ecosystems reinforced norms associated with ecological sustainability, which can be broadly applied to single species management (Turner et al., 2000; Moller et al., 2004; Phuthego and Chanda, 2004; Menzies, 2006; Rai, 2007; Ulluwishewa et al., 2008; Mulyoutami et al., 2009; Newmaster et al., 2011; Nimachow et al., 2011; Baldy, 2013; Walsh et al., 2013; Childs and Choedup, 2014; Mackey and Claudie, 2015; Mavhura and Mushure, 2019; Shokirov and Backhaus, 2020; Alexander et al., 2021; Kobluk et al., 2021; Negi et al., 2021). Traditional harvest practices often integrate triggers to slow, pause or alter harvest based on on-the-ground observations, adjusting behavior to prevent resource degradation (Walsh et al., 2013; Mavhura and Mushure, 2019). In British Columbia, the Haítzaqv (Heiltsuk First Nation) harvest feather boa kelp for food, ceremonial use and as a trade item. Ecological analysis of traditional harvest revealed that the rate of removal of kelp fronds was similar to loss incurred through wave action during the growing season, revealing how traditional harvest mimicked natural ecological processes. Moreover, the Haítzaqv provided researchers with a variety of environmental conditions, like water temperature and wave exposure, that support recovery after harvest (Kobluk et al., 2021).

In some cases, traditional human harvest behavior may shape evolutionary, demographic or spatial characteristics of populations (Herrmann, 2005, 2006; Cosby et al., 2022). In Chile and Argentina, monkey puzzle trees (*Aruacaria araucana* (Molina) K. Koch), a threatened species of conifer, are an important food source for Mapuche people, supplying nutritious nuts, called *piñones*. The accepted Mapuche harvest technique of men climbing to harvest nuts, constrained which trees within a population were harvested, since harvest was limited to trees that could support the weight of an adult human (Herrmann, 2005, 2006). This not only promoted sustainable harvest, but may have shaped genetic diversity patterns, demographic structure of populations, and evolutionary trajectories, by allowing younger or smaller trees to disproportionally contribute to population growth, since seeds from smaller class trees avoided harvest. Species valued as food, fiber, or medicine may drive traditional management practices that influence ecosystems at the landscape-level. The Karuk and Yurok Tribes of California reduce acorn infestation of black oaks by filbertworms and filbertweevils through cultural burning (Halpern et al., 2022). Management for this important first food may have shaped fire regimes and community composition within Californian forests (Kimmerer and Lake, 2001; Adlam et al., 2021; Halpern et al., 2022). Understanding human interactions with such cultural keystone species may yield broad insights about landscape management and restoration.

As globalization and other forms of anthropogenic change increase pressure on natural resources, integrating TEK into regulations supports sustainable harvest and can reduce conflict over resources (He et al., 2011; Childs and Choedup, 2014). In China, land managers successfully employed TEK to establish harvest laws to regulate an emergent mushroom market (He et al., 2011). In response to the commercialized harvest of *Thelephora ganbajun*, or ganba fungus, a type of coral mushroom native to the Yunnan province of China, land managers co-produced regulations with local communities who had sustainably harvested this mushroom, in order to support the conservation of both the mushroom and the tradition of harvest practiced by Yunnan communities (He et al., 2011). Applying traditional harvest techniques may ensure sustainable harvest, and thus support continued cultural connections with harvested species, when global markets lead to increased demand on local resources.

5.2. Improving ecological assessments

Engaging local communities in the development of ecological monitoring and assessments has the potential to advance our ability to track ecological changes (Goodall, 2008; Kakinuma et al., 2008; Ens et al., 2010; Rasalato et al., 2010; van de Pol et al., 2010; Prober et al., 2011; Leonard and Parsons, 2013; Moura et al., 2013; Gratani et al., 2014; Behmanesh et al., 2016; Savo et al., 2017; von der Porten et al., 2019; Mugambiwa and Makhubele, 2021; Pyke et al., 2021; Souther et al., 2021b). First, incorporating TEK in ecological assessments can increase monitoring efficiency and coverage, which is particularly important, given that many land management agencies lack the resources to support comprehensive monitoring programs (Souther et al., 2021b; Teixidor-Toneu et al., 2022). Traditional ecological knowledge enhances efficiency by applying detailed understanding of landscapes to survey methodology (Ballard et al., 2008). As an example, one group tasked with monitoring lynx populations on public lands in California trained local community members to census lynx. Locals increased the completion speed of the surveys due to superior knowledge of the landscape and of lynx population locations (Ballard et al., 2008). Integrating TEK of local groups into monitoring is particularly important when species or phenomena of interest are not readily observed by the general public, federal staff, or researchers, such as when focal species are remote, rare or cryptic (Parlee and Manseau, 2005; Goldman, 2007; Marin et al., 2017; Deb, 2018; Pyke et al., 2018; Baker and Constant, 2020; Sloane et al., 2021; Teixidor-Toneu et al., 2022).

Local communities distil complexity of ecological systems using TEK, employing methods like identifying indicator species linked to more complex ecological phenomena, which can be used to simplify monitoring procedures (Armatas et al., 2016; Behmanesh et al., 2016). In Iran, for instance, the government modified rangeland degradation assessments to incorporate indicators (i.e., abundance or depletion of particular grasses) used by local pastoralists, supporting widespread and consistent documentation of key ecological processes (Behmanesh et al., 2016). Local communities may also have fine-scale knowledge of systems, critical for effective management (Pyke et al., 2018; Baker and Constant, 2020; Matshameko et al., 2022). Cree fishermen in Canada described more morphotypes of fish species, potentially representing important genetic variation in fish populations, and provided more detailed information on seasonal movement, spawning behavior, and reproductive timing compared to SEK research conducted in the same region (Marin et al., 2017). These observations allowed managers to attribute declining lake trout populations, an important game fish and food source, to climate change driven loss of trout prey base (Marin et al., 2017). Finally, the deep-time perspective of TEK may be leveraged to define baseline conditions, establish restoration targets (Uprety et al., 2012; Leonard and Parsons, 2013; Gratani et al., 2014), track global change impacts (Armatas et al., 2016), and serve as an early warning system of large-scale ecological state transitions (Souther et al., 2021a). Programs integrate TEK into monitoring in a variety of ways, like co-developing monitoring protocols with local and Indigenous groups and overlaying these procedures with western SEK techniques to extrapolate observations from monitoring plots using local insights (Ballard et al., 2008). Ecological studies and management actions employing Multiple Evidence-Based approaches, which include both western and traditional science methods, likely yield a more comprehensive ecological understanding and foster creative solutions to address environmental problems (Pyke et al., 2021).

5.3. Enhancing management actions

Indigenous and local communities interact with ecosystems in a variety of ways, ranging from species-specific interactions, like removing undesirable species to reduce competition with preferred plants, or acting as ecosystem engineers by modifying soils for cultural and food-generating purposes. TEK-guided management may especially improve ecological outcomes when ecosystems co-evolved with human populations long-term, and adoption of traditional behaviors represents a restoration of essential human functions within the landscape (Pellatt and Gedalof, 2014). In Australia, reintroduction of cultural burning practiced by Aboriginal people produced unexpected secondary ecological changes, increasing the diversity and abundance of mid-sized mammalian species, whose numbers were steadily declining (Gott, 1982; Kay, 1994; Bond and Keeley, 2005; Smith, 2007; Bliege Bird et al., 2008; Kondo et al., 2012; Bird M. I. et al., 2013; Bird R. B. et al., 2013; Rangan et al., 2015; Boivin et al., 2016; Clinchy et al., 2016; Suraci et al., 2016; Smith et al., 2017; Sullivan et al., 2017; Vigilante et al., 2017; Albuquerque et al., 2018; Bliege Bird and Nimmo, 2018; Power et al., 2018; Crabtree et al., 2019). Similar patterns are emerging in the US, where cultural burning supports land management agencies efforts to re-establish natural fire regimes following 20th century fire suppressions policies (Adlam et al., 2021; Long et al., 2021). Reintroduction of fire in fire-adapted systems reduces risk of catastrophic, stand altering wildfires and removes invading, non-fire adapted species, decreasing competition for resources of endemic species. In California, US, for instance, TEK-integrated forest restoration reduced burn severity and damage caused by wildfires relative to untreated areas (Slaton et al., 2019). Other forms of traditional land management, such as grazing strategies and alteration of vegetation for agroforestry or hunting, increases plant diversity, principally through increasing the heterogeneity of management strategies on the landscape (Pyke et al., 2018; Silva-Rivera et al., 2018; Uchida and Kamura, 2020; Fabre et al., 2021). Developing a understanding of ecological systems, which integrates human functional roles, provides a more comprehensive ecological perspective and is particularly important for developing appropriate restoration actions.

Co-development of management strategies generally improves land management outcomes (Michon et al., 2007; Vaz and Agama, 2013; Albuquerque et al., 2019; Forest et al., 2019). Engaging local populations in land management decisions has been found to increase buy-in on agreed upon practices, lead to stewardship behavior and reduce exploitation of shared natural resources (Sanchez, 2000; Spak, 2005; Mackey and Claudie, 2015; Sheil et al., 2015). Similarly, regulations developed specifically to enhance cultural connections to the landscape has been shown to increase engagement with public lands and reduce conflict (Rodriguez-Navarro, 2000; Indrawan et al., 2014; Matthews, 2016). On some tribal lands, management is shifting away from western scientific concepts of management, and explicitly making decisions that improve the viability of first foods (Quaempts et al., 2018). Reframing management of public lands to prioritize cultural ecosystem services may result in more equitable land management, increase long-term support for public lands, and reduce conflict with land management agencies.

Ecological restoration projects are growing in number and scale, particularly as anthropogenic change increases the frequency and severity of disturbances, like wildfire and drought (Copeland et al., 2018). Traditional ecological knowledge can contribute to restoration success in several key ways. Local or Indigenous groups may identify restoration plant materials that are not only adapted to regional climate and soils, but are also utilized by local populations, thus improving the intrinsic value of restored lands and encouraging stewardship behaviors (Gaur and Gaur, 2004; Tarbox et al., 2020). 'Traditional technologies' may represent low-cost, culturally appropriate methods of landscape restoration. Rock dams (commonly referred to as *trincheras* or, *gabions*, in the Southwest US) are used in arid and semi-arid regions to promote growth of vegetation (Bainbridge, 2012; Cassin et al., 2021; Norman et al., 2022). These rock dams slow water infiltration and stabilize soil during rain events driving revegetation in degraded areas. The Zuni people create waffle gardens to grow dryland crops (Bainbridge, 2012).

By creating indentations in the soil for planting, dryland farmers encourage water to accumulate at the base of the plant. Applying similar techniques prior to reseeding plant materials following disturbance in dryland areas could increase plant recruitment, which is notoriously low in these systems (Bainbridge, 2012).

5.4. Identification of protected areas

Many Indigenous groups identify sacred areas (Das et al., 2021), which often represent unique species assemblages, high numbers or performance of culturally important species, and/or areas with an abundance of a limiting resource (i.e., water; Watson et al., 2003; Rai, 2007, 2011; Boillat et al., 2013; Mackey and Claudie, 2015; Friday and Scasta, 2020; Utami and Oue, 2021). In India, sacred groves of trees have higher plant diversity relative to similar unprotected habitat (Rai, 2011). The Minangkabau people in Indonesia protect areas within forests and river habitat that serve as a source population for fish and other natural resources, ensuring the long-term provisioning of these resources (Utami and Oue, 2021). Higher diversity and function of these systems may be driven through cultural practices or because these regions are ecologically unique. Regardless, incorporating sacred areas into land management strategies can improve landscape-scale conservation and ecological resilience in the context of climate change by capitalizing on extant human connections to place (Watson et al., 2003; Herrmann, 2006; Rai, 2011; Kamal and Lim, 2019; Das et al., 2021; Utami and Oue, 2021). Many Indigenous and local groups connect lineages and family to particular places. Ensuring access to these areas is important for the health of human populations and culture, while also encouraging land stewardship (Mackey and Claudie, 2015). Prioritization of sacred areas for TEK-integrated management planning, conservation and restoration actions protects ecologically important areas, while simultaneously supporting cultural practices, and priorities of local and Indigenous groups (Rai, 2007).

5.5. Identifying and coping with novel threats posed by global change

Long-term perspectives allow the identification of novel threats posed by rapid global change, and can serve as an early warning system for catastrophic ecological events (Seely, 1998; Macharia, 2004; Pamo, 2004; Pollino et al., 2007; Goodall, 2008; Liwenga, 2008; Vaarzon-Morel and Edwards, 2012; Barber et al., 2013; Leonard and Parsons, 2013; Lepofsky and Caldwell, 2013; Ruiz-Mallén and Corbera, 2013; Armatas et al., 2016; Austin et al., 2017; Farimani et al., 2017; Kainamu-Murchie et al., 2018; Kaiser et al., 2019; Arias-Bustamante and Innes, 2021; Copes-Gerbitz et al., 2021; Sinta et al., 2022). Integrating TEK into management of ecosystems affected by global change may improve outcomes, since TEK guides management actions based on ecological indicators rather than arbitrary jurisdictional or bureaucratic dictates (Bach et al., 2019). As an example, Aboriginal Australian-led weed management activities, cataloged invasive weeds based on their effects and roles within ecosystems rather than government-generated categories, like native/non-native status or abundance, which may or may not reflect impacts to ecosystems (Bach et al., 2019). Traditional ecological knowledge may also provide technological advances to natural resource management of emergent threats. In Australia, Aboriginal Australians applied natural piscicides developed for fishing to reduce abundance of invasive tilapia (Gratani et al., 2011, 2014). Since TEK-management actions are tied to temporal ecological processes rather than Gregorian calendars or funding calendars, they are easily modified to account for global change. For instance, many local and Indigenous communities ignite fires based on observed fuel loading or the occurrence of seasonal rains, allowing flexibility to shift practices that result in desired conditions (Butz and Butz, 2009; Armatas et al., 2016). An understanding of social systems related to land management may support adaptive responses to changing environmental conditions by identifying beliefs, needs or behaviors that support or constrain mitigation (Leonard and Parsons, 2013). Impoverished communities in Peru prioritized meeting immediate existential needs, precluding long-term planning necessary for climate adaptation (Popovici et al., 2021). In this case, effective climate change-integrated management also addressed societal needs of Peruvian communities. In addition to improving climate adaptation strategies, local and Indigenous people should be involved in climate adaptation planning to prevent exacerbating historic injustices, since cultural practices depend on species and places that may be imperiled by climate change (Bardsley and Wiseman, 2012; Ruiz-Mallén and Corbera, 2013; Maldonado et al., 2014; Beamer et al., 2021; Souther et al., 2021a).

5.6. The role of western scientific knowledge in the TEK-management paradigm

Traditional ecological knowledge and SEK systems are frequently contrasted, and cited as a primary barrier that prevents incorporation of TEK into land management. While some contend that TEK and SEK are inherently incompatible (Bohensky and Maru, 2011), in practice these knowledge systems are largely complementary, providing distinct benefits and possessing inherent limitations (Moller et al., 2004; Cullen-Unsworth et al., 2012; Holmes and Jampijinpa, 2013; Johnson et al., 2015; Holtgren and Auer, 2016; Zahn et al., 2018; Keats and Evans, 2020). Traditional ecological knowledge provides a long-term and comprehensive view of ecological systems, which can provide key insights for scientific inquiry and advance ecological disciplines (Moller et al., 2004). Scientific disciplines have developed experimental, statistical, and instrumental methodology that allow researchers to attribute causality to particular phenomena, detangle effects of multiple variables, and quantify the magnitude and direction of ecosystem responses to various factors. The peer-review process and mandate to publish findings supports quality control and knowledge transmission. While advancing understanding of natural phenomena, the scientific process is limited by the accuracy of instrumentation and bounds on the complexity and realism of experiments, and in some cases may not have the capacity to test hypotheses posited by TEK-holders.

Some suggest that validation of TEK-generated hypotheses using the western scientific process is disrespectful and derivative (Bohensky and Maru, 2011; Gratani et al., 2014). Without exception, no research should take place without express support from local or Indigenous communities, and TEK must be properly attributed to knowledge-holders. However, issues of disrespect can be largely addressed by valuing TEK as a complementary and important form of knowledge, and by acknowledging the limits of scientific inquiry (McMillan and Prosper, 2016). In Canada, land managers and Indigenous Canadians, adopted the conceptual framework of 'Two-Eyed Seeing', with a focus on respecting both knowledge systems and working towards mutual understanding and integration of different viewpoints in land management decisions (McMillan and Prosper, 2016). With a respectful approach, SEK can codify lessons derived from TEK, which has several important benefits. First, Indigenous and local groups are not monolithic, but represent a diversity of opinions, observations, and beliefs, which means that there may be competing hypotheses generated within communities not easily translated into management recommendations without testing (Kiptot, 2007; Knapp and Fernandez-Gimenez, 2009; Fritz-Vietta et al., 2017; St Laurent et al., 2017; Albuquerque et al., 2019; Baker and Constant, 2020; Friday and Scasta, 2020; Varghese and Crawford, 2021). Secondly, while SEK is limited in scale and scope, strict adherence to the scientific process limits bias and erroneous conclusions. Devaluing scientific knowledge has significant risks and drawbacks, as exemplified recently during the COVID-19 pandemic in which a large portion of the US population ignored medical recommendations, prolonging and extending the reach of the pandemic with catastrophic loss of life, particularly in Indigenous communities (Hatcher et al., 2020; Wang, 2021).

Federal land-managers are often tasked with maintaining ecological integrity while supporting multi-use mandates for public lands. Certain social and cultural preferences are prioritized in land management, even when ecological sciences suggest negative impacts. A key example is the development of roadways for on and off-road vehicles to access public lands for recreational purposes. Development of roadways negatively impacts ecosystem connectivity and wildlife behavior (Trombulak and Frissell, 2000; Gelbard and Belnap, 2003), yet is broadly accommodated by land management agencies, since providing public access is an inter-agency value. Protection of traditional ecological knowledge and ecocultural resources should be similarly prioritized in federal land management for cultural benefits alone, regardless of consensus of TEK and SEK.

6. Challenges to integrating TEK into land management

6.1. Lack of financial support

Co-developing management strategies that integrate TEK with local and Indigenous communities is time-consuming and resource intensive, in ways that are difficult to justify under current budget, funding, and performance assessment structures. Months of engagement may result in a single document, management action or other deliverable; yet those months of collaborative planning are vital for ethical project management (Long and Lake, 2018). Many funding sources do not provide support for project co-development, leading projects to skip the critical step of building trust and consensus (Görg et al., 2014; Johnson et al., 2015; Woodward and Marrfurra McTaggart, 2016; Pristupa et al., 2018; Adlam et al., 2021). Funding constraints often prevent providing food and travel to participants, depressing participation of historically disadvantaged, impoverished, or rural groups. Similarly, funding may not support appropriately-priced honoraria to support TEK transfer (Adlam et al., 2021). As one member of the EOCTRI directory board explained, Indigenous elders are perceived in a similar way as PhD scientists, and deserve adequate compensation for expertise.

6.2. Institutional norms and barriers

Federal, and more generally, US workforce norms that promote transience preclude meaningful long-term engagement with communities. Upward mobility within many Federal agencies often requires detailing into and/or accepting positions in other regions across the country (Diver, 2016). Revolving doors of key project personnel limit the ability to build the trust and relationships to effectively engage with local or Indigenous communities. Top-down organizational systems also echo unjust power structures, while simultaneously limiting access of local and Indigenous community members to higher level managers to co-develop management plans (Robbins, 2000; Ferse et al., 2010; Ogbaharya and Tecle, 2010; Pickering Sherman et al., 2010; Raymond et al., 2010; Gallemore et al., 2014; Diver, 2016; Schick et al., 2018; Fache and Pauwels, 2020). At times, excellent co-developed projects spearheaded by lower-level federal employees are never realized due to lack of upper-level engagement and buy-in, exacerbating sentiments of mistrust (Gallemore et al., 2014). Disciplinary and organizational silos within federal agencies and academic institutions are often inherently incongruous with holistic concepts embodied in TEK. The structure of these systems adds to project inertia, since completing the necessary tasks and gathering decision-makers to move projects forward is time-consuming. Short-term funding cycles, which typically provide a maximum of 5 years of project support, do not permit sufficient time to develop the relationships and programmatic infrastructure necessary for successful project completion and delivery of meaningful products (Keppel et al., 2012). Extending timelines for project completion may result in disengagement of local communities (Ross and Pickering, 2002; Henn et al., 2010; Görg et al., 2014).

6.3. Informational sensitivity

Due to historic injustices, many local groups, particularly Indigenous communities, are hesitant to share cultural information with the broader public (Pinel and Pecos, 2009; Johnson et al., 2015; Lynch et al., 2017; Baker and Constant, 2020). Concerns around information security may make Indigenous communities less likely to engage with land management agencies to protect cultural resources or integrate TEK into practice. Co-produced management strategies must develop strong rules regarding the release, use and disclosure of information (Chapman, 2008; Singh, 2008; Pinel and Pecos, 2009; Holcombe and Gould, 2010; Johnson et al., 2015; Lynch et al., 2017; Baker and Constant, 2020). Formalized data management plans and information sharing agreements should be developed to protect both privacy and intellectual property of local and Indigenous groups. Informational advisory boards, like the EOCTRI *Chi̓chil* advisory board, can review content prior to publication (Figure 4). Western scientific scholars are codifying methods to cite and attribute local and Indigenous knowledge (MacLeod, 2021). Incorporation of TEK into management must not be extractive, but beneficial to participating groups. Governing and academic institutions should support the professional development of local and Indigenous leaders to guide appropriate use and incorporation on TEK (Latulippe and Klenk, 2020).

6.4. Disparate data types

Traditional ecological knowledge is often passed through generations and communities in oral histories and information is generally qualitative, rather than quantitative (Prober et al., 2011; Long and Lake, 2018). For governing or land management institutions, analytical evidence generated through quantitative statistical approaches is often favored, and thus TEK is often translated to SEK frameworks (Ross and Pickering, 2002; Pickering Sherman et al., 2010; Lemieux et al., 2018; Lindsay et al., 2022). Translating TEK to SEK at times results in losses of meaning, because topics of faith or spirituality by definition cannot be tested *via* the scientific process and thus are dismissed as irrelevant to management (Prober et al., 2011; Long and Lake, 2018). Such cultural differences between land managers and local groups can lead to misunderstandings or generate unbalanced power dynamics that devalue TEK in favor of SEK (Salmon, 2000; Houde, 2007; Raymond et al., 2010; Quaempts et al., 2018; Friday and Scasta, 2020; Huambachano and Cooper, 2020). Reconciling different knowledge types is time-consuming, requires establishing a shared vocabulary, identifying metrics that can be evaluated, and creating a respectful environment for knowledge sharing (Keats and Evans, 2020). Because local and Indigenous communities are diverse, careful consideration must be given when conducting outreach to identify TEK-experts in order to create a holistic understanding of an ecosystem. In many cultures, for instance, women and men hold different knowledge of the landscape (Pfeiffer and Butz, 2005; Wirf et al., 2008; Pinel and Pecos, 2009; Elias et al., 2017; Pristupa et al., 2018; Rumbiak and Wambrauw, 2018; Nayak, 2019). Meeting times and locations should be created such that no group is systematically excluded from conversations. For many US Indigenous communities, respected knowledge holders are often elderly and may have mobility or other issues that must be addressed to ensure their participation (Kiptot, 2007; St Laurent et al., 2017; Williams et al., 2020).

6.5. Bridging the local-national scale

By nature, TEK is local, yet public land management occurs at a variety of scales, ranging from local to national-levels. Extrapolating information from one project area to another may be impossible, though broad themes and concepts will no doubt emerge and support programs nationally (Cox and Elmqvist, 1994; Robbins, 2000; Ballard et al., 2008; Raymond et al., 2010; Watson, 2013; Bocco and Winklerprins, 2015; Armatas et al., 2016; Fernández-Llamazares et al., 2016; Schick et al., 2018). Local communities must respond to emergent environmental issues, yet often, due to bureaucratic structures, decision-making power often resides with institutions or officials located far from management areas (Nooteboom and de Jong, 2010; Mistry et al., 2016). On the other hand, programs that are too large or complex, risk being so cumbersome and impersonal as to lose the consensus of participants necessary to effectivity function (Bocco and Winklerprins, 2015; Fernández-Llamazares et al., 2016).

7. Best practices and emerging tools to bridge TEK and SEK

Integration of TEK into land management and scientific inquiry must be ethical and inclusive. Several best practices for working with local and Indigenous knowledge emerged from this review, including the need for:

1. Rigorous safeguards to protect intellectual property around TEK;
2. Respectful knowledge sharing and co-creation of products, with formalized partnership agreements that outline roles and expectations at the onset of projects;
3. Prioritization of long-term consistent engagement of partners, with a focus on community and relationship-building; and
4. Proper acknowledgement and compensation for TEK.

These basic precepts could be expanded or adjusted to effectively protect and engage local or Indigenous communities depending on project needs. However, projects that explicitly integrate informational protections, specify collaborative best practices, particularly related to TEK attribution and compensation, and center relationships from the outset are more likely to lead to long-term meaningful outcomes (Chapman, 2008; Jones et al., 2008; Singh, 2008; Cullen-Unsworth et al., 2012; Woodward and Marrfurra McTaggart, 2016; Lynch et al., 2017; Albuquerque et al., 2019). Frameworks, such as ‘Two-Eyed Seeing’, offer conceptual structures to bridge TEK and SEK systems (Preuss and Dixon, 2012; McMillan and Prosper, 2016; Badry and Hickey, 2022). In essence, ‘two-eyed seeing’ is a collaborative strategy that aims to respectfully and equally represent both TEK and SEK perspectives during project development (McMillan and Prosper, 2016). Analytical methods to support project co-creation within the framework of ‘Two-Eyed Seeing’ and similar paradigms include Actor-Network Theory (ANT; Badry and Hickey, 2022). Actor-network theory is rooted in social-ecological theory, and provides a framework to investigate emergent properties of coupled human-environmental systems including critical system components, interactions and feedbacks (Badry and Hickey, 2022). In this vein, Bayesian Belief Networks (BBNs) allow users to explore system dynamics by using oral interviews and other forms of qualitative data to identify common vocabulary, structures, and processes (Liedloff et al., 2009). Another potentially powerful tool for incorporating TEK in land management Participatory Geographic Information Systems (PGIS), which is a form of participatory planning using maps. The use of maps to guide discussions provide a bridge among different knowledge systems (Puri and Sahay, 2003; Robbins, 2003; Sandström et al., 2003; McCall and Minang, 2005; Puri, 2007; Laumonier et al., 2008; Torres-Meza et al., 2009; Cullen-Unsworth et al., 2012; Hoverman and Ayre, 2012; McCallum and Carr, 2012; Cullen, 2015; Gadamus and Raymond-Yakoubian, 2015; McGetrick et al., 2015; Lynch et al., 2017; Albuquerque et al., 2019; Peart, 2019; Cho and Mutanga, 2021; Shaw et al., 2021). Other emergent methodologies, such as art-based ecological projects (Höivik and Luger, 2009; Foley, 2017), ecosystem accounting (Normyle et al., 2022), online collaborative tools (Pert et al., 2015), and other technologies (Touchette et al., 2021), could further support TEK-integration into land management. Land managers may benefit from training in group facilitation and frameworks for working with diverse human populations. Most critically, integrative projects, particularly when working with historically marginalized populations, must center respectful relationships by valuing different viewpoints and building trust (Jones et al., 2008; Cullen-Unsworth et al., 2012; Woodward and Marrfurra McTaggart, 2016; Lynch et al., 2017; Albuquerque et al., 2019; Badry and Hickey, 2022).

8. US policy pertaining to TEK

Within the US, there is a policy framework that could be expanded to enhance protection for ecocultural resources and prioritize TEK-integrated management actions on public lands (Figure 4). Policy relating to TEK began with the introduction of the Federal Trust Responsibility around 1831, which established a perceived responsibility of the Federal government to Native Nations *via* their government-to-government relationship (Berkey, 2006). While not specific to TEK, the Federal Trust Responsibility marks the initial recognition of the so-called trust relationship. The Federal Trust Responsibility has been loosely recognized by administrations throughout time and is characterized by ambiguity, providing little accountability or legal strength (Berkey, 2006). Into the 1900s, there was little to no activity surrounding TEK at a policy level. Later in the 1960s, a glimpse of recognition of traditional knowledge occurred through the verbiage in Section 106 of the National Historic Preservation Act, mentioning 'special expertise' when referring to the level of involvement by Indigenous peoples (Advisory Council on Historic Preservation, 2021).

More specific consideration of Indigenous peoples' knowledge systems and rights occurred first at the international level during the 1980s and 1990s with an increase in language within international environmental law (Colchester, 2004). The United Nations Economic and Social Council established the Working Group on Indigenous Populations in 1982, which shortly after began the two-decade-long process of drafting the Declaration on the Rights of Indigenous Peoples (Colchester, 2004; United Nations, 2007; Robinson et al., 2021). In 1992, the United Nations Conference on Environment and Development, also known as 'Earth Summit,' introduced a call to action to governments to integrate TEK in research, land management, and conservation but only at the 'appropriate level' (United Nations Sustainable Development, 1992). Simultaneously, the UN Convention on Biological Diversity recognized Indigenous peoples as knowledge holders with traditional ways of life relevant to conservation and biodiversity efforts (United Nations Sustainable Development, 1992; United Nations, 1992). By 2007, the UN finally formalized the Declaration on the Rights of Indigenous Peoples, which included rights to their traditional knowledge (Robinson et al., 2021). Upon formalization, 144 countries voted for the declaration and 4 countries voted against, one of which was the United States.

While some Federal agencies such as the Environmental Protection Agency (EPA) had mentioned cooperation with Indigenous peoples in their policies as early as the 1980s, the focus was often in consideration of the Federal Trust Responsibility and limited to reservation lands (Environmental Protection Agency, 1984). During the mid-2000s, there was a gradual recognition and incorporation of TEK within individual Federal agency statements and policies, such as the EPA, National Park Service, United States Fish and Wildlife Service, and the USFS. However, there was still no comprehensive Federal policy on TEK. In 2011, the United Nations Decade on Biodiversity began, which emphasized place-based knowledge and recommended the consultation of Indigenous and local communities to implement the strategic plan surrounding biodiversity conservation (United Nations Environmental Programme, 2011). Former President Barack Obama issued an executive order in 2013 establishing the White House Council on Native American Affairs, reaffirming the Federal Trust Responsibility and communicating support for honoring Indigenous sovereignty and self-determination (The White House Office of the Press Secretary, 2013). In the same year, the National Congress of American Indians passed resolution #REN-13–035 titled: Request for Federal Government to Develop Guidance on Recognizing Tribal Sovereign Jurisdiction over Traditional Knowledge (National Congress of American Indians, 2013). The following year US Secretarial Order No: 3335, Reaffirmation of the Federal Trust Responsibility to Federally Recognized Indian Tribes and Individual Indian Beneficiaries – recognized the failings of the Department of the Interior in fulfilling the Trust Responsibility and called for collaboration and partnership on mutually beneficial projects in a 'New Era of Trust', but without specific mention of TEK (US Secretary of the Interior, 2014).

The 2010 Nagoya Protocol on Access and Benefit Sharing was an important international agreement that helped to implement protections for traditional knowledge holders regarding genetic resources. The Protocol, enforced in 2014, underscores the rights of Indigenous communities to grant access to genetic resources, the necessity of prior informed consent, and equitable benefit sharing to ensure recognition and compensation to the knowledge holders (United Nations Environmental Programme, 2011). The presidential proclamation that designated the Bears Ears National Monument also established the Bears Ears Commission, which communicated TEK as a 'resource' to be protected and heard rather than knowledge formation which should be built upon (The White House Office of the Press Secretary, 2016). Additional international policy continued to incorporate key perspectives from TEK, such as viewing ourselves as a part of nature rather than separate from, as referenced in the 2017 OSLO manifesto (Ecological and Governance Association, 2016).

Further mentions supporting TEK integration in international policy are included in the UN Post 2020 Global Biodiversity Framework draft and the 2021 UN Decade on Ecosystem Restoration (United Nations Environment Program, 2021a,b). Only in the last few years has the United States begun to formally recognize TEK as a knowledge system as valuable as western science and one to be considered in Federal decision-making. The United States delivered its mission to the UN in 2019, citing the intention to form a legal framework to incorporate traditional knowledge into US government decision-making. (Hauser, 2019). The Advisory Council on Historic Preservation (2021) released a recommendation to revise Section 106 of the National Historic Preservation Act to specifically define and incorporate traditional knowledge. The Biden Administration's commitment to 'strengthening Nation-to-Nation relationships' has increased more concrete recognition of TEK in US policy. In November 2021, the Administration released a memorandum for the heads of departments and agencies on Indigenous Ecological Knowledge and Federal Decision-Making. The memorandum officially formalized TEK as a valued knowledge system and recognized the 2013 request from the National Congress of American Indians (Executive Office of the President, 2021). The same day, Joint Secretarial Order No: 3403 was issued on 'Fulfilling the Trust Responsibility to Indian Tribes in the Stewardship of Federal Lands and Waters,' which officially included the incorporation of Indigenous knowledge to Federal land and resource management as part of the Federal Trust Responsibility (US Department of the Interior, 2021).

In 2022, further efforts toward integration of TEK into policy include verbiage presented in: Executive Order #14072 'Strengthening the Nation's Forests, Communities, and Local Economies,' Executive Order #14049 'White House Initiative on Advancing Educational Equity, Excellence, and Economic Opportunity for Native Americans and Strengthening Tribal Colleges and Universities,' and Executive Order #13990 'Protecting Public Health and the Environment and Restoring Science To Tackle the Climate Crisis.' As a response to the formal recognition of TEK as a valued knowledge system in November 2021, the Biden Administration finally released a formalized plan on 'Indigenous Knowledge Guidance for Federal Agencies' in December 2022 (The White House, 2022). The plan, which is the first of its kind, is intended to support agencies in understanding TEK, further develop relationships with Indigenous peoples, and incorporate TEK into Federal research, policies, management, and decision-making (Executive Office of the President, 2022). A framework such as this cannot be developed in a vacuum and requires ample input and perspective. The guide was developed through the White House Office of Science and Technology Policy and the White House Council on

Environmental Quality, with input from 25 Federal agencies, 100 Native Nations, Indigenous youth, and various public and organizational sources. The Biden Administration has made historic and laudable advancements to prioritize protections for Indigenous groups in land management. This important progress can be built upon by increasing representation of and centering Indigenous peoples in planning, land management, and goverment, and more formally protecting important natural resources and cultural and landscapes.

9. Discussion

In the 20 years since TEK entered the lexicon of western SEK, numerous studies have examined TEK application to land management from both a social and ecological lens. Taken together, studies have advanced our understanding of the nature of TEK, its transmission among knowledge holders, cultural importance, utility in land management and conservation, and benefits as context for understanding ecological change. One critical development has been the identification of a signature of past Indigenous groups within modern ecosystems (Bliege Bird et al., 2008; Bird R. B. et al., 2013; Bird M. I. et al., 2013; Sullivan et al., 2017; Power et al., 2018; Adlam et al., 2021). This finding expanded the ecological role of non-agricultural societies, which was often ignored or minimized, resulting in the fetishization of 'pristine' ecosystems, absent of humans (Vining et al., 2008). Adopting a community-integrated approach to land management, rather than deprioritizing human roles within landscapes, will likely increase the efficacy of management, conservation, and restoration strategies.

Simultaneously, the realization that ignoring the concerns of human populations impedes successful land management is driving numerous agencies and groups to prioritize collaborative planning at initial stages of project development. Conservation movements and land management policies that disregard community input may inadvertently harm local and Indigenous communities and livelihoods, and thus lack long-term stability (Vining et al., 2008; Johansson et al., 2019; Campbell, 2020). A prime example, conservation easements or carbon conservation areas in tropical regions were often established without consulting with local groups, or equitably sharing benefits or payments for ecosystem services. Such mismanagement and exclusion of traditional harvest practices within conservation areas resulted in illegal behavior like poaching, increased conflict and resentment, and further marginalized impoverished communities (Johansson et al., 2019; Campbell, 2020). Similarly, agencies in the US that established barriers to prevent traditional harvest on public lands depressed the ability of Indigenous communities to practice cultural activities, increasing resentment towards the government, despite the fact that little, if any, evidence suggests that traditional harvest negatively impacts target populations (Souther et al., 2021b). Co-developed land management and conservation policies bolster the long-term success of ecological protections (NEPSTAD et al., 2006; Reniko et al., 2018; Schuster et al., 2019; Schang et al., 2020). Prioritizing local and Indigenous perspectives in land management decisions is an important goal simply to support cultural practices and social justice, and likely improves understanding of ecological systems and management outcomes; suggesting that TEK integration into land management should be a primary objective of US land management agencies.

We identified several fundamental gaps in the TEK-literature. Studies rarely included both social and ecological data and infrequently applied inferential statistics, which precluded generalizing to other systems. Few studies were conducted outside of Australia, the US, and Canada, again limiting our ability to understand how patterns vary across landscapes and cultures. The model of coupled social-ecological systems provides a framework to more completely understand TEK and land management (Liu et al., 2007; Long and Lake, 2018). Long and Lake (2018) adopt a coupled social-ecological systems frame to contextualize management outcomes. Specifically, authors describe the feedback loops that have created 'social traps' for many US Indigenous groups, in which separation of Indigenous communities from ancestral lands contributed to mis-management of natural resources, which in turn, degraded ecological systems. Ecological decline then contributed to ecocultural erosion, as loss of access to first foods and sacred spaces further impoverished and degraded the health of communities. Using this frame work, decisions can be made to avoid, prevent or stop social-ecological feedbacks that that result in persistent, undesirable states (Long and Lake, 2018). This is particularly important as climate change creates social-ecological perturbations that could further degrade the function of coupled systems (Long and Lake, 2018). Future research should focus on developing analytical methodology to study and model complex systems, in order to provide generalizable insights and generate projections of coupled-human and natural systems.

Traditional ecological knowledge systems are currently imperiled by a variety of factors, including modernization, globalization (Mistry, 2009; Camacho et al., 2012; Juanwen et al., 2012; Mackey and Claudie, 2015; Amelia et al., 2018), resource exploitation (Rai, 2011; Mackey and Claudie, 2015; Kuklina et al., 2022), development including agriculture, climate change, loss of knowledge holders (i.e., elders), and shifts in land tenure to private land ownership (Pangging et al., 2011; Rai, 2011; Juanwen et al., 2012; Rodenburg et al., 2012; Scales, 2012; Mackey and Claudie, 2015; Schmidt and Pearson, 2016; Selemani, 2020). Within this manuscript, we detailed numerous benefits of TEK to land management, which included providing insights into sustainable management of natural resources, improving ecological assessments, and addressing novel threats driven by global change. Urgent action is needed to enshrine the protection and incorporation of TEK into land management strategies at national levels (Armatas et al., 2016; Kanwar et al., 2016; Keats and Evans, 2020; Das et al., 2021). Creating national-level policies ensures consistency across agencies and may increase the adoption rate of TEK-integrated management approaches. Scaffolding to create comprehensive TEK-policy exists in the US, and is broadly supported by the Biden administration. Concerted efforts to integrate TEK into to land management, particularly in the US, could support ecological and cultural health and reduce the likelihood of global change further harming marginalized groups.

Author contributions

SS conducted the literature review and co-authored the manuscript. SC conducted the policy review and co-authored the manuscript. NL provided content guidance and editing. All authors contributed to the article and approved the submitted version.

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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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Supplementary material

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