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Environmental Services: A New Approach Toward Addressing Sustainable Development Goals in Sub-Saharan Africa

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The physical environment provides resources and specific types of environmental services relevant to the maintenance of human livelihoods globally and with specific reference to sub-Saharan Africa, including soils, food, and water systems. Previous studies on the shared nexus of such resources commonly view these as self-contained systems operating independent of their physical contexts provided by landscape-scale geomorphology and its related processes. This study critically examines the viewpoints adopted by such nexus studies with specific reference to sub-Saharan Africa, arguing that these studies are reductive, considering only the shared disciplinary overlap (nexus) and not their wider contexts, and are based on only a limited understanding of the workings of physical systems. This study argues that considering the attributes of the physical landscape and its provision of environmental services provides a broader and scientifically-informed context for understanding of interlinked issues such as relationships between soil–food–water systems. Framing such "nexus" studies in this wider context can derive a better understanding of the connections between different elements such as soil, food, and water, amongst others, and with respect to the United Nations' Sustainable Development Goals. The concept of environmental services is therefore a more powerful tool to examine both the connections between physical and human environmental processes and properties in sub-Saharan Africa, and to address overarching environmental issues such as land degradation, soil erosion loss, water scarcity, and impacts of climate change.

Keywords: environmental resources, sustainable development goals, ecosystem services, nexus, landscape development, sustainability, Sub-Saharan Africa

INTRODUCTION

The physical landscape is the basis for the provision of different types of environmental resources (O'Farrell et al., 2010; Thondhlana and Muchapondwa, 2014; Falayi et al., 2019; Ragie et al., 2020). Environmental resources can be defined as any properties or attributes of the physical environment, including its climate, that provide direct or indirect services of different types to local communities. Environmental resources can therefore be considered as related to, but broader than, ideas of ecosystem services (van Jaarsveld et al., 2005; King-Okumu, 2018). For this reason, the concept of *environmental* *resources* and the services that they provide (termed *environmental services*) is a more useful and integrated approach that is founded on ideas of Earth System Science that describe the interlinkage of changes that take place in the physical environment (Clifford and Richards, 2005). Consideration of environmental services, through the provision of different types of environmental resources, is of relevance to studies of physical–human relations in sub-Saharan Africa where issues of environmental sustainability are important (e.g., Hoffman et al., 2007; O'Farrell et al., 2010; Vogel et al., 2016), as are expressed in the United Nations' Sustainable Development Goals (SDGs) (Millennium Ecosystems Assessment, 2005). Several studies have examined how communities make use of environmental resources in their immediate localities, illustrating the local-scale relationships of people to their surrounding environments (e.g., Hoffman et al., 2007; Casale et al., 2010; Thondhlana and Muchapondwa, 2014; Cole et al., 2017; Omisore, 2018; Falayi et al., 2019; Ragie et al., 2020). These relationships have often been examined in the context of resource sustainability, by which the use of certain environmental resources is evaluated over time with respect to changes in resource properties and their availability (e.g., Hallowes et al., 2008; Swemmer et al., 2019; Wolff et al., 2019). However, this analysis of relationships between different communities and environmental resources is usually based on localized and individual case studies. What is critically lacking is an evidence-based theoretical context in which to link different case studies together, to aid their interpretation, and as an overarching framework for evidence-based decision-making.

Many previous studies have described the relations between different elements in physical and human environments with respect to their shared *nexus* (**Figure 1**). This term, which is not well-described although commonly used in the literature, refers the thematic interconnection or area of overlap between two or more elements of the human and/or physical environments. As such, the shared nexus between these different elements is a qualitative and poorly defined space that is dependent on the capacity of individual researchers to make intellectual links between these elements. Thus, nexus studies do not always provide an adequate intellectual foundation for either designing or interpreting field-based studies, or in applying an understanding of these co-relationships to solve a practical problems, such as soil erosion or declining agricultural yields. This means that many nexus studies, while purporting to be integrative and based on ideas in sustainability, cannot be readily applied to address SDGs.

Several different examples of nexus studies in sub-Saharan Africa have been reported in the literature (**Table 1**). *Energy*, *water*, and *food* are the most common elements considered in these studies, either together or in combination with other elements. The majority of nexus studies provide local examples of physical–human relationships; only few studies have examined the links between physical–human nexuses to broader aspects of sustainability and the SDGs. For example, Ramutsindela (2003), Wolff et al. (2019) and Musakwa et al. (2020a) described land-use management implications of the physical–human nexus with specific reference to urbanization, land reform and tenure, and their relationships to nature and biodiversity conservation.

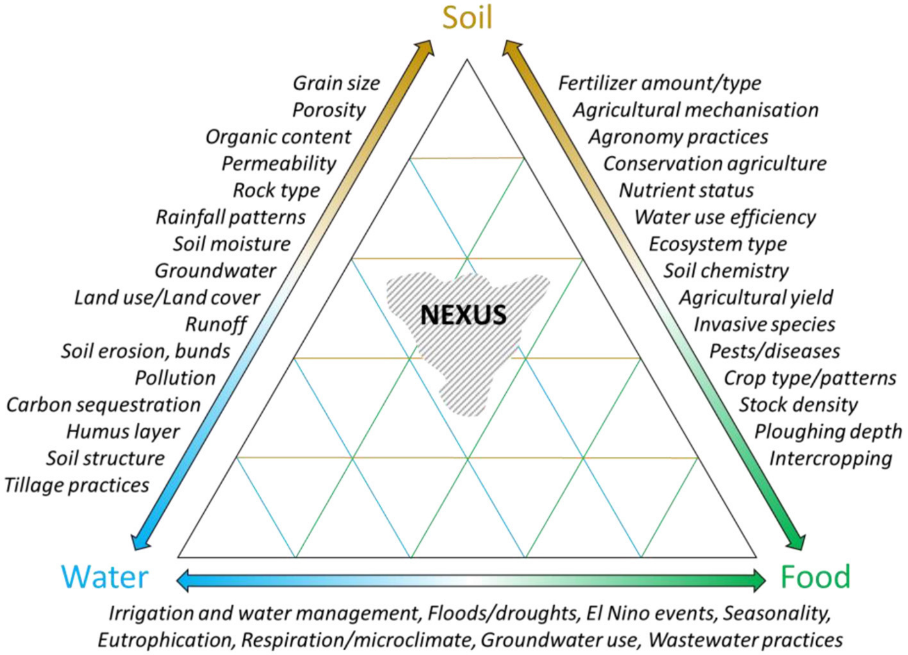


FIGURE 1 | Illustration of the interconnections between soil, food, and water systems and the particular elements that link these systems together (listed around the outside of the triangle). The soil–food–water nexus represents some poorly-defined region in the middle of this triangle (shaded).

TABLE 1 | Examples of nexus studies in South Africa.

Nexus type	Examples described in the literature (source)
Agriculture–population	Alola and Alola, 2019
Energy–climate	Bazilian et al., 2011
Urban–rural	Constant and Taylor, 2020
Urbanization–food security	Jonah and May, 2020
Energy–water	Hoseini et al., 2016; Ololade, 2018
Land–water	Marcatelli, 2018; Rosa et al., 2019
Environment–trade	Udeagha and Ngepah, 2019
Growth–poverty–inequality	Akanbi, 2016
Energy–climate–economic growth	Cowan et al., 2014; Akadiri et al., 2019; Azam, 2019; Bekun et al., 2019; Khan et al., 2020
Biodiversity–poverty–inequality	Graham and Ernstson, 2012
Energy–pollution–*growth*	Magazzino et al., 2020
Energy–water–CO_2	Madolo et al., 2018
Energy–water–waste	Wang et al., 2018
Food–energy–water	Ozturk, 2017; Zaman et al., 2017; Mabhaudhi et al., 2018, 2019; Mpandeli et al., 2018; Zhang et al., 2018; Sahle et al., 2019; Simpson et al., 2019; Nhamo et al., 2020a,b; Bellezoni et al., 2021; Yuan et al., 2021
Water–energy–food–climate	King and Jaafar, 2015

Items of these nexuses that are specifically mentioned in the United Nations' Sustainable Development Goals are listed in italics.

Several studies have also considered the relationship of water management to sustainable development (Jonker, 2007; Mabhaudhi et al., 2018, 2019; Nhemachena et al., 2020) but this is viewed mainly as a water budget (supply/demand) issue rather than as a system that links synergistically to other systems (soil, ecosystems, agriculture, health, pollution).

Despite the fact that most nexus studies have a clear—albeit unstated—application to SDGs (marked in **Table 1**), and can be applied to a range of cross-cutting physical–human environmental issues, these studies are rarely framed in a context of either sustainable development (e.g., Walmsley, 2002; Hoffman et al., 2007; Nhemachena et al., 2020) or Earth System Science that informs on co-relationships to physical processes in the landscape (Knight, 2015; Verburg et al., 2015). This is a key limitation of nexus studies because it means they are not informed by the physical and human environmental processes that impact on issues in sustainability and the SDGs. Nexus studies, by definition, are reductive because they consider co-relationships of different elements (food, water, energy, etc) through a very narrow and exclusionary lens. They consider these different elements as distinct and mutually exclusive with respect to their properties or dynamics or controls, except for some specific areas of thematic overlap (their *nexus*).

This paper tackles this systemic weakness of nexus studies by proposing a new, holistic and integrated framework that examines the application of *environmental services* and their associated *environmental resources* to address the aspirations of the SDGs. These related elements are explored through the commonly-examined "nexus" of soil–food–water systems as has been widely discussed in the literature in sub-Saharan Africa (**Figure 1**). This paper (1) examines the nature of this nexus, drawing from previous studies in the literature; (2) reframes this nexus using ideas of environmental systems, their resources and services; (3) discusses the nexus of soil–food–water systems using a specific example of smallholder farmer practices in Limpopo Province, South Africa; and (4) provides a new way of examining co-relationships between soil, food, and water through the concept of *cascading environmental systems*. A critical outcome of this study is an evidence-based theoretical context of physical and human systems relevant to SDGs, and issues of sustainability and sustainable development more generally, and especially in a sub-Saharan Africa context.

THE SOIL–FOOD–WATER NEXUS

The flow of energy and matter through landscapes is controlled by topography and is driven by biophysical processes and water flow. Soil, food, and water systems thus have very different relationships to the physical environment: water relates strongly to climate, soil to geology, and "food" merely represents the acquisition and commodifying of biological resources by human activity. "Food" is therefore a value-laden concept, being a subset of ecosystem services, and is mediated by socioeconomic and cultural attributes of different regions, people, and contexts. This means that soil, food, and water are not of equal or comparable status within a single "nexus," even though studies that address these elements within a single nexus assume that they are. Soil (land surface), food, and water systems in sub-Saharan Africa have been examined in several nexus studies and with respect to the nature of the relationships between these elements as viewed from different perspectives (e.g., decision-making, climate change adaptation, land degradation, regional economic development, sustainable water management, etc) (Mpandeli et al., 2018; Nhamo et al., 2020a,b). This means that such nexus studies take different disciplinary viewpoints, and in emphasizing certain of these elements, can result in only a partial understanding of these interrelationships. **Figure 1** outlines the detailed nature of interactions between soil, food, and water systems. Each axis describes the relationships between these different elements. It is notable that no nexus study, presented in the literature, has examined these elements in detail or described the theoretical basis of these relationships. The co-relationships between soil, food, and water (shown in **Figure 1**), however, are now examined in detail.

Soil and water systems focus on how the physical and chemical properties of soil influence water retention and throughflow properties and processes. Specific controls on soil and water system properties include aspects of climate (rainfall patterns, runoff, soil erosion), geology (rock type, grain size, porosity, permeability, groundwater position, and dynamics), soil properties (grain size, organic content, soil structure, soil moisture capacity), vegetation (land use, agriculture type, humus/nutrient content), and management structures (field bunds, tillage practice). Relationships between these different elements have been discussed in several studies. For example, soil properties such as carbon content have been explicitly linked to minimal tillage conservation agriculture methods (e.g., Willcocks and Twomlow, 1993; Bationo et al., 2007; Mchunu et al., 2011; Simwaka et al., 2020). Here, conservation agriculture techniques give rise to changes in soil and water properties, with an increase in porosity resulting in an increased capacity for soil moisture storage, increase in soil carbon stock, and changes in particle size distributions within soils. Water processes within the soil are associated with chemical translocation, which is of particular relevance for nutrients and soil fertility (Smaling et al., 1993; Mabuza and van Huyssteen, 2019; Teffera et al., 2019). Studies have also been concerned with rainwater harvesting and its effects on soil moisture retention (van Rensburg et al., 2012). *Soil and food systems* describe ecosystem type and productivity that relates to soil nutrient status and the agronomy practices that affect soil properties. Soil and food systems therefore include aspects of soil management (fertilizers, nutrient status, plow depth), crop type, and agricultural practices (agronomy practices, intercropping, harvesting, and land management practices), and agricultural ecosystem management (invasive species, pests/diseases). Balancing soil nutrient status and plant growth requirements is a key component of integrated soil and food systems. Studies that consider these systems therefore focus on how different cropping systems or stock density affect soil properties. Examples include the role of beans and other staple crops in soil nitrogen fixation (Mthembu et al., 2018; Muoni et al., 2019; Namatsheve et al., 2020), micronutrient provision within soils as a result of specific crop types and practices (Nziguheba et al., 2016; Kihara et al., 2020a), relationships between agricultural yield and soil fertility (Tan et al., 2005; Lal, 2009; Soropa et al., 2019), the role of additions of fertilizer and manure in food production (Vlek, 1990; Mafongoya et al., 2006), the relationship of soils to ecosystems and biodiversity in agricultural systems (Agegnehu and Amede, 2017; Kamau et al., 2019; Kihara et al., 2020b), and the role of different agronomy practices such as intercropping and livestock/arable combinations on soil fertility and agricultural yield (Gowing et al., 2020; Hoffmann et al., 2020; Reetsch et al., 2020). These studies on soil and food systems highlight the critical role of human activity in changing the nature of the land surface (vegetation, soil A-horizon, input of water/fertilizer) that then has impacts on soil properties. Further, maintenance of soil properties (structure, thickness, organic and moisture content, nutrient status) is the basis for sustainable food production (Vlek, 1990; Lal, 2009; Bindraban et al., 2012; Graef et al., 2015; Solomon et al., 2016). Interrelationships of *food and water* systems are based on the different water requirements for different crops or agricultural systems, managing water for irrigation during dry periods, and managing the effects of excess and wastewater during wet periods. Water use efficiency with respect to food production are explicitly linked to sustainability and with reference to SDG 2 (food security) (Wallace and Gregory, 2002; Cook et al., 2009; Nyam et al., 2020). Studies on food and water systems have focused on water use efficiency with respect to specific crops (Makurira et al., 2011; Nyakudya and Stroosnijder, 2011; Olivier and Singels, 2015), rainwater harvesting (Botha et al., 2012; Baiyegunhi, 2015; Mo et al., 2018), and rainfed agricultural systems (Mutiro et al., 2006; Biazin et al., 2012; Haarhoff et al., 2020). These studies show the key role of water availability and management in influencing food production systems. Water management is also influenced by crop type and mulch cover, which can reduce evaporation and increase soil moisture retention by up to 30% (Biazin et al., 2012; Olivier and Singels, 2015). Studies have also shown that effective water management can lead to increased yields and higher gross margins (Makurira et al., 2011; Sime et al., 2015).

Apart from individual shared elements that link up individual soil, food, and water systems (**Figure 1**), several studies have also examined this soil–food–water nexus in the context of sustainable development. For example, Love et al. (2006) and Kadyampakeni (2014) argued that SDG 2 (food security) can be addressed through increased access to fertilizers, technology transfer and training, soil-water conservation methods, mixed livestock and arable agriculture, and farm diversification. It is notable that each of these proposed interventions involves co-relationships between different elements of physical and human systems, and that these relationships are not straightforward or without impact. As an example, increased access to fertilizer as a simple action point requires input from or influence by a range of actors, processes and properties, and in turn fertilizer input impacts upon a range of issues related to the physical environment, farm properties, and wider socioeconomic systems (**Figure 2**). Thus, addressing this action point requires a fuller consideration of systems' properties, which is not usually done in nexus studies. Further, this highlights the problems of enacting seemingly-simple management decisions when also set against such naïve and poorly-defined statements as "end hunger, achieve food security" of SDG 2, for example. This means that many nexus studies only describe broad and generalized relationships with respect to SDGs (Ololade, 2018; Zhang et al., 2018; Simpson et al., 2019), and lack specific and evidence-based scientific detail that is set in a theoretical context (Graham and Ernstson, 2012). To address this, the theoretical context of *environmental services* is now proposed as a way to better understand the co-relationships of different physical and human elements, as described in nexus studies.

ENVIRONMENTAL SERVICES AS A BASIS FOR UNDERSTANDING OF SOIL, FOOD, AND WATER SYSTEMS

The Nature of Ecological Environmental Services

Ecosystem services are well-known and documented especially in a southern African context (van Jaarsveld et al., 2005; Egoh et al., 2008; Fenta et al., 2020; Mowat and Rhodes, 2020) and these are linked directly to human–environment (socio-ecological) relationships and aspects of sustainable development (Bailey and Buck, 2016; Sigwela et al., 2017; Cerretelli et al., 2018; Bengochea Paz et al., 2020). Many local case studies worldwide have described different ecosystem

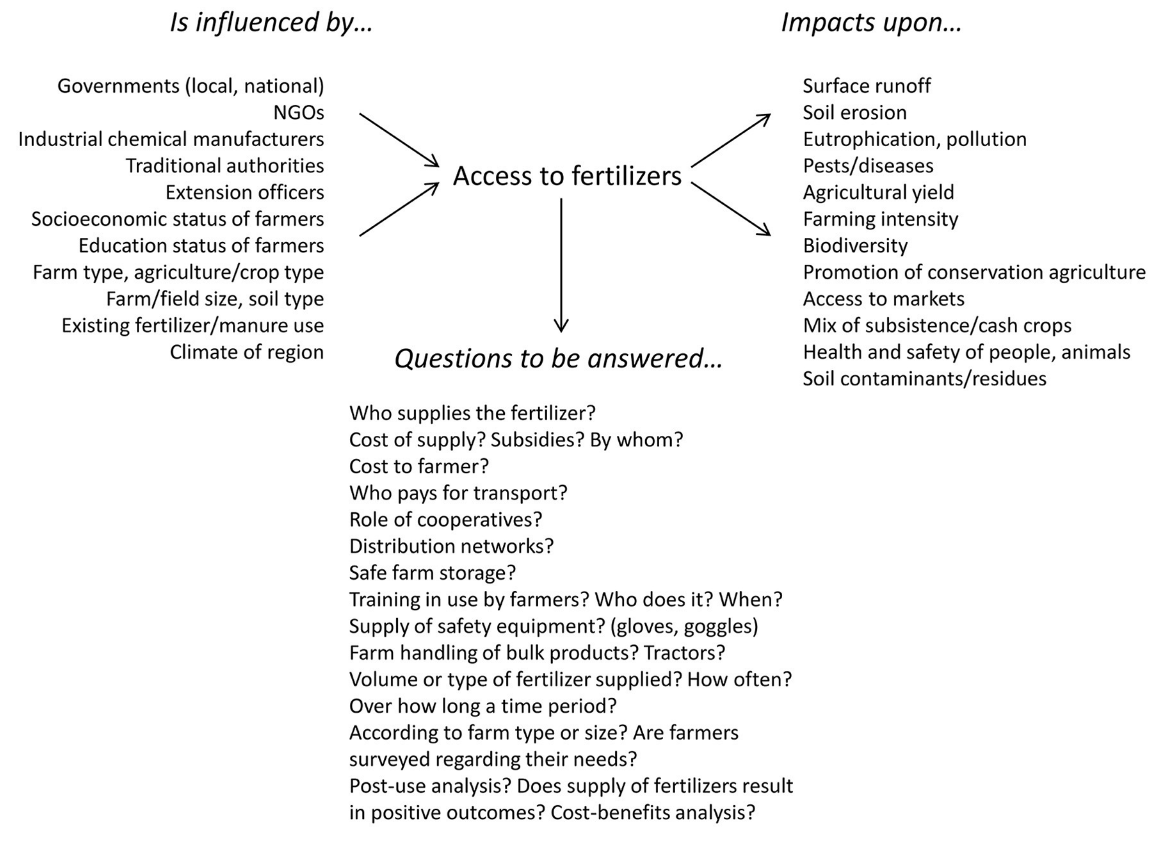


FIGURE 2 | Example of how a simple intervention such as access to fertilizer (Love et al., 2006) links to wider aspects of nexus intersections in the physical and human environments.

services and their uses by communities in different, mainly agricultural, contexts (e.g., Mensah et al., 2017; Swemmer et al., 2019; Herd-Hoare and Shackleton, 2020; Lhoest et al., 2020). The conceptual basis for understanding these ecosystem services is well-founded because it is based on ecological processes set in a landscape context, and studies of ecosystem services are framed by well-defined theoretical approaches, which include:

- Socio-ecological approaches that consider human use and ecological resources as part of a continuum (e.g., Temesgen and Wu, 2018; Bengochea Paz et al., 2020);
- Monitoring and modeling of variations in aboveground productivity using remote sensing tools such as normalized difference vegetation index (NDVI) values (e.g., Lindeskog et al., 2013; Ayanlade and Proske, 2016; Cho and Ramoelo, 2019);
- Valorizing ecosystem services based on calculations of ecosystem use and areal coverage of different ecosystem types (e.g., Costanza et al., 2011; Anderson et al., 2017; Turpie et al., 2017; Niquisse and Cabral, 2018);
- Interpreting different service types and provision through ideas of natural capital (e.g., Costanza and Daly, 1992; Blignaut and van der Elst, 2014); and
- Payment for ecosystem services (PES) (e.g., Jackson and Palmer, 2015; Haile et al., 2019).

However, these different approaches adopted in studies of ecosystem services do not explicitly consider how ecosystems influence environmental variables such as geomorphology, soils, water availability (rivers, groundwater) and climate, or how local communities may use or value these properties and services. Despite this importance, only a few studies on ecosystem services are set in a broader environmental context (e.g., Egoh et al., 2009; Pettinotti et al., 2018; Balbi et al., 2019). This omission is surprising given the wide literature on the relationship of ecosystem service provision to land degradation (e.g., Smiraglia et al., 2016; Sutton et al., 2016; Tarrasón et al., 2016; Turner et al., 2016; Cerretelli et al., 2018). In addition, environmental services, provided by or contingent upon the physical landscape, have not been explicitly considered as part of sustainable development strategies in developing world contexts, or as key elements of SDGs, despite the plethora of "nexus" approaches that are linked to examination of the SDGs (Cumming et al., 2017; Nhamo, 2017; Omisore, 2018; Dawson et al., 2019; Jiménez-Aceituno et al., 2020; Nhemachena et al., 2020).

Based on this discussion, it is evident that there are limitations of ecosystem services alone to apply to the wide range of

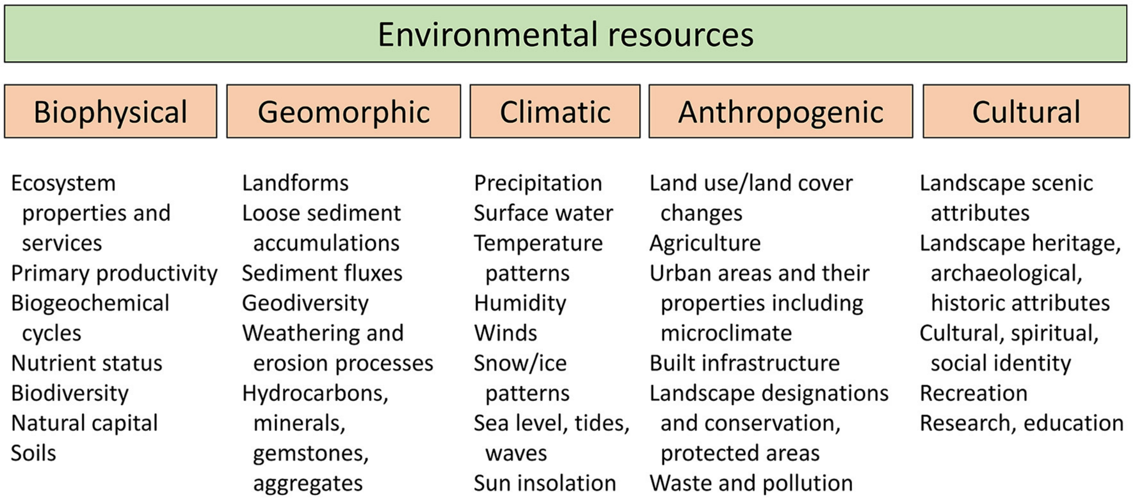


FIGURE 3 | Illustration of different types of environmental resources [informed by Gray (2004), Millennium Ecosystems Assessment (2005)]. Note that ecosystem resources and services are a subset of broader environmental resources and services.

environmental factors that give rise to changes in the physical or human environments, or to describe their interconnections. This does not mean that ecosystem service approaches are not useful either on their own merit or in addressing the SDGs, but merely that they do not explicitly consider wider environmental factors as contributors to ecosystem processes and therefore service provision. For this reason, landscape-scale environmental factors (e.g., geology, geomorphology, soils, water, climate) can be considered as *environmental resources* that are potentially available for use by other Earth systems and by human activity (**Figure 3**). In so doing, these environmental resources then provide a range of *environmental services*. This approach therefore views human activity and human intervention in Earth systems as a key component in the provision and use of environmental resources on a global scale (e.g., Knight and Harrison, 2014; Knight, 2015), therefore that environmental resources and human activity are intimately related (**Figure 4**). This contrasts with many studies that view ecosystem services as some fixed, pre-existing and inherent entity of the physical environment that is separate from human activity and the human world, and that human activity seeks only to draw from ecosystem services rather than interact with it (e.g., Chaigneau et al., 2019; Lhoest et al., 2020). In the Anthropocene, several studies show that environmental resources (*sensu lato*) are vulnerable as a result of human activity and climate change in combination (Knight, 2015; Bradshaw et al., 2021), which sets the scene for their more careful examination with respect to achieving future developmental benchmarks such as the SDGs. Environmental resources can be classified into biophysical, geomorphic, climatic, anthropogenic, and cultural resources types (**Figure 3**). Relationships between these take place along a continuum between those resources that are wholly related to the physical environment, and those that are wholly related to the human environment (**Figure 4**). The applicability of an environmental resources and services approach to examining soil, food, and water systems is now presented. The purpose of this more detailed analysis is to highlight how an environmental service approach is more useful and integrative, compared to a reductive nexus approach.

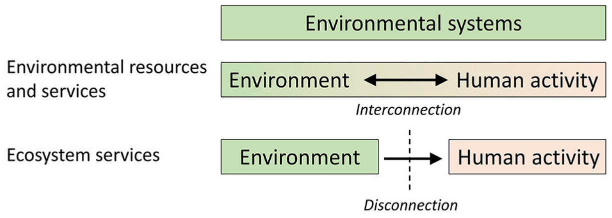
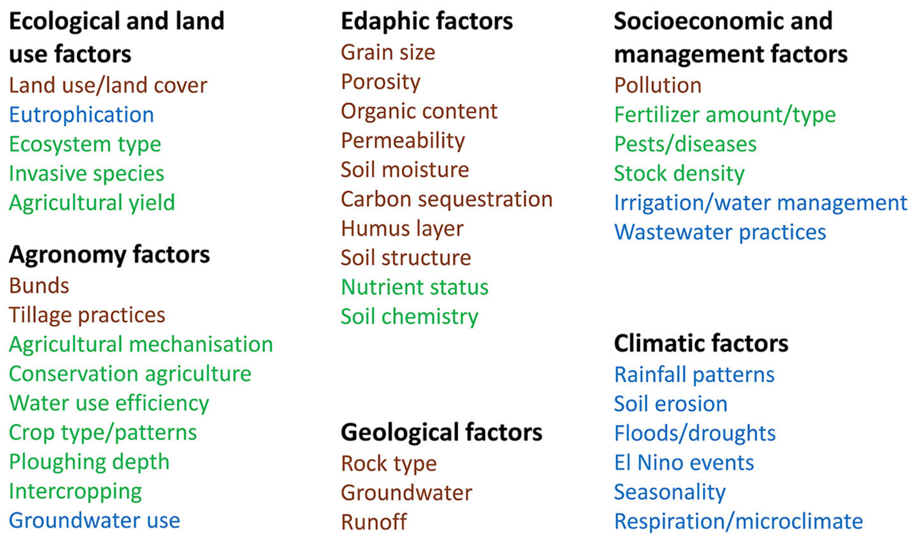


FIGURE 4 | Illustration of how environmental resources and services link together aspects of the physical environment and human activity, in contrast to many studies of ecosystem services.

Environmental Services and Soil, Food, and Water Systems

Soil, food, and water systems can not only be conceptually related to each other (cf. nexus studies; **Figure 1**) but also to other environmental systems. As such, a reductive nexus approach does not describe the interrelations between individual elements and their wider environmental contexts. **Figure 5** builds from **Figure 1** by taking all the integrated factors that link soil, food, and water systems together and grouping them according to their major controls. These different factors are color coded according to whether they broadly correspond to soil, food, or water systems. This shows that environmental services provided by soil, food, or water systems are influenced by a range of different factors (**Figure 5**). Further, individual elements can also be considered as providing environmental services to other elements, which highlights the intersectionality between



Ecological and land use factors
Land use/land cover
Eutrophication
Ecosystem type
Invasive species
Agricultural yield

Agronomy factors
Bunds
Tillage practices
Agricultural mechanisation
Conservation agriculture
Water use efficiency
Crop type/patterns
Ploughing depth
Intercropping
Groundwater use

Edaphic factors
Grain size
Porosity
Organic content
Permeability
Soil moisture
Carbon sequestration
Humus layer
Soil structure
Nutrient status
Soil chemistry

Geological factors
Rock type
Groundwater
Runoff

Socioeconomic and management factors
Pollution
Fertilizer amount/type
Pests/diseases
Stock density
Irrigation/water management
Wastewater practices

Climatic factors
Rainfall patterns
Soil erosion
Floods/droughts
El Nino events
Seasonality
Respiration/microclimate

FIGURE 5 | Grouping of different factors that link soil, food, and water systems together (**Figure 1**) according to their major controls. The different factors are color coded according to whether they correspond to soil (brown), food (green), or water (blue, following **Figure 1**).

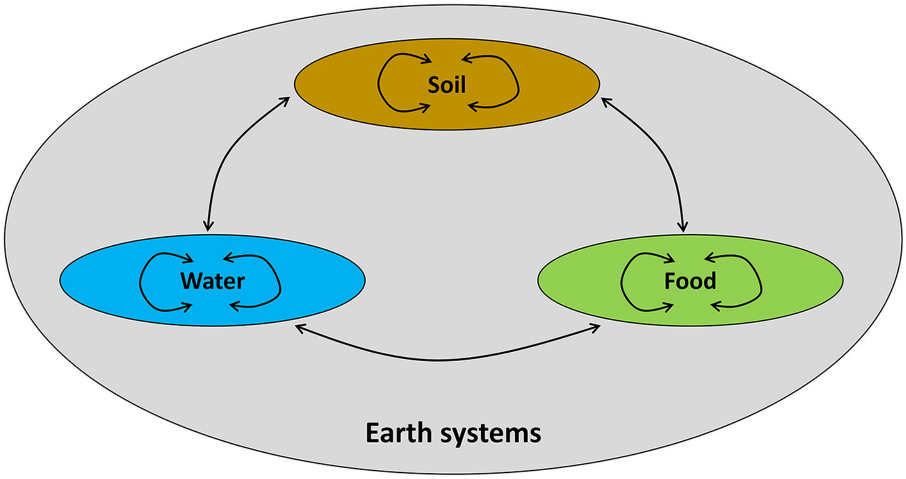


FIGURE 6 | The nature of cascading systems as applied to soil-food-water systems examined in this study.

environmental resources, their services, and commodification of these elements by local communities. Here it is argued that a useful conceptual framework for understanding the interconnections between these different elements is that of a *cascading system*, in which there are active feedbacks between different elements that are driven by flows of energy and matter. These cascading systems and their applications to the environment are now examined.

Cascading Environmental Systems

The concept of cascading systems refers to how information and energy is dispersed (cascaded) amongst the constituent elements of a network, within and between each system and subsystem (**Figure 6**). A key property of cascading systems is that, through feedback processes, dynamic equilibrium of the system as a whole can be maintained (Pratt and Eslinger, 1997). This conforms with the workings of feedbacks in Earth Systems (Clifford and Richards, 2005). Cascading systems are best considered as "bottom-up" systems subject to self-organization, in which the nature of their network relations (network topology) emerge over time as energy and matter flow through the system (Pratt and Eslinger, 1997; Gleeson and Durrett, 2017). These are non-dimensional systems and thus do not correspond to any specific spatial or temporal scales (Gleeson and Durrett, 2017) but are subject to system perturbations that have impacts on system dynamics, including non-linear and lagged forcing–response relations (Young et al., 2017). These properties of cascading systems match well with the ways in which physical processes of weathering, erosion and ecosystem changes are experienced in the landscape, which can also be considered to operate under non-dimensional boundary conditions (e.g., Molden and Bos, 2005).

The cascading nature of integrated soil–food–water systems is now examined, and this takes place in the wider context of Earth Systems in which there are feedbacks within and between each of these different elements (**Figure 6**), and where both physical and human environmental factors are involved (**Figure 1**). Climate forcing of weathering and erosion processes at a landscape scale (Dixon et al., 2009) gives rise to the generation of loose surface materials that transform into soil by development of surface vegetation. By processes of negative feedback, bedrock weathering rates decrease over time and this is accompanied by a decrease in slope angle as progressive soil creep driven by gravity takes place (Phillips, 2005). This gives rise to enhanced slope sediment yield and therefore the net transfer of soil volume from upper/midslope locations to mid/footslope locations (**Figure 7**). Likewise, there are also feedbacks between soil properties, runoff and surface ecosystems, and these include hydrological (interception, root system uptake, surface desiccation) and mechanical processes (anchoring processes that increase soil strength and reduce erosivity) (Marston, 2010). Soil erosion is enhanced under agricultural land uses where the natural vegetation cover is replaced by sown crops of different types that leave the soil surface bare after harvest, and where changes in soil structure and chemistry take place by deep tillage and addition of fertilizer (Vanwalleghem et al., 2017). Geological background erosion rates on soil-mantled slopes is on the order of 0.001–1 mm yr^{-1} whereas under agriculture of different types this is increased to 0.1–80 mm yr^{-1} (Montgomery, 2007). Enhanced soil erosion is therefore associated with a decrease in agricultural yield (Montgomery, 2007; Vanwalleghem et al., 2017). However, this is set against the concept of soil loss tolerance, in which soil erosion operates until such a time as when agricultural yields are negatively affected, prompting a management response (Li et al., 2009). Thus, the relationship between soil and food systems is influenced by feedbacks that also includes the human environment, set within the context of Earth systems (**Figure 6**).

There is a positive relationship ($r = 0.592$) between soil erosion loss and 30-min breakpoint rain intensity (EI_{30}) (Kinnell, 2010), and this relationship has been used for predicting spatial patterns of soil erosion loss in Africa under climate change (Diodato et al., 2013). Studies have also identified that ecological responses to climate change lead to changes in agricultural productivity (Higgins et al., 2002). These reflect temperature and precipitation changes as forcing factors for phenological and primary productivity responses (e.g., Anderson et al., 2015; Porkka et al., 2016) but these factors also affect soil chemistry, nutrients, and carbon storage (Quinton et al., 2010), and it is this that eventually affects outcomes of food security (Kang et al., 2009; Sonwa et al., 2017). Jägermeyr et al. (2016) suggested that more efficient water use can increase kcal-equivalent production by 26% globally, corresponding to increased volumetric global food production by 41%. This highlights the co-relations between soil, food, and water systems (**Figure 6**) and that this understanding can be applied to SDGs (Charlton, 2016; Nhemachena et al., 2018; Newell et al., 2019).

FIGURE 7 | Example of soil erosion on an agricultural field, showing midslope erosional gullies and soil deposition at the footslope (bottom of the image).

Case Study: the Example of Soil–Food–Water Systems in Limpopo, South Africa

Limpopo Province in northeast South Africa is a rural and semiarid region (mean annual rainfall of 598 mm) where there are more than 4 million smallholder and subsistence farmers (Aliber and Hart, 2009). Farming is therefore a key livelihood strategy and important for food security and nutrition (van Averbeke and Khosa, 2007; Aliber and Hart, 2009; Musakwa et al., 2020b). Products include both staple crops for consumption (maize, butternut, cabbage, beans) and vegetable market crops for sale (spinach, lettuce, tomatoes, carrots, onions) (Bharwani et al., 2005; Mahlangu et al., 2020; Musakwa et al., 2020b) (**Figure 8**). Soil types in the region, within the Limpopo River catchment, are mainly sandy loam luvisols that are favorable for agriculture but which require additional fertilizer (Molepo et al., 2017). Techniques used include the application of manure and compost, crop rotation and intercropping, and farmers are explicitly aware of the ability of these methods to increase soil nutrients and reduce erosion loss (Rusere et al., 2020). Water management is also a key issue in this area and experimental studies have shown that agricultural yields on sandy loam soils can be increased by up to 20% with effective water management (Magombeyi et al., 2018), and this can also increase vitamin availability at the household level (van Averbeke and Khosa, 2007). Most (60%) of surveyed smallholder farmers in central Limpopo report challenges in accessing water, mainly through groundwater boreholes (Chikozho et al., 2020). There may also be inadequate rainwater storage facilities (e.g., **Figure 8D**), competition for water between users, loss of water by infiltration, damage to

FIGURE 8 | Examples of agricultural activities in Limpopo Province, South Africa. **(A)** Agricultural fields at Mamotintane, where the total farm size is 9 ha with scattered rectangular farm plots for individual smallholder farmers. **(B)** A community-shared field (1 ha) at Segoptje. **(C)** A field 4 ha in size at Sickline with rectangular farm plots. **(D)** Irrigation system used for watering crops during the dry season (photos: Rirhandu Chauke).

canals and furrows, and general increased aridity (Kativhu et al., 2020).

Analysis of the challenges faced by smallholder farmers in Limpopo shows that aspects of both soil, food, and water systems are important, and that these are linked together in several different ways (Radosavljevic et al., 2020; Rusere et al., 2020). For example, food insecurity arises as a combination of lack of education, job opportunities, mobility, health, demographic factors, and other socioeconomic factors (Oni et al., 2010; Ramos-Mejía et al., 2018). Smallholder farming is therefore a life support strategy for more than just the provision of food resources, being linked explicitly to SDGs 1, 2, 3, 11, 12, 13, 15 (see https://sdgs.un.org/goals) (e.g., Dawson et al., 2019; Newell et al., 2019). The success of smallholder farmer activity in Limpopo has also been critically linked to the presence and nature of government support mechanisms, including social grants, training, and agricultural extension (Kativhu et al., 2020). Some smallholder farmers may also be part of cooperatives and this can help in marketing of products, sharing of seeds and expertise, and can increase resilience (Bharwani et al., 2005; Aliber and Hart, 2009; Mahlangu et al., 2020). This example from Limpopo Province shows the interconnected nature of environmental systems and services, and the important strategic role of governance and management institutions in contributing toward the success of soil, food, and water systems in the context of sustainable development.

DISCUSSION

Understanding the relationships between soil, food, and water systems is fundamental to addressing the SDGs in the context of ensuring food and water security in the developing world. Most previous studies, in particular those that take a nexus approach, have a limited and reductive focus because they only consider the narrow interconnections between soil, food, and water, and not the wider environmental contexts that help frame these interconnections (**Figure 1**). These interconnections are well-demonstrated in Limpopo Province where the activities of smallholder farmers are taken in response to the nature of soil, water, and nutrient requirements for their crops, but which are also affected by wider socioeconomic factors of the marketplace and by certain government interventions. Consideration of environmental services (e.g., Jonker, 2007; Pettinotti et al., 2018) is a useful approach toward addressing the multiple stressors that lead to societal vulnerabilities in sub-Saharan Africa (Casale et al., 2010; Vogel et al., 2016; Falayi et al., 2019). Several studies have identified the correspondence between SDGs and aspects of the environment (*sensu lato*), including climate and ecosystems (e.g., Walmsley, 2002; Cumming et al., 2017; Nhamo, 2017; Omisore, 2018; Dawson et al., 2019) but this recognition has not followed through into meaningful developmental strategies that use environmental measures as performance indicators (Nhemachena et al., 2018; Le Roux and Pretorius, 2019; Jiménez-Aceituno et al., 2020). There is therefore a disconnection between the driving factors behind sustainable development, and the performance indicators used for monitoring achievement of SDGs (e.g., Patole, 2018; Schipper et al., 2021). This is clearly an issue for correctly identifying, enacting and monitoring the success of sustainable development strategies (Knight, 2015).

Management of environmental resources (**Figure 3**) is commonly framed in terms of sustainable development (Hallowes et al., 2008; Cumming et al., 2017; Falayi et al., 2019; Wolff et al., 2019), but an alternative viewpoint is where socioecological processes between people and the environment are also considered (e.g., Bowd et al., 2015; Ramos-Mejía et al., 2018; Fedele et al., 2020; Herrfahrdt-Pähle et al., 2020). Here, human activity can be viewed as either an integrated element of the Earth system and synergistically influencing ecological processes and ecosystem services through feedback processes (Swemmer et al., 2019; Musakwa et al., 2020a; Ragie et al., 2020), or as an external driver of irreversible environmental change and degradation (D'Alessandro and Zulu, 2017; Schmiedel et al., 2017; Ashukem, 2020). Balancing these different perspectives is necessary for a more scientifically-grounded and evidence-supported basis for (1) understanding of environmental issues (*sensu lato*) and their contexts in the developing world and specifically sub-Saharan Africa; (2) developing appropriate tools for engaging with communities and other stakeholders on environmental and sociocultural issues; (3) developing long-term strategies that converge on achieving both specific SDGs and recognizing the intersectionality of all SDGs with respect to the natural environment and human communities; and (4) identifying appropriate and multidimensional performance indicators that can be used consistently and objectively to describe the nature of environmental change, changes in environmental resources and their services, and considering the functionality of Earth and environmental systems that deliver these resources and services in different ways. The concept of cascading environmental systems, in which there are feedbacks between and within different components within systems, provides a more useful framework for describing and interpreting their co-relationships (**Figure 6**). These relationships can also better describe interconnections to the human environment and how environmental resources and services are commodified and used by individuals and communities.

CONCLUSIONS AND FUTURE RESEARCH OUTLOOKS

Environmental resources and services provide the means to fulfill the SDGs but the nature and dynamics of these resources and services are still not well-known, in particular in sub-Saharan Africa where food and water insecurity are significant developmental issues (Casale et al., 2010; Omisore, 2018; Dawson et al., 2019). It is notable that previous studies taking a nexus approach to different issues including food, water, energy, waste, climate, land, and economic growth do not explore the detailed interconnections between these elements, or use the powerful interpretive framework of Earth Systems (**Table 1**). This is a key limitation of such studies. It also means that the data required to inform on the success of SDGs have to consider the nature and feedbacks of different variables that operate within environmental and Earth systems. Examining these evidence-based relationships from specific case studies is an important future research priority.

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/s.

AUTHOR CONTRIBUTIONS

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

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