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Why are sustainable practices often elusive? The role of information flow in the management of networked human-environment interactions

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ABSTRACT

Analyzing the spatial and temporal properties of information flow with a multi-century perspective could illuminate the sustainability of human resource-use strategies. This paper uses historical and archaeological datasets to assess how spatial, temporal, cognitive, and cultural limitations impact the generation and flow of information about ecosystems within past societies, and thus lead to tradeoffs in sustainable practices. While it is well understood that conflicting priorities can inhibit successful outcomes, case studies from Eastern Polynesia, the North Atlantic, and the American Southwest suggest that imperfect information can also be a major impediment to sustainability. We formally develop a conceptual model of Environmental Information Flow and Perception (EnIFPe) to examine the scale of information flow to a society and the quality of the information needed to promote sustainable coupled natural-human systems. In our case studies, we assess key aspects of information flow by focusing on food web relationships and nutrient flows in socio-ecological systems, as well as the life cycles, population dynamics, and seasonal rhythms of organisms, the patterns and timing of species' migration, and the trajectories of human-induced environmental change. We argue that the spatial and temporal dimensions of human environments shape society's ability to wield information, while acknowledging that varied cultural factors also focus a society's ability to act on such information. Our analyses demonstrate the analytical importance of completed experiments from the past, and their utility for contemporary debates concerning managing imperfect information and addressing conflicting priorities in modern environmental management and resource use.

1. Introduction

Human actions have influenced entire ecosystems and, in the process, have led to a wide range of different outcomes: some positive (Ostrom, 2009; Trant et al., 2016a; Bliege Bird and Nimmo, 2018; Moritz et al., 2018), but others negative (Cardinale, 2012; Boivin, 2016). The scale of these interactions is increasing in scope and intensity (Fanin, 2018), with anthropogenic activities fundamentally reconfiguring the biosphere (Ceballos et al., 2017). Limits to how we perceive and act on information gathered from the environment – what we term *information flow* – can make management practices difficult, as key data may be unavailable, unknown, or even unknowable. Today, as in the past, cultural priorities can diverge from and supplant ecologically beneficial strategies, or can serve as a cultural lens through which information is interpreted, leading individuals and communities to make choices that are unsustainable in the long-term (Kwok, 2017). This may be a result of

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limited information flow, the temporal mismatch between short-term gains and long-term sustainability (Cumming et al., 2006), or likewise could indicate conflicting values and beliefs, a relevant circumstance today (Hulme, 2009; Hulme, 2016). Conflicting cultural priorities may take many forms; information flow may be fragmented and partial because of the costs of gathering that knowledge, or information may not be acted on by decision makers, as the cost of acting on it might be perceived as prohibitive (Boyd et al., 2011). In this paper, we argue there is a clear and present need to better conceptualize how information availability, information quality, and its use impacts ecological management for good or for ill.

We leverage archaeological datasets to assess how spatial, temporal, cognitive, and value-based limitations impacted the generation and flow of information about ecosystems to past societies, and thus led to compromises in sustainable practices. These data help to elucidate how human access (or lack thereof) to different kinds of information has promoted or inhibited sustainable ecosystem management, and we suggest ways to minimize detrimental impacts from limited information flow now and into the future. Our work integrates with foundational work by Ostrom (Ostrom et al., 1999; Ostrom, 2009) suggesting the need for multilevel nested frameworks for managing social-ecological systems. We augment this by suggesting that the past offers examples of experiments with sustainable social-ecological systems, and present the Environmental Information Flow and Perception (EnIFPe) model, a formal conceptual model that can enable better understanding of limits to actions to achieve sustainability.

Using terminology from cultural evolutionary theory, we define information as that which is transmitted culturally within a group of individuals through copying or as learned socially within a group or via experimentation such as trial-and-error. Information can be acquired via “genetic inheritance from biological parents” or “individual learning, where there is no influence from conspecifics” (Mesoudi and Whiten, 2008, p. 3489). In addition to individual learning practices, cultural transmission of information via the copying of individual learners offers a high fidelity of information between individuals and groups. The combination therein covers information that is acquired through observation of the environment or social actors in society (i.e., social learning), or transmitted through copying or memetics (i.e., cultural transmission).

Outcomes of human interactions with other organisms have defined key aspects of environmental quality, human health, food security, and well-being throughout human history (McGlade, 1995; Kirch, 2005; Erlandson and Rick, 2009; Braje and Erlandson, 2013; Schwindt, 2016; Crabtree, Vaughn and Crabtree, 2017; Crumley, 2021) and continue to shape those features in the present. Historical perspectives, therefore, illustrate that practices associated with terrestrial and marine resource use are rarely uniformly “good” or “bad”; environmentally destructive practices can be implemented alongside sustainable practices (Dugmore, 2006; McGovern, 2007; Crumley, 2021). In many societies the successful accrual of information and development of sustainable practices can be encapsulated in the concept of TEK—Traditional Ecological Knowledge (Lepofsky, 2009; Nicholas et al., 2014). Here, we are particularly interested in contrasting when and where information is difficult or impossible to assimilate, resulting in unsustainable practices, as opposed to circumstances when information can be codified in TEK and acted upon, given specific cultural norms. However, understanding the sustainable accumulation of environmental knowledge into cultural practices necessitates lengthy time horizons encompassed by historical and archaeological disciplines (Crumley, 1994; Crumley, 2017; D’Alpoim Guedes et al., 2016; Armstrong, 2017; Hartman, 2017; Jackson et al., 2018).

There is a long history of ecological research illuminating the ways that human actions can have cascading negative (and occasionally positive) effects on ecosystems, and the implications for conservation and management (Crabtree and Dunne, 2022; Estes and Palmisano, 1974; Worm et al., 2009; Fulton, 2010; Yodzis, 2010; Dunne, 2016; Crabtree, Vaughn and Crabtree, 2017; Crabtree, Bird and Bird, 2019; Crabtree et al., 2020). Building on the momentum of that work, we draw on well-resolved regional cases of the long-term consequences of the settlement of previously unoccupied islands of Eastern Polynesia and the North Atlantic, as well as those arising on long-settled continental landscapes in the American Southwest. Using these examples, we present a model that describes how information flowing between humans and from ecosystems can lead to sustainable practices. We discuss instances of top-down control, but also note many situations resulting from bottom-up effects of individual actors reacting collectively to environmental cues (Lepofsky and Kahn, 2011; Moritz, 2016; Moritz et al., 2018). We identify pathways to different sustainability outcomes to assess multi-generational interactions within ecological networks. We define successful outcomes as those that promote the range, quality, and persistence of ecosystem services while avoiding or mitigating opposite consequences. While it is well understood that conflicting priorities can inhibit successful outcomes (Barthel, Crumley and Svedin, 2013; Boivin, 2016; Barfuss et al., 2020), our case studies suggest that imperfect information can also be a major impediment to sustainability.

2. Theory

2.1. The conceptual model

A number of frameworks exist for assessing the structure and sustainability of social-ecological systems, tracking the interactions between users, resources, and systems of governance (Ostrom, 2009; Ostrom and Cox, 2010). However, few have quantified the spatial and temporal interplay between resource units and the availability of practical, actionable information among users. Here, we present EnIFPe, which examines the scale, tempo, and quality of information flow within and between communities and which promotes sustainable coupled social-ecological systems. This model considers environmental information expressed over varying temporal and spatial scales that humans may or may not have access to, including:

- **vulnerabilities** in ecological and social systems that may be the result of other factors such as climate change
- **drivers** producing ecological networks that become more simplified, less robust to species loss, and less stable given perturbations
- **ecological interactions** that change populations through actions such as hunting, animal husbandry, and agriculture

Using this framework, we ask whether information flow with high spatial fidelity and a strong correspondence to ecosystem function facilitates decision-making that:

- results in human-ecosystem interaction networks becoming richer, more robust to species loss, and more stable when experiencing external perturbations such as climate change
- enables humans to invade systems without initiating cascading extinctions or creating instabilities in local ecological networks

Critically, we define sustainability following Robinson (2004, p. 370) as “the ability of humans to continue to live within environmental constraints”. In this context, sustainable practices balance the efficient, beneficial use of ecosystem services in the short-term without compromising the use of such resources by future generations to meet their needs (World Commission on Environment and Development, 1987, p. 43).

To examine how well the EnIFPe model captures well-studied events, we first develop it in the North Atlantic and then apply it to understand information flows in Eastern Polynesia and the American Southwest, with supporting documentation from the Arctic and the Pacific Northwest. We propose that information flow changes with perception and cognition of new ecosystems, as well as the directness, frequency, and duration of human-ecosystem interactions; collectively these processes materially impact the knowledge that underpins action. Finally, we assess when ecosystem interactions occur in information-rich or information-poor contexts, and the extent to which these impact sustainable practices and ecologically and/or culturally informed decisions and human responses to environmental change. Applications to past systems provide insights useful for understanding how current societies can better use information flows to adapt to current and future changing conditions.

The EnIFPe model assumes that a society's understanding of the lived environment — the total biotic and abiotic environment that people interact with and have a direct understanding of — is variable. Some often-used and accessible areas (e.g., house gardens, intensively farmed plots) are well known and provide a flow of information that is intimate and regularly updated. In contrast, information becomes more limited when activities move beyond intensively managed regions into hinterlands (such as high-altitude zones) and remote, rarely visited areas (such as adjacent rock islets) where episodically available resources are exploited (e.g., migrating animals, berry patches). It is, of course, both infeasible and impractical to access perfect information on every aspect of the environment; this model formalizes the relationship between total available information and the perceived subset that people use to create knowledge and inform action.

2.2. The formalized conceptual model

In order to conceptualize the flow of information in complex social-ecological systems, we identify-four categories that form a nested set. *Total Information* or In_t (1) encompasses all possible environmental variability. *Available Information* or In_a (2) is the subset of Total Information that humans have access to given various filters and constraints. *Usable Information* or In_u (3) is the subset of Available Information that is potentially usable given processing and other costs. *Wielded Information* or In_w (4) is the subset of Usable Information that is actually implemented; there may be additional costs or barriers to sharing information for other reasons (e.g., cultural norms), explaining why information may not be wielded. Finally, information is degraded by losses due to perception (λ); these perceptual losses can occur for any number of reasons from 1 to *n*, be they cognitive (e.g., memory), intergenerational transmission, geographical limitations, spatial limitations, or any other number of constraints on sharing information. These may be formalized as:

$$\lambda_{1\cdots n} = \lambda$$

If we begin by assuming that we cannot access *Total Information* (In_t) of the lived environment and that the information is then degraded by losses due to cognitive perception:

$$In_t(\lambda) = In_a$$

which composes the *Available Information* In_a for an individual or a group. This In_a then is subject to processing costs η_p to create the information that can be accessed and used, as:

$$(In_a)\eta_p = In_u$$

Not all potentially usable information, however, will be wielded to one's benefit. The information a community wields, In_w, is in turn usable information subject to the costs of taking action η_a. We know that *Useable Information* In_u will be a subset of any In_u where it is degraded by the costs associated with acting upon it, η_a, so:

$$(In_u)\eta_a = In_w$$

This wielded information, thus, is itself total information, In_t, that is degraded by spatial, temporal, cognitive, or other perceptual losses (λ) as well as processing and actioning costs (η_p, η_a).

Consequently,

$$In_w = (((In_t(\lambda))\eta_p)\eta_a)$$

or:

$$In_t(\lambda) = In_a$$

$$(In_a)\eta_p = In_u$$

$$(In_u)\eta_a = In_w$$

where:

In_t = total information.
In_a = available information.
In_u = usable information.
In_w = wielded information.
λ = losses of information due to perceptual limitations ($\lambda_{1\ldots n}$).
η_p = cost of processing *available information* to become *usable information*.
η_a = cost of actioning *usable information* to become *wielded information*.

The ability to process and implement information leads to variability in how humans interact with and respond to their biotic and abiotic environments. Accurately wielding information can foster higher knowledge of an environment and of ecosystem processes, which in turn can influence a community's ability to react to exogenous or endogenous impacts; partial or inaccurately wielded information in this sense would reduce knowledge. However, information flow is often variable and when new conditions arise (e.g., flooding conditions along a riverbank) individuals may or may not be able to react in a commensurate way. Their ability to respond depends upon the accessible information and how they choose to wield it.

2.3. Applying the EnIFPe model

Consider a society living in a landscape where they have near total information about some portions of the landscape, yet they are lacking information about other portions. Following work by Nelson et al. (2016) we conceptualize these according to a four-part scale (from "no loss" to "yes losses") with losses and costs expressed the following way. We assume that **Total information = In_t = 1** and losses and costs are expressed as:

- **no loss of information (no; 1.0)**
- **partial loss of information (more no than yes; 0.75)** ("limited" perception, processing or actioning)
- **substantial loss of information (more yes than no; 0.25)** ("compromised" perception, processing or actioning)
- **near total loss of information (yes; 0.1)**

In Table 1 we examine losses and costs according to multiple well-studied events in Medieval Iceland. In our first example we can see that Hicks et al. (2016) identify sustainable wildfowl strategies around Lake Mývatn (what we term Landscape A). While these areas were still subject to losses of information, the relative small amounts of losses led to high amounts of information flow. In contrast, when there are multiple elements of perception that are compromised by losses and no elements are unaffected, events such as the extinction of the great auk can occur (what we term below Landscape B). For an individual in Landscape A, In_a would equal 0.75 (75 %), while in Landscape B their In_a would equal 0.10 (10 %). We suggest that the processing costs may be the same in both landscapes, here set to 1, since the society employs the same technologies in these different landscapes.

Substituting the above values into the EnIFPe model, we can see that the usable information would be either 75 % or 10 % of Total Information:

$$(In_a)\eta_p = In_u$$

$$(0.75|0.1)1 = 0.75|0.10$$

If there are further processing costs, as we explore in Table 1, the amount of information that can be acted upon decreases. In the example of Landscape A, increasing the number of fields (which would require more information) can lead to decreases in available information. Two areas would lead to information of about half, 0.56, since $(((1(0.75))0.75)1) = 0.56$. Likewise, in Landscape B we can see that losses can accumulate, with $(((1(0.10))0.10)0.10) = 0.001$. In Table 1 we see, for example, that Medieval Icelandic society was required to make different choices in landscapes with less available information than in others where there was greater available information. Holding all other values constant (i.e., values of 1), the magnitude of the losses and costs (i.e., values at 0.75 or 0.25) dramatically impacts the resulting quantity of information available.

Table 1

Applying the EnIFPe Model to multiple case studies in Iceland, demonstrating how changes in perception, costs, and losses, can impact the amount of wielded information for a society.

Information flow	**Value**	**Examples**	**Status**
No losses or costs of information: it is perceived, processed, and actioned with high fidelity (((1(1))1)1)=1	1		Landscape A ‘Green’ **>0.42**
Although there may be some combination of limited losses or costs to perception, processing, and/or actions, the costs are minor and do not compromise sustainable outcomes. There are some losses and costs (0.75 for one or more aspect), but in all cases it is more “no” to those restrictions than “yes.” For three unique areas we have three unique solutions: one area, e.g., (((1(0.75))1)1)= 0.75 two areas, e.g., (((1(0.75)) 0.75)1)=0.56 three areas, e.g., (((1(0.75))0.75) 0.75)= 0.42	0.75 0.56 0.42	*Wildfowl and wetland management in Mývatn district, Iceland* (Hicks *et al*., 2016; Sigurðardóttir *et al*., 2019) Key threshold below **0.42**	
At least one defined aspect of perception/processing/action is compromised by losses or costs. While not near total, that element is more “yes” than “no”, e.g., (((1(0.25))1)1)=0.25 This may be compounded by other limitations, e.g., (((1(0.25))0.75)0.75)=0.14	0.25 0.14	*Early arable activity in Iceland* (Simpson *et al*., 2002) Key threshold >**0.14 < 0.10**	Amber **0.14-0.42**
One defined aspect of perception/processing/action has a near total loss or cost, with some “yes”, while others are “no”, e.g., (((1(0.10))1)1)=0.10 OR One defined aspect of perception/processing/action has near total loss or cost, and this is compounded by more than one aspect of perception/processing/action being compromised, e.g., (((1(0.10))0.25)0.25)=0.06 OR	0.10 (0.06) 0.01 <0.01	*Woodland management, Þjórsárdalur, Iceland* (Sigurmundsson *et al*., 2014) *Rangeland management, Iceland* (Dugmore *et al*., 2020)	Landscape B ‘Red’ **<0.1**
One aspect of perception/processing/action has no loss or cost but two aspects have near total loss or cost, e.g., (((1(0.10))1)0.10)=0.01 OR Multiple elements of perception/processing/action have a near total loss or cost and no element is unaffected, e.g., (((1(0.10))0.1)0.25)=0.0025 and (((1(0.10))0.10)0.10)=0.001		*Extinction of the great auk* (Bengtson, 1984)	

The formalized mathematical model can be instrumental for understanding how different quantities of available information could have radical impacts on outcomes in a simulated environment where we care about heterogenous landscapes and the effects of these impacts over time. The results above demonstrate how small changes can have large impacts on the experience of the society and how impacts can be compounded. In the following sections we discuss the implications of poor information flow across space and through time for three main societies: Eastern Polynesia, Medieval Iceland, and the Ancestral Pueblo Southwest.

3. Discussion

3.1. *Examining variability of information flow in real systems*

As the EnIFPe model illustrates, the extent of information flow is impacted by conceptual limitations. While frequent information flow may decrease the lambda parameter losses due to regular status updates, it is not the only influencing factor. In Fig. 1 we present an idealized schema whereby management intensity (presumed information flow and local/traditional ecological knowledge) declines with distance (either a physical distance or a “friction” distance) from the settlement. While we recognize that there will be patches of strong information flow that do not conform to a pattern of decline with distance (e.g., relating to a particular resource, activities, and times of the year, such as dairy production or fodder collection from outlying shielings), the simplified schema in Fig. 1 conceptualizes how the spatial dimensions of our lived environment shape our ability to wield information.

1a) Spaces centered on heavily managed and extensively transformed parts of the environment. This region is primarily related to spaces occupied by domesticated species. Information on the development and well-being of domesticated plants and animals is usually very high, since they occupy spaces that have been heavily *modified* by niche construction, are *tended* for diseases, are *managed* for their growth and reproduction, and are *culled* at a logical rate. These spaces are often close to occupation sites and/or are visited frequently. Taxa are observed for long periods of time and through all their life cycles. As a result, losses of information due to spatial and temporal limitations are low (i.e., 0.75 – 1), although actioning usable information may be limited, compromised, or face near total impediments. Interactions with these taxa are shaped by high levels of available information. Overall, losses of information (λ) may be quite low, but can be affected by η_a.

1b) Wild species harvested within the managed realm, but extending to unmanaged peripheries. Available information about the ecosystems that support these taxa can, in certain circumstances, rival that related to domesticated species (i.e., 0.75 – 1). Communities may, for example, enhance habitats for selected taxa to augment their productivity in ways that are based on nuanced and detailed environmental information. Activities such as diverting drainage to maintain wetland fodder production areas in Northern Iceland are based on an information flow that has suffered from minimal losses due to temporal or spatial factors and have been effectively actioned. Other aspects of this type of activity may, however, lack critical information (i.e., 0.1 – 0.75). Rangelands may have areas that are visited too infrequently to note changes or be subject to changes unfolding over multigenerational timescales that are not observed, and thus potentially take users unawares. Overall, losses of information due to spatial limitations (λ) increase and may be compounded by impediments to processing (η_p) and actioning (η_a) the information.

2) Wild species harvested within the managed realm, but who range far beyond it. These examples include migratory birds who nest and breed in managed parts of the landscape. While people may have substantial knowledge of this system *while the birds are present*, they are unable to monitor the system beyond breeding season. Knowledge of this system is highly seasonal and corresponds to a system with the potential for high information losses (reduced λ) due to spatial and temporal limitations.

3) Wild species harvested outside the managed realm and ranging far beyond the known space. These examples include birds, gadid fish, migratory marine mammals, and other migratory taxa. Similar to 2 above, people may know of the usual migration of these taxa, but will not be able to predict with fidelity when (and where) the migrations will happen, or assess the health of the populations concerned. Examples of this include migratory birds that nest in remote locations beyond the contiguous known environment, or distant colonies of mammals that can be harvested by hunters ranging outside of well-known spaces. Acquiring nuanced, high-quality information for these types of taxa is subject to major barriers imposed by a physical separation and episodic contact. Enhancing information flow in these circumstances is costly. Events that occur far away (predation, sea ice changes) may make harvest untenable. These systems correspond to a

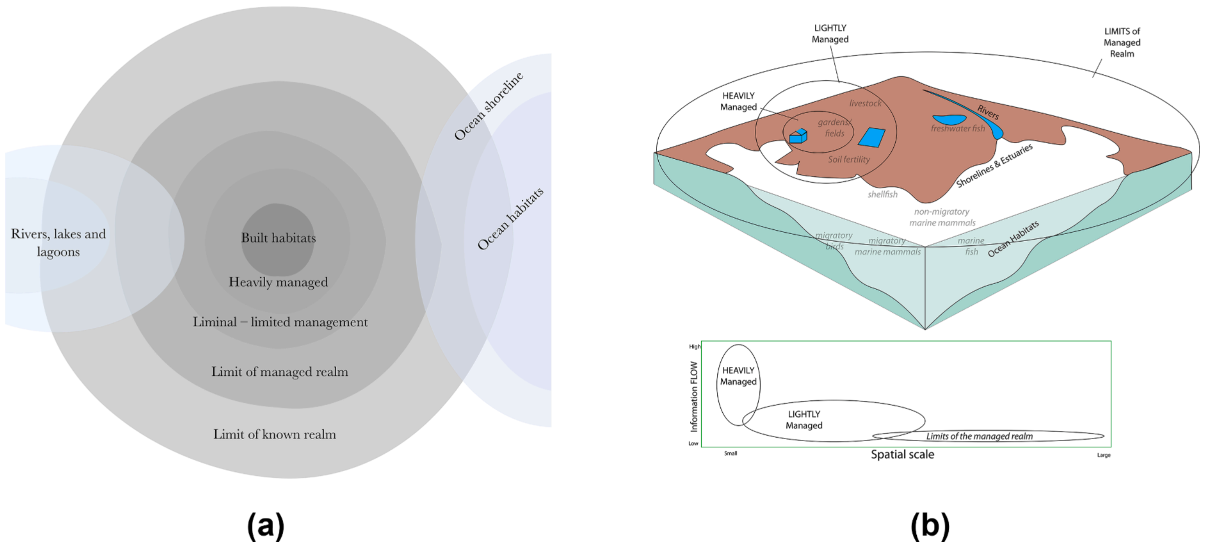

Fig. 1. a) A conceptual model of managed and known realms around a settlement bordering a coastline. The visual model illustrates how human socio-ecosystems range from heavily managed cores to lesser-known peripheries, bounded by the unknown. Four key groups of interactions are identified. b) A conceptual model of the spatial distribution of ecosystem services and taxa exploited around a settlement site in the Scandinavian North Atlantic during the Viking Age- early modern period.

very low information flow system. Overall, losses of information due to spatial, conceptual, and temporal limitations (λ) are high. Even if costs of processing and actioning information (η_p and η_a) are low, the sustainability of these operations may rely on chance and a limited scale of exploitation (Landscape B in Table1).

As can be seen in the two parts of Fig. 1b, in a settlement bordering a coastline, the amount of information will change across space, with heavily contacted areas having the highest amounts of information. Migratory animals will only appear at certain times throughout the year, making the information gleaned from contact with them seasonal and subject to environmental impacts (for example, sea ice melting earlier one year than another). These can provide unique challenges for a society as it attempts to access information for sustainable outcomes and successfully action that information.

The EnIFPe model dovetails with concepts from niche construction theory. In niche construction, organisms alter their environments, modifying the conditions that they—and other commensal organisms—experience. “The organism influences its own evolution, by being both the object of natural selection and the creator of the conditions of that selection” (Levins and Lewontin 1985, p. 106). The EnIFPe model helps conceptualize exactly how the flow of information can change as niches are constructed, helping increase the flow of information for the organisms (also see Ellis, 2015). These modified landscapes can then become anthropogenic biomes, or anthromes, which “represent heterogeneous landscape mosaics that emerge through sustained human-environment interaction” (Ellis, 2021, p. 6) and would have high levels of information. Yet, as we explore below, there are limits to the ability to increase information.

3.1.1. *The limits of perception*

The ability to gather, process, and wield information on the lived environment, as explored in our formal conceptualization, is subject to limits in perception (Ingold, 1993; Ingold, 2002) that may derive from spatial constraints, changing temporal patterns, and/or the challenges of processing new information. Cultural norms and practices clearly affect people’s ability to act on such information, but here we are primarily interested in the ability to gather it.

Information flow may be compromised if incoming data mismatches understanding. In contexts of new colonization, such as with the Eastern Polynesian Islands and the North Atlantic Islands, issues of cognition and temporal scale are interwoven as arriving communities try to map their pre-existing ecological knowledge onto new landscapes (Dugmore, 2006; Rockman, 2009a). Different landscapes may look similar but present false analogies; when the first Norse settlers encountered Icelandic grasslands in the late 9th century they were confronted with a subset of the taxa from northwest Europe, thus bearing superficial resemblance to Scandinavia. Yet these grew upon critically different soils leading to reduced carrying capacities and the potential for threshold-crossing types of soil erosion (Dugmore, 2009; Streeter et al., 2015). Similarly, Polynesian voyagers moving from a geologically young island with high soil nutrient status may not have initially perceived the low-nutrient soils of geologically older islands which were at risk for deforestation and erosion (Kirch, 2007). In such contexts, generations must build an appropriate depth of traditional and local ecological knowledge for superficially similar landscapes that change in response to human intervention and niche construction.

If a society is unable to connect, remember, or inscribe information in a way that is usable to subsequent generations, important gains from learning may be lost or may have to be recreated, often with a substantial time lag (Boyd et al., 2011). Issues of landscape learning (and relearning) will apply in times of environmental change when place-based learning loses utility due to the scale of local change and moving ecotone boundaries (Rockman and Steele, 2003; Berkes and Turner, 2006; Dugmore, 2006; Turner and Berkes, 2006; Halstead and O’Shea, 2009). Of course, even if information is available, that does not mean it will be encoded into TEK (Riede, 2011; Riede, 2012; Zeder, 2015a; Zeder, 2016a); degradation of information can be the result of a lack of prioritizing, a lack of caring, or a lack of interest.

Finally, temporal dimensions of information loss pose unique challenges. Before the development of instrumentation, few sequences of observation were continuous, although many non-instrumented observations enshrined in cultural memories have accurately captured environmental phenomena such as solstices and other celestial events marking times for annual planting or harvesting (Kahn and Lepofsky, 2022; McCluskey, 1977). The challenges resulting from temporal dimensions of information loss can be the result of fragmented or truncated sequences of observation that result from partial or limited understanding of shorter-term processes such as diurnal cycles, weather, and seasonality. Even more challenging are longer-term episodic, cyclical, and directional environmental variation (e.g., typhoons, drought, gradual climate warming), particularly ones that exceed a human generation or lifespan. Systems may have lead times and lags which complicate observation, with observed effects happening long after the event has concluded, and populations may experience the loss of elders or individuals with special knowledge and unique experience, thus hindering learning (Boyd et al., 2011). Even if the transmission of information through time appears to be functioning, its accuracy and utility may degrade due to error-prone transmission, changes in meaning, cultural displacement, and environmental change. Thus, disconnects in information flow perception, processing, inscription, and transmission can affect the long-term development and maintenance of TEK in addition to impacting the development and sustainability of human-environment interactions.

An example that illustrates the contrasting spatial and temporal extent of information is the case of the fateful Franklin Expedition that attempted to navigate the Northwest Passage in 1845–1846. At the time, the British Navy had advanced scientific mapping, steam-powered ocean-going ships, and extensive, calculated rationing for Arctic voyages (Withers and Keighren, 2011; MacDonald and Withers, 2016). However, “the aura of invincibility” surrounding the Franklin expedition had masked the possibility of failure (Cavell, 2009). Trapped in sea-ice close to King William Island, the crews of the ships Erebus and Terror abandoned their vessels in the winter of 1846–1847 before succumbing to starvation, scurvy, and—possibly—lead poisoning from canned rations.

The British explorers lacked knowledge of local resources, including seals, caribou, musk ox, salmon, and trout that were hunted by the Netsilik Inuit, and instead relied on preserved foods carried with them. (Boyd et al., 2011 p. 10920) explain that “explorers [often] die or suffer terribly owing to the lack of crucial information about how to adapt to the habitat”. In contrast, the Netsilik Inuit had developed a cumulative knowledge of the local environment from centuries of local habitation that they combined with highly refined technologies and skills for hunting and fishing and surviving extreme cold. Diary and ethnographic accounts do record encounters between members of the Franklin Expedition and the Netsilik Inuit (Savelle, 1985), yet an inability to communicate (and even an unwillingness to learn) prevented the transmission of knowledge from Netsilik Inuit to the explorers.

This historic case illustrates the spatial limits and temporal extent of information flow. The Netsilik Inuit developed highly adaptive technologies and knew the location, variation, and limits of local resources through a steady accumulation of environmental knowledge transmitted across generations (Rockman and Steele, 2003; Rockman, 2009b). As Laland and Brown (2006) remind us, even a society with advanced technologies can, in new environments, “experience limits to its tolerance space, outside which it is unable to behave adaptively” (Laland and Brown, 2006, p. 98).

3.2. *Why sustainable practices are often elusive: The consequences of variable information availability*

Thus far we have explored barriers to the collation of environmental information and the subsequent challenges of turning available information into wielded information that impacts decision-making. We conceptualize this by suggesting that information may be unavailable because of temporal gaps, limited spatial coverage, and/or a lack of perception (λ). We recognize that acquiring total information is unlikely and impractical, but argue that uneven information gathering and fundamental limits on observations in some cases can explain inconsistent outcomes vis-à-vis humans and their environments.

3.2.1. Cusp bifurcations

Cultural practices enable societies to adapt to changing environments, particularly local human-induced changes (Adderley and Simpson, 2005). By maximizing available, usable, and wielded information, it may be possible to identify problematic changes (Fig. 2). To address the need for informed decision-making, societies may intentionally or unintentionally boost available information by observing what happens when they manipulate food webs, constrain wild populations, and modify species' niches. However, it is possible that unsustainable practices will not be identified, that they may be detected but downplayed, that information blind-spots align and reinforce each other, and that issues are detected too late. It is exceedingly challenging for humans to understand and respond to both the short- and long-term fluctuations in populations that are the outcome of interactions among species with varying demographics and life-histories such as lifespans, reproductive rates, and mobilities that operate over varying time scales (Hastings, 2016). If problematic changes are identified after the system has crossed a critical threshold, remedial action may not be possible over realistic time scales (Scheffer et al., 2009; Scheffer et al., 2012; Lade and Gross, 2012; Liu, 2015). The scale of complexity in a given social unit or set of units, as Shin (2020) recently argued, can also have an increased influence on the importance of information processing. Yet, early warning signals of imminent threshold change (Rockström, 2009; Scheffer et al., 2009; Lade and Gross, 2012; Liu, 2015) may not be identifiable (also see Biermann and Kim, 2020). Our model suggests that to detect warning signals by perceiving an overall direction of change and discount the increased noise from variability, individuals would need to have sufficient understanding of the state before the transition as well as sufficient ability to overcome bias (Kahneman et al., 2021). In this case information flow may play a limited role in the avoidance of these cusp bifurcations, our η parameters above.

Our model predicts that if ecosystem changes (or sufficiently clear signals) are identified, sustainability can be pursued despite instability in environmental variability or harvest success (Fig. 2). In the model, this would be accomplished through rapid increase of usable and wielded information. Yet when they are not identified, coupled natural-human systems can shift to a new state that can have significant consequences for societies and ecosystems alike. In our model this would be an indication of low amounts of usable and wielded information. These changes can be natural environmental fluctuations or anthropogenically induced by the society experiencing the change. Extensive rangeland erosion in Iceland, for example, represents one such tipping point (see Table 1) in the past, as does a regional elimination of species, such as walrus in Iceland, and great whales in the surrounding seas after the 17th century (Thórarinsson, 1961; Allen and Keay, 2001; Roman and Palumbi, 2003; Streeter and Dugmore, 2014; Streeter et al., 2015; Keighley, 2019).

Most changes in socioecological systems that we are viewing through archaeological and anthropological data are not, however, cusp bifurcations, with resulting fundamental asymmetries. Rather, they can be usefully considered in terms of their outcomes of reductive homogenization and enhancement, or their conflicting types of extraction or asynchronous timing, the drivers of which may be explained in whole or in part by information availability and its use.

3.2.2. Reductive homogenization

Humans may reduce the richness, abundance, and evenness of ecological communities (intentionally or accidentally), a process we call reductive homogenization. This can be through direct effects on populations, such as over-harvesting, or through indirect effects, such as removing a key species that has cascading impacts on the abundances of

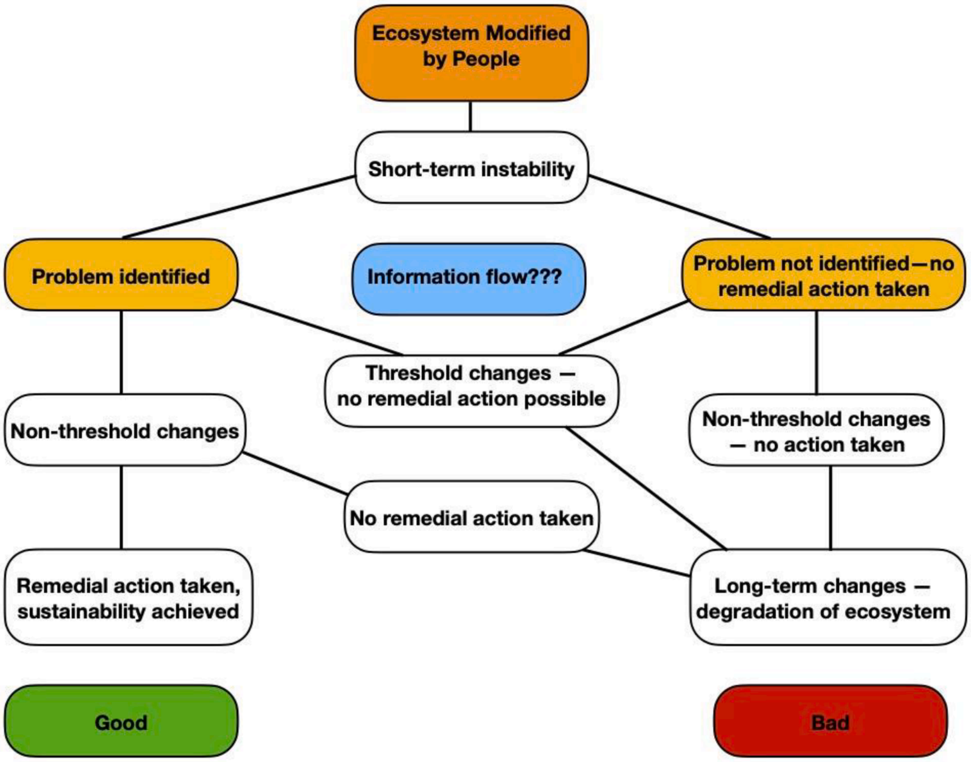

Fig. 2. Schematic diagram illustrating when sustainability can and cannot be pursued in a system.

other taxa (Abrams et al., 1996). Within the Ancestral Pueblo in the North American Southwest, reductive homogenization was the outcome of intensified maize production, which concomitantly decreased piñon-juniper forests. This slow process led to grassland encroachment throughout the region (Crabtree, Vaughn and Crabtree, 2017; Crabtree et al., 2020). In the Society Islands of Polynesia, endemic trees and plants lacking important economic uses were gradually removed over time (Dotte-Sarout and Kahn, 2017). These were replaced with Polynesian introductions: plants and trees brought by the first colonizers with significant subsistence and economic use. The anthropogenic creation of forests led to lower diversity in endemic species and greater abundance of economically useful species (Kahn, 2015; Stevenson et al., 2017). In these examples, reductive homogenization happened at slow rates that likely seemed insignificant over a single lifetime, but which had major cumulative effects, a circumstance that illustrates the potential temporal barriers to effective information flow and its negative outcomes.

3.2.3. *Enhancement*

Sometimes the introduction of a species or increased disturbance can directly increase species richness and biodiversity. Where previously there had only been the Arctic fox, the introduction of several domesticates (e.g., cattle, horses, sheep, goats, pigs, and dogs) increased the number of terrestrial mammals on the North Atlantic islands. Imported cereals were cultivated and with the introduced mammals and trade goods came insects (Dugmore, 2005; Panagiotakopulu and Buckland, 2017). In the Ancestral Pueblo southwest the introduction of maize provided a new and abundant food source for herbivores, and thus led local increases in their abundance (Crabtree, Vaughn and Crabtree, 2017). Often, enhancement and reductive homogenization go hand-in-hand. Pueblo people initially enhanced taxonomic richness of the southwest by bringing in cultivars and by feeding populations of turkey (also dependent on cultivars). Yet this cultivated landscape, with its effective flows of information, eventually pushed the forests to the periphery as populations increased, leading to a reduced local ecosystem consisting of a grass-dominated habitat (Crabtree et al., 2020). In Iceland, introductions boosted the taxonomic richness of depauperate islands, but the impacts of grazing led to large-scale soil erosion (Arnalds and Barkarson, 2003; Crofts, 2011), which created an *ovigenic landscape* structured by the impacts of livestock grazing (Dugmore et al., 1991).

3.2.4. *Conflicting extraction*

Humans often have conflicting needs to extract resources that are incompatible in the sense that the two resources cannot coexist within the limits of the managed realm. Consequently, while people may rely on two habitats or taxa that each provide unique benefits, humans may preferentially target the growth of one over the other due to a perception of immediate needs. Balancing the tradeoffs that arise from conflicting demands for alternate ecosystems in a way that promotes sustainable outcomes over the long term may be compromised by an unequal flow of information about different parts of the ecosystem.

On Rapa Nui in Eastern Polynesia, endemic trees were collected as firewood and for use in constructing houses and canoes. Slash and burn agriculture, which resulted in wind erosion, higher evapotranspiration, and reduced soil moisture retention, as well as the loss of bird guano inputs into soil nutrient regimes, also contributed to extensive deforestation (Stevenson et al., 2006; Kirch, 2017). Unbeknownst to its settlers, soil degradation on Rapa Nui was likely both more rapid and severe than in other parts of Eastern Polynesia, given the island's high aridity and size relative to human population (Ladefoged, 2005). The native forest failed to regenerate, ultimately influencing major socio-political shifts in settlement patterns. Tree loss also precluded the construction of long-distance voyaging canoes that would have allowed for interactions with distant neighboring island groups, thereby buffering the negative impacts of deforestation (Kahn, 2022). A lack of environmental information of Rapa Nui's soils created a blind spot for the settlers and ultimately unknowable unknowns came to materially affect the outcomes of land use decisions and compromise long term sustainability. The multi-generational changes to forests and soil quality led to restrictions in the availability of information flow and accumulated significant costs in terms of its use, corresponding to λ and η in our EnIFPe model.

Sometimes conflicting extraction can be mediated. In Iceland, woodlands that were a key source of charcoal for both iron production and the maintenance of iron tools (Church, 2007) were once widespread. Simultaneously, woodlands needed to be cleared to create both grazing and areas of fodder production. A progressive multi-century contraction of woodlands in Iceland was, however, arrested in medieval times when small areas of woodland were conserved for the continued multi-century production of charcoal (Dugmore, 2006; Dugmore, 2007). In this case the conflicting extraction of charcoal and areas for fodder were reconciled through learning. This process was aided by clearly observable contraction of woodland areas over multi-generational timescales across a large island, in the context of a literate, record-keeping, and increasingly hierarchical society, with patterns of ownership codified in law.

3.2.5. *Asynchronous timing*

Asynchronous timing can lead to some of the largest challenges for people, presenting a potential cognitive barrier (λ) to creating usable information. One example of this is understanding the relationship of reproduction and its impacts in later years. In northern Iceland the annual eider duck egg harvest demonstrates how asynchronous timing could lead to unstable systems, yet also how through the process of learning, remedial action promotes sustainability (Hicks et al., 2016). Here, the effects of too great a harvest of eggs would not be felt for several years, until the annual recruitment of young adults into the breeding population faltered and bird colonies contracted. The Icelanders, therefore, needed to have a multi-year perspective on the dynamics of duck populations and the ability to turn environmental information into appropriate actions to promote sustainability. In the case of Iceland, laws were developed to govern and limit the harvest of eider eggs from each nest, manage nesting grounds to minimize disturbances, and to protect adult birds to ensure the persistence of the colonies and a sustainable exploitation of eggs over multiple centuries (Brewington, 2015; Hicks et al., 2016). The critical challenge for human populations is therefore to learn how to *recognize the cause and effect* even if the cause and effect are asynchronous by years or even generations.

BOX 1.

Case Study	Human impacts
	Reductive homogenization
Scandinavian N. Atlantic islands	Icelandic walrus colonies extirpated (Keighley, 2019); extinction of great auk (Bengtson, 1984); soil erosion impacts 15–30 % of the land area of Iceland (Thórarinsson, 1961; Arnalds, 2015).
Eastern Polynesia	Native forests cleared of non-economic species, local extirpations or extinctions of land snails, land birds, some plant and tree species (Steadman, 2006; Prebble and Dowe, 2008; Kahn, 2015; Dotte-Sarout and Kahn, 2017; Christensen, Kahn and Kirch, 2018).
American Southwest	Fields cleared of pinyon/juniper, locally extirpated ungulates (Bombaci and Pejchar, 2016).
American Northwest	Localized overharvest of yew trees (*Taxus brevifolia*) (Turner and Cocksedge, 2001; von Blanckenburg, 2005).
	Enhancement
Scandinavian N. Atlantic islands	Introductions of domestic animals and plants, plus invertebrates and weed species (Dugmore, 2005; Schofield et al., 2013). Creation of wetlands, and the maintenance of wetlands through the control of inflows of both water and sediment. Irrigation and drainage of field systems; manuring (Adderley, Simpson and

(*continued on next page*)

(*continued*)

Case Study	Human impacts
	Vésteinsson, 2008; Buckland, 2009; Sigurðardóttir et al., 2019).
Eastern Polynesia	Polynesian introductions (plants, animals) provide economically useful taxa (Dotte-Sarout and Kahn, 2017); semi-cultivation of species in marginal zones (Lepofsky, 2003); increase in marine productivity via fishing weirs (Kahn, n.d); increase of coastal plain (and thereby agricultural production) via colluvial inputs from interior shifting cultivation.
American Southwest	Opportunities for native grass encroachment; introduction of maize, beans, squash; promotion of domestic turkey (Crabtree, Vaughn and Crabtree, 2017).
American Northwest	Deposition of organic food waste in coastal shell middens enhanced forest productivity (Trant et al., 2016b). Localized clam gardens increasing production through habitat creation/modification (Groesbeck, 2014; Toniello et al., 2019; Lepofsky, 2021).
	Conflicting Extraction
Scandinavian N. Atlantic islands	Domestic animal grazing and the conservation of timber for charcoal production (Tisdall et al., 2018).
Eastern Polynesia	Reduction of native forest to create agricultural plots impacted bird, landsnail, insects, and plant/tree composition; creation of grasslands and fernlands with fire resistant biota (Kirch, 2007; Orliac et al., 1997).
American Southwest	Needing pinyon/juniper forests while also needing cleared maize fields (Crabtree, Vaughn and Crabtree, 2017).
American Northwest	Regular harvesting of cedar bark for basketry, clothing, mats, conflicts with interest in the felling large trees for later uses such as for poles beams/posts/canoes/plank etc. (Eldridge, 2017).
	Asynchronous timing
Scandinavian N. Atlantic islands	Positive management: Harvesting eggs and maintaining bird colonies (McGovern, 2007).
Eastern Polynesia	Effects of land clearance and bird loss on soil nutrients, forest regeneration (Kirch, 2017; Kirch et al., n.d).
American Southwest	Unanticipated flooding in Hohokam devastates irrigation infrastructure causing abandonment in 14th century (Nelson, 2012).
American Northwest	Widespread cultural protocols and harvest practices to manage exploitation of salmon migrations in coastal rivers and safeguard future runs (Amoss, 1987; Cullon and One, 2013; Langdon et al., 2020).

3.3. *How information flow can promote sustainable practices*

We suggest that by promoting information flow, collating and wielding the information, and decreasing the potential information losses in our cognitive model, societies can learn how to enhance sustainable practices. In this section we present examples of how acute information flow that did not have to overcome temporal, spatial, or cognitive barriers led to more sustainable practices. In contrast, cases of unsustainable practices can be argued to contain elements of poor information flow where aspects of ecosystem function that were unknown or unknowable to the communities played a pivotal role in the outcomes. We do not highlight cases where information may have been ignored, though we recognize that this is an additional problem in achieving sustainability. While we suggest that total information flow is unlikely, prioritizing the collection, maintenance, and processing of information over multiple temporal and spatial scales will lead to learning and a better ability to respond to environmental pressures and effectively evaluate tradeoffs among competing demands. Further, the following examples demonstrate how by ensuring that degradation of information is not synchronous, societies may be better able to confront unexpected challenges.

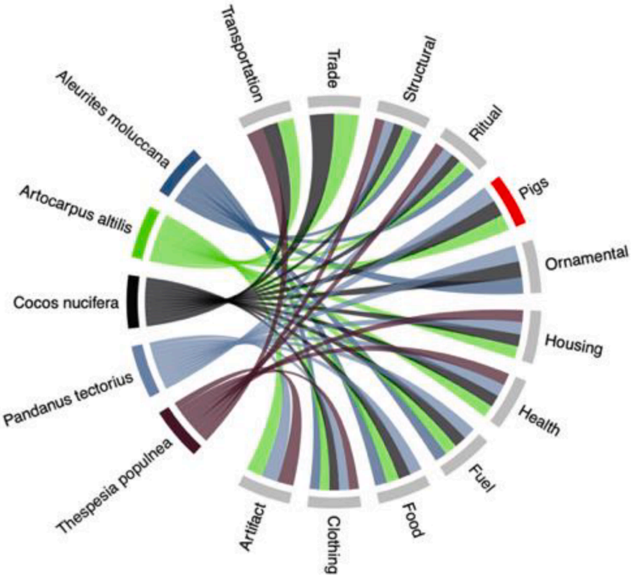

Fig. 3. Circle plot showing the five most important species to Eastern Polynesians of Mangareva, 12 types of uses of them (from Transportation to Artifacts) and a node for pigs showing that they were in direct competition with people for these taxa. The plot is derived from our Human Centered Use Web database (Kahn, 2021). From 20 published and unpublished sources, we mined taxa use data for algae (34 taxa), birds (32 taxa), coral (25 taxa), fish (230 taxa), invertebrates (52 taxa), mammals (8 taxa), plants (192 taxa), and reptiles (4 taxa). 434 uses of these taxa were coded across eight use categories: food, medicinal, clothing, ritual, fuel, housing, ornamental, and artifact.

3.3.1. *Adaptive governance: Avoid conflicts to promote diverse knowledge and multi-stakeholder deliberation*

Occasionally, societies recognized conflicting extraction and took remedial action. For example, while the domestic pig is an important food in the ritual, nutritional, and social lives of Polynesians, inhabitants of smaller marginal islands, such as Mangareva, recognized that pigs were in direct competition with people for local foodstuffs (Fig. 3). While most other Polynesian archipelagoes continued to raise pigs until European contact (Giovas, 2006), pigs on Mangareva were extirpated before colonial arrival (Kirch, 2007), ensuring that the island's ecosystem did not move past a tipping point and could continue in a sustainable fashion. This adaptation—of recognizing the detrimental impacts of pigs on Mangareva's ecosystem—enabled humans to invade this system without causing the local ecological network to unravel.

3.3.2. *Management promoting cultural practices that lead to conservation and maintenance*

In the past, the intentional conservation of a taxon or ecological service was often carried out via implementation of rules with sanctions for rule breakers. While human actions can lead to taxa or resources persisting in a given area, those relationships are difficult to disentangle from the historic record. Rather, humans at times learned to create rules governing specific interactions, such as collective ownership and common-pool resource management (Moritz et al., 2018). In the Society Islands, while the proximate goal of elite-sanctioned restrictions (*rahui*) was to stockpile commoner-supplied goods for elite feasts and *rites de passage* (Oliver, 1974), the system also conserved resources over the long term and codified a paradigm of conservation into community practice (Lepofsky and Kahn, 2011; Bambridge, 2016).

3.3.3. *Ecosystem stewardship and resilience thinking: Cultural barriers and limits to knowledge*

We define cultures that are capable of identifying and responding to environmental change in a timely manner as practicing sustainable strategies. Cultures that are capable of identifying and responding to environmental change in a timely manner, by definition, retain high adaptive capacity (Smit and Wandel, 2006a). However, this capacity is determined by the social, political, and economic constraints of society as a whole (Smit and Wandel, 2006b). Such constraints also determine the ease with which information flows across the physical landscape (ecological knowledge) and from person to person (via social interaction or cultural exchange). As archaeological and historical research has shown, the fidelity of information transmission about environmental change can be enhanced and limited by cultural transmission and social learning (Boyd et al., 2011).

Supporting sustainable social-ecological systems is a pertinent and on-going challenge in the 21st century (Ostrom, 2009; Rockström, 2009). The ability to identify and address early warning signals for a critical transition, such as connectivity and homogeneity, is significant (Scheffer et al., 2009; Steffen, 2015). We suggest that seven spatial and temporal categories of knowledge are required to support system function and integrity to ensure sustainable social-ecological systems:

1. *Time depth*. Long-term information about human impacts on the environment is essential for making management decisions (Kwok, 2017). An insufficient understanding of human impacts on ecosystems can lead to 'shifting baseline syndrome', in which successive generations of environmental managers misidentify already heavily degraded ecosystems as pristine (Jackson, 2001). Archaeology and history can examine the complete history of human impacts on local and regional ecosystems (Romanowska et al., 2021a,b; Silva, 2022; Jiménez et al., 2022; Hambrecht, 2020).
2. *System boundaries*. Knowledge of interactions taking place at the boundaries of the system is essential to holistic resource management. Knowledge of the interactions that take place at the edge of social-ecological systems may not be well understood, leading to uncertainty.
3. *Scale of knowledge*. Attention to multiscalar interactions is a complex but necessary step in managing socio-ecological systems. Regular monitoring and reviews of ecosystem knowledge (both academic research and citizen knowledge) are necessary to support the functioning of dynamic ecosystems Cumming et al. (2006). As Ostrom (2009) explains, a clear understanding of individual users and entire ecosystems are necessary to maintain sustainable resource use.
4. *Resolution*. Regular monitoring is useful if the resolution of information is sufficient to identify and understand changes that serve as early warning signs that socioecological systems are approaching a tipping point. Transparent monitoring strategies are required to identify important provisioning, regulating, supporting, and cultural services vital to ecosystem sustainability and the communities therein.
5. *Certainty*. Both time depth and resolution will support a clear understanding of system complexity. Short timescales—and short-termism—will not provide sufficient certainty about how ecosystems respond to exogenous shocks. Historical and archaeological data are essential to understanding long-term socio-ecological sustainability, including sustainable resource use, climate variability, and traditional ecological knowledge (Crabtree et al. 2020; d'Alpoim Guedes et al., 2016; Nelson et al., 2016; Berkes and Turner, 2006).
6. *Open access*. Users within the bounds of the system should have free access to learning and information in order to make decisions and understand system rules.
7. *Knowledge potential*. The capacity to obtain and act upon environmental knowledge requires a reflexive response to social and cultural factors influencing behaviors and practices. Human security research has, in recent years, shown the importance of addressing social, economic, and cultural barriers that inhibit the ability of certain groups in society from adapting to environmental challenges (O'Brien et al., 2013; Sen, 1982).

Together with these seven categories of resource knowledge, historical evidence of information flow can provide important lessons for contemporary environmental managers and policy-makers.

Alongside the growing scientific evidence that humans cause global- and regional-scale environmental change, there are myriad proposed strategies for mitigating and adapting to this change (Castree, 2016; Castree, 2017; Dessler and Parson, 2019). In geography and anthropology in particular, significant attention is drawn to the differences between "disembodied global scientific" and "local, embodied" knowledge (Mahony and Hulme, 2018, p. 396). In this article, we have illustrated the value of quantifying the spatial, temporal, and scalar dynamics of environmental information flow. In so doing, we have highlighted the potential contribution that deep-time conceptualizations of information flow have for bridging the gap between local knowledge and global scientific knowledge of environmental change for the promotion of sustainable resource use. Three key discontinuities in the global history of humanity have been recognized by Lehman (2021) relating to humans 1) becoming dominant predators within food webs, rather than prey (though see Bird et al., 2021 for a discussion of human embeddedness), 2) becoming mutualists with food species, and 3) adopting a regime of controlled fertility. It is notable how information flow, in terms of available, usable, and wieldable information, plays a driving role in these discontinuities, and is central to understanding the quality, pattern, timing and pace of change, and how that is shaped by cultural diversity (Burke, 2021).

Falsification

Our formalized conceptual model sits between Niche Construction Theory (NCT) and Optimal Foraging theory (OFT) insofar as the EnIFPe model does not assume optimum behaviour and accounts for the disjuncture between perfect information and the perceptual and observable limits that constrain sustainable resource use. This, Zeder (2015b, 2016b; also see Boivin, 2016) argues, is essential to building a general theory of behaviour that accounts for the role of human agency and non-human organisms in shaping their evolution.

To falsify our information flow model, we do not attempt to organize a theory of human behaviour that simply accounts for the optimum energetic efficiency of resource use, rather, we focus on specific available information and the limitations on the use of such information by a given cultural group. Our model could, for example, start with dietary breadth information (often used in OFT) before considering the cognitive and physical constraints on the efficacy of a given resource-use strategy (as accounted for in NCT) (Laland and O'Brien, 2010; Zeder, 2015b; Zeder, 2016b).

In Table 1 we present several cases where outcomes were sustainable (e.g., wetland management) and where outcomes were not sustainable (e.g., the extinction of the great auk) which we further examined in Box 1. In the future, EnIFPe models could be falsified by examining these cases or other global cases where sustainability mismatches information. For example, we propose that the ability to account for the delay between when eider duck eggs were hatched and the return of breeding pairs (approximately-three years) suggested high information flow for Icelandic societies. Historically, that rules were recorded regarding the sustainable harvest of eider eggs and heavy penalties were levied for those who defected from this rule, supports our model. Yet if, instead, we found this high information in the written record but eider harvest still became unsustainable, we would hypothesize a mismatch between information flow and ultimate action. In this way our model can be verified or falsified, as the mismatch between outcomes and action illustrates differing processes of information flow.

4. Conclusions

With reference to "completed experiments" from the past, our use of archaeological and historical data emphasize the importance of spatial, temporal, cognitive, and value-based limitations that impact the generation and flow of information about ecosystems to societies, and thus lead, at least in part, to compromises in sustainable land and marine use practices.

We present a formally-defined conceptual model $In_w = (((In_t(\lambda))\eta_p)\eta_a)$ in which societies that dampen priorities that degrade environments have information flow with high fidelity, combined with an ability to accurately assess and respond to that information, leading to sustainable strategies. Societies can also modify behaviors and re-prioritize, even when re-orientation is costly (e.g., Polynesians removing pigs) as long as the decision is made in time to avoid a catastrophic cusp bifurcation where societies cannot return to the previous ecosystem state.

Information quality and the pathways by which it reaches individuals impacts the perception of environments as well as potential actions to mitigate and adapt to shifting environmental challenges. With increasingly precise instrumented sensing abilities and data handling (e.g., remote sensing and ground-based environmental monitoring), modern societies can gather better empirical data on the environments that humans interact with and more accurately detect their changes. We argue, however, that beyond data gathering the ability to process, understand, and utilize information fundamentally affects our ability to successfully manage dynamic systems over multigenerational timescales.

As human impacts are leading to environmental changes on a global scale, the accurate assessment of environmental cues assumes ever greater significance. Will societies recognize vastly different qualities of information flow, and distinguish between areas where decisions can have a sound basis in environmental knowledge and where it's a "shot in the dark"? Can we recognize leads and lags in system responses as well as our own biases and limits of detection? We propose that with interventions to i) ensure effective information flow, ii) embrace different cognitive and philosophical perspectives, and iii) recognize and reduce conflicting utilization, we can promote sustainable solutions to contemporary environmental challenges. If we can identify where our information is degrading—the lambda parameters in our conceptual model—and how we are utilizing that information, we can be better prepared to make choices that lead to long-term sustainability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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