TITLE:

CASCADING IMPACTS OF ENVIRONMENTAL CHANGE ON INDIGENOUS CULTURE

AUTHORS: Yletyinen, J.[1], Tylianakis, J.M.[2], Stone, C.[3], Lyver, P.O.B.[1]

AFFILIATIONS:

1. Manaaki Whenua Landcare Research New Zealand Ltd., PO Box 69040, Lincoln 7640, New Zealand
2. University of Canterbury, School of Biological Sciences, Private Bag 4800, Christchurch 8140, New Zealand
3. Stone Consultants, 2280 Russell Road, RD4, Hikurangi, Northland, New Zealand

CORRESPONDING AUTHOR: yletyinenj@landcareresearch.co.nz

ABSTRACT:

Global environmental and societal changes threaten the cultures of Indigenous Peoples and Local Communities (IPLC). Despite the importance of IPLC worldviews and knowledge systems to human well-being and biodiversity, risks to these cultural resources are commonly simplified or neglected in environmental impact assessments, in part because cultural impacts are often indirect and therefore difficult to demonstrate. Here, we show that dependency of a culture on the environment can be mapped through human connections with biophysical elements in their environment. We illustrate a rich variety of cultural values that connect an indigenous Māori tribe in New Zealand with their local environment, then evaluate the

resilience of this socio-environmental value system to environmental changes. Our results detail how loss of access to key environmental elements can have extensive direct and cascading impacts on multiple facets of indigenous cultural heritage. Consequently, considering only direct effects of environmental change on cultural heritage, or treating the richness of IPLC environmental relations simplistically, can severely underestimate the seriousness of environmental impacts on IPLC culture. Thus, protecting Earth's cultural and biological diversity requires inclusion of human-environment relationships in environmental impact assessments.

KEY WORDS: indigenous peoples, local communities, resilience, cultural heritage, socio-ecological systems, networks

Rapid environmental change and socioeconomic globalization pose significant threats to global biodiversity and cultural heritage (1–4). Of specific concern are Indigenous Peoples and Local Communities (IPLC, i.e. ethnic groups who are descended from, and identify with, the original inhabitants of a given region, in contrast to groups that have settled, occupied or colonized the area more recently). IPLC commonly depend on the local environment and biodiversity for livelihoods, identity, knowledge systems and general wellbeing, among other things (5, 6). Therefore, limiting their ability to adapt to environmental changes may lead to irreversible cultural degradation (7, 8). Furthermore, in addition to being part of humanity's cultural diversity, IPLC cultural heritage is now increasingly valued in global environmental governance for its rich diversity of approaches for sustainably living with environment (9, 10). Hence, cultural degradation may precipitate further environmental degradation (7, 9). Yet, environmental impact assessments and 'top-down' decision-making often undervalue threats to IPLC cultural heritage, potentially eroding indigenous and local knowledge systems

(ILK), spiritual connections to land, plants and animals, and food security (11). This omission can arise from difficulties in capturing the myriad ways in which culture can be impacted by changes to the biophysical environment, in particular because the impacts could be indirect.

Evaluating the dependence of a culture on their local environment or *vice versa*, and then estimating the culture's resilience to environmental change, is a complex task (11–14). The connections between culture and environment are complex, localized and adaptable to varying degrees (7, 8, 15). In environmental impact assessments and decision making, the intangible aspects of culture (e.g. values, beliefs) frequently become invisible because of their non-materialistic characteristics (11, 16–18). Consequently, many important considerations for IPLC cultural resilience remain marginalized in environmental impact assessments, while the more easily quantified impacts of environmental change (e.g. financial costs and benefits) become over-emphasized (11, 16, 17). In general, the simplification of cultural heritage in frameworks that assess humanity's dependence on nature hinder understanding of the multiple ways that humans and environment connect, and the ways in which different cultures express these connections (18). Importantly, a recent study warned that policies or environmental changes that suppress the engagement of IPLC with their environment can trigger self-reinforcing mechanisms that drive degradation or persistent loss of IPLC cultural institutions and knowledge systems (7). It is therefore highly likely that environmental change has both direct (e.g. 19) and indirect impacts on IPLC cultural heritage. While indirect impacts are commonly difficult to detect in complex systems, their role may be significant for understanding resilience (20).

Here, we investigate relationships between intangible elements of an indigenous culture (its values) and their local biophysical environment. Specifically, we illustrate the complex

connections both among these values, and between values and elements of the biophysical environment. Subsequently, we estimate the degree to which cultural heritage may be degraded by environmental change, including both direct and indirect effects. We adopt a perspective that dependency of a culture on the environment can be understood by mapping and investigating patterns formed by a human community's connections with biophysical elements in their environment. Connectivity between system elements is a common indicator of resilience: in a highly connected system, impacts in one part of the system can spread rapidly and unconstrained to all or most system elements (21). Such connectivity-based vulnerability has been proposed to exist in diverse systems, such as food webs, ecosystems, social networks, finance systems, global anthropogenic networks and socio-ecological systems (22–27). In a cultural system characterized by high connectivity, environmental perturbation may not be restrained to only part of the cultural heritage, such as knowledge relevant to a specific species; it could influence other cultural practices and knowledge spheres as well. In contrast to this potential vulnerability to spreading perturbation, high connectivity may ensure maintenance of a system: local damage caused by a perturbation may be compensated by "inputs" from interlinked components, leading to repair of the damage through redundancy (21, 26). For example, IPLC knowledge connected to diverse biophysical elements would allow shifting from a declined resource to more abundant ones to maintain culturally important food preparation, harvesting practices and ecosystem stewardship goals (8). Because IPLCs strongly rely on local environments, their cultures may be characterized by tightly integrated cultural and biophysical complexity. Given the potentially detrimental effects of indirect environmental impacts and general system structure on IPLC cultures, we suggest that a simplified view on IPLC socio-ecological complexity (e.g. focus on cultural elements associated with a single species) could provide a narrow understanding of cultural resilience.

The first step to understanding connectivity-based resilience of cultural heritage to environmental change is to map the characteristics of the culture's socio-ecological complexity and identify its important elements and interactions (21). We first captured a representation of an indigenous values system associated with the community's local environment. For this purpose, we conducted interviews with Ngātiwai, an indigenous northern tribe of Māori people in New Zealand, to examine i) the richness of values (cultural complexity) that the community associates with their offshore islands and adjacent marine environment, and ii) the level to which the community associates these values with specific biophysical elements (biophysical complexity of the socio-ecological system), i.e. species, ecosystems, landscape features (e.g. 28, 29) (see Methods). Thus, formation of the socio-ecological system in our study is based on integrating two concepts that describe non-materialistic human-environment relationships. First, human values underlie cultural identities and, to a large part, success of environmental stewardship (16, 30–32). An important category of values that connect people to place are human-environment relational values, i.e. "*values linking people and ecosystems via tangible and intangible relationships […], as well as the principles, virtues and notions of good life that may accompany these*", including e.g. moral and familial responsibility to non-humans (33). Second, some plant and animal species and ecosystem elements (e.g. water, snow) have a direct relevance in people's lives and identity. Such 'cultural keystone' species and elements can be detected in IPLC traditions, genealogy, foods, songs, vocabulary, and cultural activities (14, 34).

After identifying key values and biophysical elements, we map the connectivity of an indigenous socio-ecological system by conducting thematic analysis on interview data and transforming it into a socio-ecological network, i.e. a system representing connectivity among values and biophysical elements. In the network, connections between nodes represent

126 dependency or support (the same as in 19). For example, access to land ("land" node in
127 Figure 2) maintains the value of people being connected to their location (PTL in Figure 2),
128 which, in turn, enables harvesting and procurement of customary foods (HAR in Figure 2).
129 Importantly, our network approach allows us to acknowledge that environmental change can
130 have cascading impacts on the culture and interaction with the environment. In so doing, we
131 extend on recent work connecting indigenous knowledge with a component of the
132 environment (19) by also including other connections among and between cultural and
133 biophysical subsystems. Our final objective is to determine the potential for environmental
134 changes to indirectly impact culture within the value system.
135
136 In New Zealand, native plants and animals are under significant pressure from multiple
137 drivers, including climate change, urbanization and introduced species (35). For instance,
138 90% of sea bird species and 80% of shorebird species are either threatened with, or at risk of,
139 extinction (35). Moreover, indicators estimating the health of New Zealand's ecosystems
140 suggest that several rare ecosystems, especially those in coastal areas, are threatened with
141 environmental tipping points (35). We define a culture's resilience to environmental change
142 as ability to face environmental change (or societally-driven change in their access to local
143 ecosystems [36]) without degradation or loss of their core values and practices (cf. 37–39).
144 This definition is in accordance with the need of the Ngātiwai tribe to adapt to global
145 environmental change without losing their core identity and values. For the purpose of
146 understanding socio-ecological connectivity from this perspective, we define a "core value
147 system" associated to the Ngātiwai islands as the set of most frequently mentioned values and
148 the strongest co-occurrence of values with other values and biophysical elements in the
149 Ngātiwai interview data.
150

By illustrating the complexity of cultural heritage linked to local environment, we wish to strengthen the position of IPLC to demonstrate how the vitality of their culture and ability to safeguard biodiversity relies on access to, and rights to govern, their local ecosystem elements. Our study does not aim to deliver deeper knowledge of Māori culture. A scientific representation of a value system (in our study, networks and verbal definitions) inevitably includes a reductionist approach to a culture. Rather, we present a scientific tool that enables IPLC to communicate their cultural dependence on the environment to decision-makers.

Cultural values of the islands and seascape

The rich variety of cultural values that the Ngātiwai tribe associated with the biophysical elements of their local environment provides a detailed perspective on the multiple ways that their culture and local environment are connected. In total, our thematic analysis of 24 interviews revealed 22 values associated with the tribe's relationship with their offshore islands and seascape (Figure 1, definitions in Supplementary Materials Table S1).

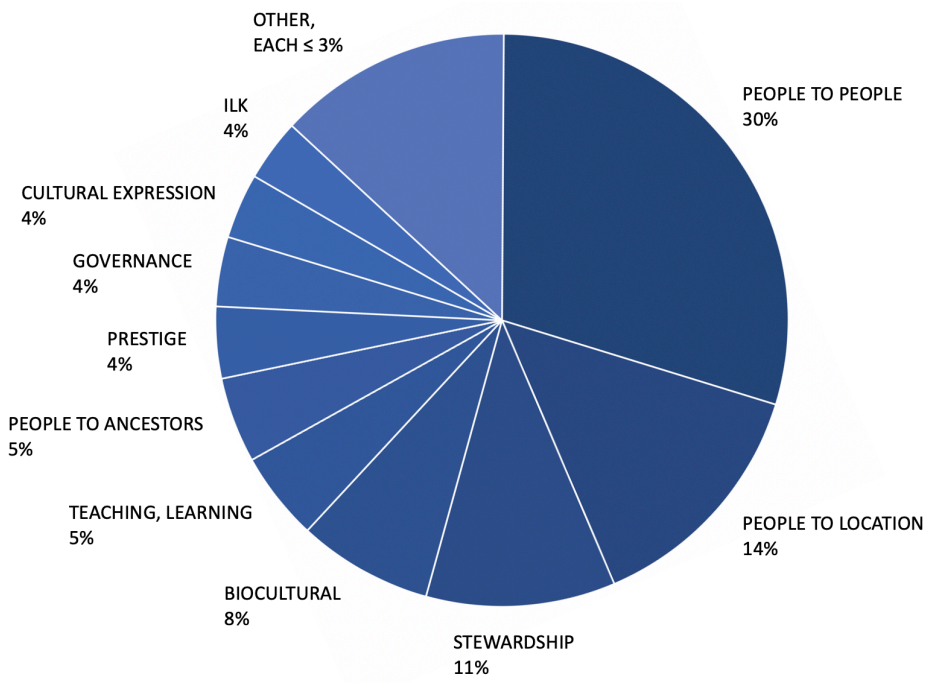


Figure 1. Values associated with the islands of Ngātiwai. *The size of each sector reflects the relative frequency of each value in conversations around the islands. The value system associated with the islands reflects meaning, care, connection and responsibility, including both people-people and people-environment connections. "Other" sector includes: harvesting (3%), operationalisation (2%), customary economy (2%), western conservation (2%), physical health (1%), commercial and business (1%), historical activites (1%), spiritual health (1%), involvement (>1%), normalisation (>1%), mental health (>1%), recreation (>1%). Definitions of the values are available in Supplementary Materials Table S1.*

Overall, the values that describe Ngātiwai's relationship with the local environment extended beyond the immediate benefits of biophysical elements, such as food, conservation status or aesthetic qualities. The values most frequently associated with the local environment reflected connections between people, including future generations, connection to place, and to a lesser extent connection to ancestors (Figure 1). These values were defined by key Māori cultural concepts such as genealogy (*whakapapa*), togetherness of people (*whanaungatanga*),

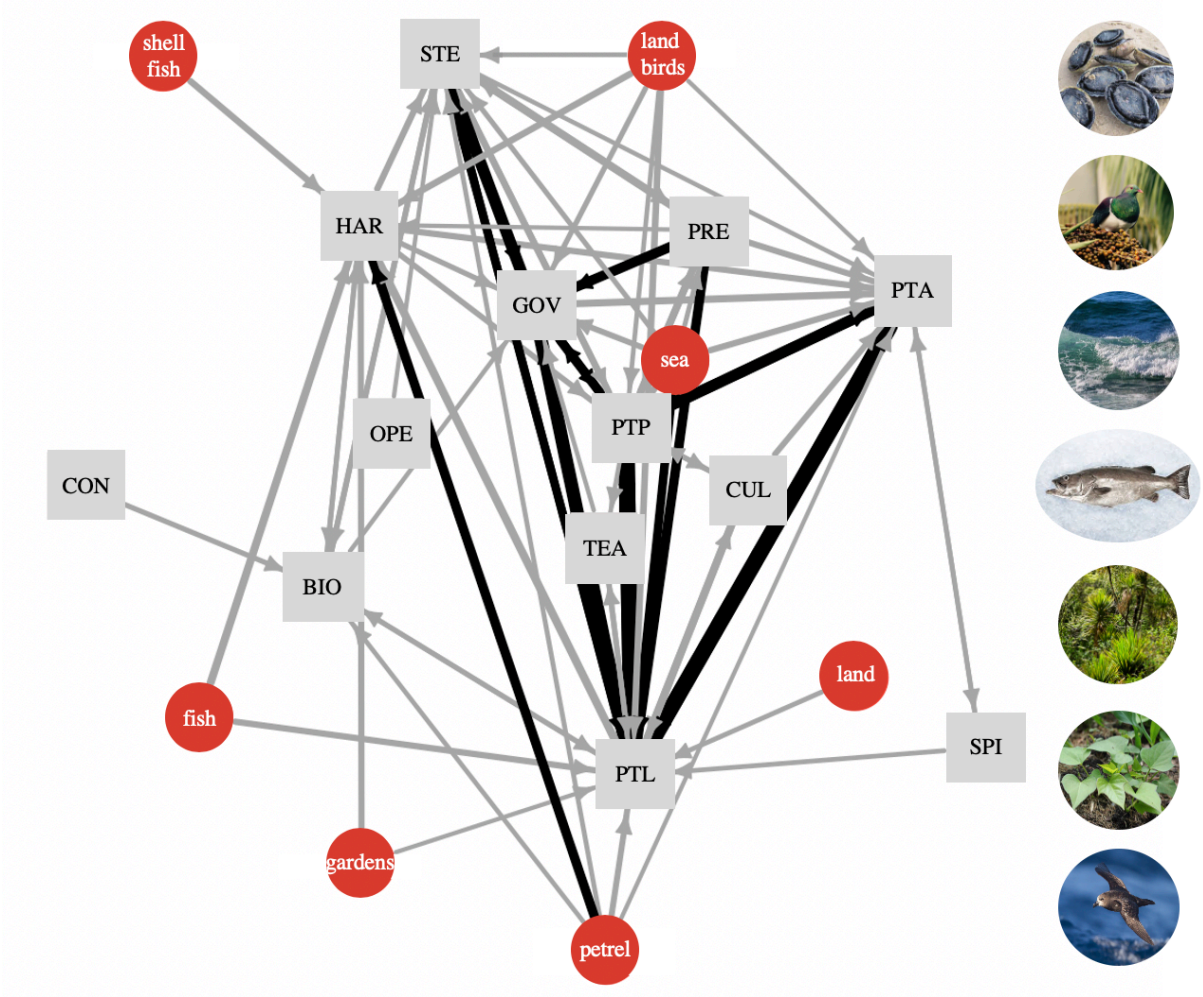
practice of caring for others (*manaakitanga*), enduring connection to land and community (*matemateāone*) and identity (*ahikaaroa*) (Supplementary Materials Table S1). In addition, the stewardship (*kaitiakitanga*) and biocultural (*koeau*) values commonly associated with the environment served to emphasize approaches where humans are recognized as an integral and intrinsic part of the environment, influencing the actions made in the service of sustaining the life force (*mauri*) of the environment and people embedded in it. In so doing, the Ngātiwai human – environment values connect the tribe to their past, future, community and place, which are key components of cultural identity and holding the authority to make decisions about local place and community. The values include both physical and spiritual connections with the islands (cf. 15, 40); Ngātiwai (the name means 'the people of the sea') connect strongly to the ocean in their character and genealogy. The least frequently mentioned values were centered around market-based activities (e.g. ecotourism opportunities) and/or preservation-based, western conservation approaches that treat humans as separate from the environment (e.g. islands managed as Nature Reserves that restrict Ngātiwai and public access).

Furthermore, each value had associations with multiple biophysical elements, suggesting a tightly interconnected socio-ecological system. The Ngātiwai respondents mentioned numerous biophysical elements (n = 41, Supplementary Materials Table S2) in these discussions on the importance of the islands to the tribe and their engagement with, and future aspirations for, the islands. Most values were connected with (i.e. associated with) numerous biophysical elements (16 values with > 20 elements), and the average number of biophysical elements connected to each value was 26 (Supplementary Materials Table S3). These connections were fairly equally distributed among the 41 biophysical elements. The biophysical elements had on average 14 value connections, and over half (29) had 10 or more

values connected to them. Four biophysical elements were associated with all values: sea, fish, land birds and shell fish. The values people to location (38 elements) and governance (37 elements) were associated with almost all biophysical elements.

Core connections in the socio-ecological network

For estimating the potential for direct and indirect impacts within this network, we focus on the core of the value system. Degradation or loss of culture's core values due to environmental change would pose the greatest threat to cultural resilience. The sub-network of strongest connections in the socio-ecological system (hereafter 'core network') that emerged from our interview data consists of a subset of 13 values and seven biophysical elements (Figure 2). The biophysical nodes of this core network differ in scale, which differs from the western-science representation of ecological networks (e.g. food webs), where all nodes are typically species rather than a mix of species and habitats. Many core values depend on biophysical elements, as indicated by direct links between value nodes and biophysical elements (Table 1, Figure 2). Note that we purposefully did not choose a priori to extract both biophysical and cultural nodes; rather, we extracted only the strongest network relations (as determined from the interview data) for the core network. The embeddedness of biophysical elements in the core values system provides evidence that several *strong* connections exist between values and biophysical elements in the Ngātiwai system. Therefore, many core values can be directly and strongly impacted by loss of access to biophysical elements.



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234

235 ***Figure 2. Core socio-ecological network: interrelatedness of Ngātiwai islands-associated***
236 ***cultural values and biophysical elements.*** *The square nodes represent values and round*
237 *nodes biophysical elements. Pictures on the right provide a representatives images on the*
238 *biophysical elements included. The direction of the links represents a supporting relation.*
239 *Weights of the links (standardized to 0-1) illustrate the strength of dependency (based on*
240 *frequency of co-occurrence in the interview data) between each pair of values or value and*
241 *biophysical element. Black link color indicates the strongest links in the core network (> 0.5*
242 *link weight). The values are abbreviated as PTA: people to ancestors, PTP: people to people,*
243 *PTL: people to location, CON: western conservation, BIO: biocultural, TEA: teaching and*
244 *learning process, OPE: operationalization, PRE: prestige, HAR: harvesting, SPI: spiritual*

health, GOV: governance, STE: stewardship. Definitions of the values are available in Supplementary Materials Table S1.

***Table 1. Direct supporting connections between values and biophysical elements in the core network**. Biophysical links column shows the number of incoming network links that each core value receives from biophysical nodes. Several values (eight out of 13) in the core value system are directly associated with biophysical elements, many (six) of them with more than one.*

VALUE	BIOPHYSICAL LINKS
HARVESTING	5
PEOPLE TO LOCATION	5
PEOPLE TO ANCESTORS	3
STEWARDSHIP	3
GOVERNANCE	2
PEOPLE TO PEOPLE	2
BIOCULTURAL	1
PRESTIGE	1
CUSTOMARY ECONOMY	0
OPERATIONALISATION	0
SPIRITUAL HEALTH	0
TEACHING AND LEARNING PROCESSES	0
WESTERN CONSERVATION	0

The core network showed strongest dependencies between connection-based values (people to location, people to ancestors, people to people) and values connected to environmental governance (prestige, governance, stewardship) (Figure 2). Of value – value dependencies, connection-based values were linked to self-determination, interdependence and the right to make decisions about place: stewardship (*kaitiakitanga*) and governance (*tino*

rangatiratanga). Aligned to these values were, in turn, other values such as prestige and authority (*mana*) and the inter-generational transmission of traditional knowledge (e.g., *whakaheke kōrero*). Notably, two of the strongest possible connections (black links in Figure 2) in the core network include biophysical elements, i.e. links between petrels and customary harvesting, and between sea and the value of connection between people and location. Hence, the biophysical elements and associated dependencies sustain several values that enable the Ngātiwai to practice customary ecosystem management. For example, the practices and processes associated with foods (e.g. Figure 2: land birds) reinforce the customary right to make the decisions about the environment (Figure 2: governance, prestige) but also the way in which the customary management is implemented (Figure 2: stewardship, harvesting). The (inter)dependencies in the core network indicate that loss of access to local biophysical elements could have considerable effects on the culture and well-being of people. Moreover, this change would feed back to influencing the local ecosystems by affecting the ability of the Ngātiwai to manage their environment.

Potential for direct and indirect impacts of environmental change

To understand the potential for changes in the biophysical environment to have direct and cascading effects on cultural values, we investigated the direct and indirect connections that individual biophysical elements have in the core value system. In essence, this practice illustrates the cultural niches of each biophysical element. For this purpose, we extracted ego networks (a network approach used in social science [41]) for each biophysical node. Ego networks with path length one from each biophysical node include only value nodes that are directly connected to the biophysical node, i.e. directly dependent on each biophysical node (Figures 3 and 4a). Ego networks with path length two include all nodes within two steps of

the focal biophysical node, i.e. indirectly dependent on the biophysical node (Figure 4b, Supplementary Materials Figure S1).

A striking feature in the ego networks is that perturbation from any biophysical element can indirectly impact almost the entire core value system (Table 2, Supplementary Materials Figure S1). In practice, the result means that once the perturbation from an biophysical element enters the value component of the socio-ecological system, the perturbation can spread practically unconstrained. Thus, change of access to any of the biophysical elements included in the core network can cascade 'rapidly' (within only two steps) even to values that are not directly linked to the affected biophysical element. In contrast, if a core network were characterized by clusters of values with few connections between the value clusters, this would contain the impacts from the environment to subsets of values (e.g. 23). If only direct connections between values and biophysical nodes were investigated, using ego networks with path length one, the risks of environmental change on the Ngātiwai culture seem less severe. Loss of access to sea, land birds and petrels could have severe effects on their own: they each affect almost half of the core value system (six values each). In contrast, loss of access to gardens, fish, land and shellfish would each appear to have a direct degrading effect on only one or two core values.

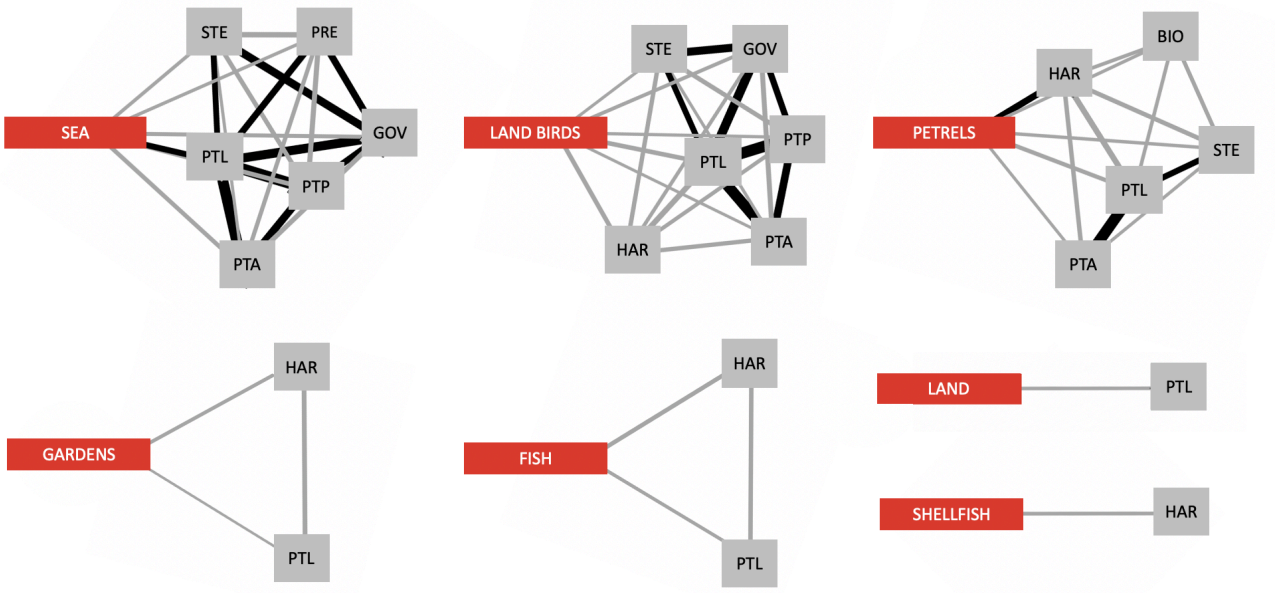


Figure 3. Unique niches of biophysical elements in the core value system. *Ego networks illustrate the roles that biophysical elements play in the Ngātiwai core value system. These networks (with path length one) include only nodes that are directly connected to the focal biophysical element (in red) and all connections among the included nodes. Black links demonstrate the strongest links of the core network (link weight > 0.5), such that the linked elements were most frequently mentioned together during interviews. The values are abbreviated as PTA: people to ancestors, PTP: people to people, PTL: people to location, CON: western conservation, BIO: biocultural, TEA: teaching and learning process, OPE: operationalization, PRE: prestige, HAR: harvesting, SPI: spiritual health, GOV: governance, STE: stewardship. Definitions of the values are available in Supplementary Materials Table S1.*

Table 2. The number of nodes in each ego network, including the biophysical node. *Path length is the minimum number of links that can separate the biophysical node from other nodes for them to be included in the biophysical node's ego network. The number of cultural values directly dependent on each biophysical node is presented in the Path length: 1*

column, and the number of values indirectly dependent on biophysical nodes is presented in the Path length: 2 column.

	PATH LENGTH: 1	PATH LENGTH: 2
SEA	7	12
LAND BIRDS	7	12
PETRELS	6	12
GARDENS	3	10
FISH	3	10
LAND	2	7
SHELLFISH	2	10

The generic ability of perturbations to cascade across the core network can also be expressed (to much less detail) by calculating the average path length of the core network, i.e. the shortest path between all possible pairs of network nodes. The average path length in the core network is indeed short: 1.63, due to the many connections between the elements (Figure S2).

Finally, the ego network results indicate that the biophysical elements in the core value system are not substitutable (cf. 42): they have unique cultural niches (i.e. connections to sets of cultural values; Figure 3). In practice, when access to a biophysical element is lost, the substituting element (e.g. store-bought food) may not fulfill the entire cultural niche. In this sense, large environmental impacts on culture can be explained by degradation of the cultural niche that the biophysical element occupies. Furthermore, since the Ngātiwai values have connections to multiple biophysical elements, it is more likely that the loss of a biophysical element would lead to degradation of a value than a loss of it – unless access to several biophysical elements are lost simultaneously. However, note that, in reality, there may be

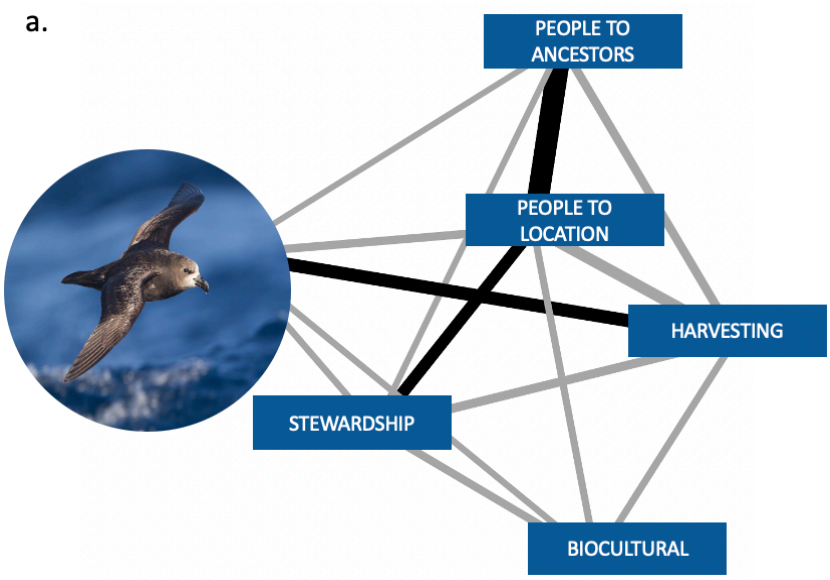
additional variation in the cultural characteristics of each connection; rather than being binary, as depicted here for simplicity, a biophysical element may contribute unique richness to a specific value to which it is connected. Lastly, value-value connections could, at least partially, contribute to maintenance of values that have lost connections to biophysical elements. For example, when there is awareness of potential impacts of environmental perturbation on culture, a community can purposefully organize activities that maintain their identity and cultural heritage despite environmental change (i.e. strengthen other connections to at-risk values or create new connections to them) (43).

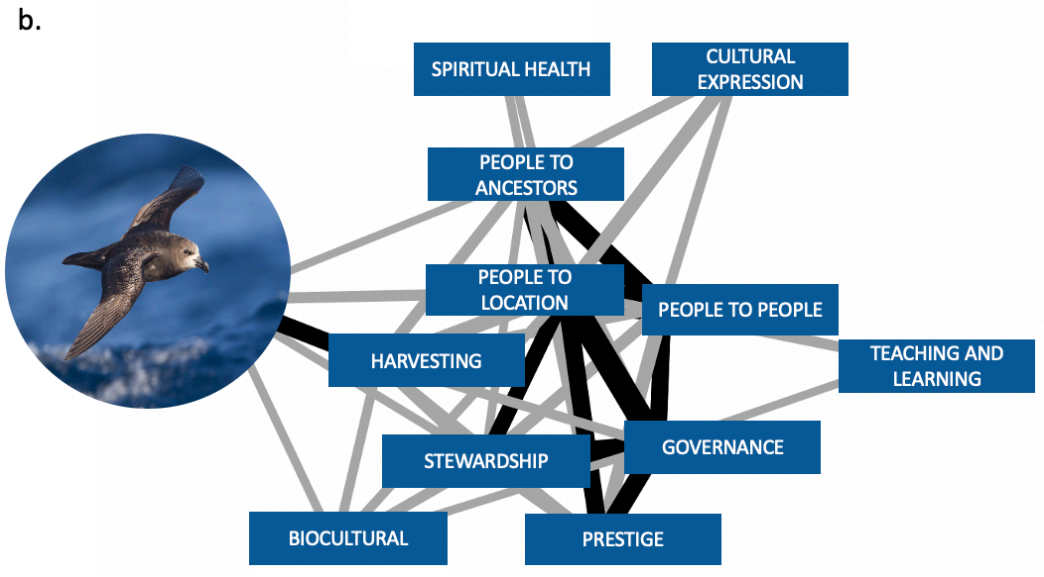
Joint consideration of biological and cultural resilience

Our study illustrates in detail the strikingly rich variety of cultural values that an indigenous tribe (Ngātiwai) associate with the biophysical elements of their local environment. The multiple ways that the Ngātiwai culture and environment are connected through human – environment values shape not only the tribe's relationship with the physical and meta-physical environment, including environmental governance forms, but also their identity and relationships between people in the past, present and future. In line with previous views on the inseparability of IPLC and their land (15, 40, 44), our results demonstrate an indigenous culture based on a tightly woven cultural and biophysical complexity, both in the number and strength of human – environment connections. However, this strong integration of values and biophysical elements also enables environmental changes to produce wide-spread direct impacts on the culture (core value system). Naturally, these changes may also be caused by societal changes that restrict access to, or use of, the environment, such as conservation policies and regulation (36). The strong interdependencies between values, and between values-and-biophysical elements, enable powerful cascading, indirect impacts on the

Ngātiwai cultural heritage. In addition, these impacts can influence ecosystems by altering the ability of the tribe to successfully interact with, and manage, the local environment. Similar phenomena likely take place in other IPLC cultures (7). For example, weakened sea ice limits the ability of young Inuit people to learn ice-related traditional ecological knowledge and, in so doing, may limit their ability to care for ice, such as perceiving less need for climate mitigation (8). Consequently, with detailed evidence, our results highlight how ignoring the characteristics of IPLC socio-ecological complexity or evaluating only direct effects of environmental or societal changes on IPLC will provide a narrow understanding of IPLC resilience. Importantly, exclusion of indirect effects can significantly downplay the seriousness of impacts that loss of access to local environment could have on IPLC.

The importance of understanding direct and cascading effects of environmental perturbation on culture are exemplified by the cultural niche of petrels (Figures 4a, b). Declines in petrel populations (e.g. 45) can reduce a tribe's ability to engage in a harvesting practice, which over time can erode cultural identity linked to that species, as well as knowledge systems and pathways, and customs and norms (e.g., management strategies, prayer, songs, proverbs). Petrels hold immense value because gifting harvested chicks as food demonstrates caring within the community (*manaakitanga*), provides identity (*ahikaaroa*) to tribes with access to this resource, nourishes one's spiritual essence (*wairua*), and embodies the authority/ prestige of the individual and/or tribe to care for their natural resources (*mana*).





Figures 4a and b. The role of grey-faced petrels in Ngātiwai core value system*. The direct connections from petrels to values demonstrate the critical role that a species can have in supporting IPLC values (4a). Inclusion of second order connections (path length two) shows that the changes in access to petrels can indirectly affect almost the entire Ngātiwai core value system associated with the islands (4b). Link weights represent the strength of dependency between values. Black links represent the strongest connections in the core network. Definitions for the values are available in Supplementary Materials Table S1.*

Nevertheless, our results should not be interpreted as environmental change having sole power to determine the persistence of IPLC into the future. At best, resilience can be maintained if, when needed, stronger parts of the socio-ecological system can adapt to support the cultural or environmental components under threat at the time (46). For example, reliance on social relations and cultural ties during ecological disruptions can significantly mediate the effects of resource declines in indigenous and local communities (47). Similarly, a community can intentionally revitalize practical cultural activities, such as craft courses, language classes, and food preparation, to "see and act their own way" when access to a cultural keystone species is limited (43). These adaptations likely take place on several scales and interact with each other, such as adapting to local species fluctuations in the framework of global environmental agreements (46). On the other hand, the environmental change - driven processes that erode resilience of IPLC cultures may be further amplified by associated socioeconomic changes (e.g. 44), such as purchasing resources from supermarkets instead of achieving them through local harvest or community trade. Therefore, institutional and economic support that fit the local ecological and social context can make a significant difference by not restricting IPLC adaptive strategies and capacity to organize their institutions and livelihoods (44, 48, 49). In consequence, environmental impact assessments and solutions must include joint consideration for biophysical and cultural resilience, in which the inseparability of people and environment is seen as an exchange and process (cf. 7, 15, 40).

To the authors' knowledge, this is the first study to use network science to link cultural values and biophysical elements together. To validate our depictions, our results were presented back to the Ngātiwai Kaumatua (Elder) Committee for consideration and were approved for release. However, we acknowledge that, despite our best attempts, our work

422 includes a degree of cultural simplification. We recognise that an immense depth of different
423 understandings and perceptions lie within each of the value groups identified in this study.
424 Our approach also treats human values as separate entities, although boundaries between
425 values reflecting identity, spirituality, culture and environment may be blurred (16, 50)
426 (though our conclusion that these many facets of culture can be collectively impacted would
427 still hold). Further, our approach strives to verbally describe multi-faceted cultural concepts,
428 potentially including misinterpretations (51). Nevertheless, our work provides an initial
429 attempt to illustrate in detail some of the intangible elements of IPLC culture associated with
430 local environment in a way that enables improved communication with decision-makers on
431 the scale of cultural erosion risk. The network approach adopted here provides tremendous
432 potential for more in-depth inclusion of IPLC cultural aspects into environmental impact
433 assessments and decision-making.
434
435 As diverse worldviews create differences in how cultures understand value and connect to the
436 environment, building socio-ecological resilience to on-going, unprecedented environmental
437 change will require impact assessments and policies that acknowledge the importance of
438 human values, beliefs, identities and thoughts in environmental management (11, 18, 52). In
439 conclusion, our study shows that integrating and understanding the relations between IPLC
440 cultural heritage and biophysical elements is critical for understanding the full impacts of
441 environmental change on human well-being and ability to care for the environment. In so
442 doing, we demonstrate that the ability of many IPLC to sustainably live in close contact with
443 the environment is strongly supported by constant interaction with nature. Safe-guarding the
444 world's biodiversity and cultural diversity for future generations thus requires environmental
445 governance strategies that support the rich relations that many IPLC have with environment.
446 For cultures that have become decoupled from their environments, it could also involve a

reawakening of values that resets their relationship with the natural world and the community around them.

SUPPLEMENTARY INFORMATION is available on [journal online link].

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AUTHOR CONTRIBUTIONS

PO'BL, JY and JT conceived the idea. JY and PO'BL designed the study. PO'BL and CS designed the cultural values framework. PO'BL and CS conducted and coded the interviews. JY analysed the data and JY, PO'BL and JT interpreted the results. JY and PO'BL wrote the initial manuscript and all authors contributed to the final manuscript. All authors have approved the manuscript for publication.

AUTHOR INFORMATION (COMPETING INTERESTS)

Authors declare no competing interests.

METHODS

Approval for this study

This study builds on a 20-year research partnership between Ngātiwai and Manaaki Whenua Landcare Research and was conducted under the approval and directorship of the Ngātiwai Kaumātua (Elders) Committee and the Ngātiwai Trust Board. Terms and conditions for conducting the research were agreed between parties as per Cultural Safety Agreement (16/04/29) and Manaaki Whenua − Landcare Research Human Ethics Permit.

Study context

The islands of Ngātiwai in New Zealand have extensive historical features and occupation sites associated with the tribe. While there are few signs of fortifications, stone-faced terracing, platforms and extensive agricultural structures (e.g., stone rows, mounds, and walls) are present. These northern islands contain a diverse biota and an indigenous flora that is no longer present on the New Zealand mainland. Many of the islands are nature reserves and ranked as internationally significant because of rare and endangered fauna and flora and local endemics that occur naturally or have been translocated to these sites [e.g., little spotted kiwi (*Apteryx owenii*), kākāpō (*Strigops habroptilus*), red crowned parakeet−kākāriki (*Cyanoramphus novaezelandiae*), kākā (*Nestor meridionalis*), Bullers shearwater (*Ardenna bulleri*), pycroft petrel (*Pterodroma pycrofti*), tuatara (*Sphenodon punctatus punctatus*), skinks (e.g., Marbled skink, *Oligosoma oliveri*), geckos (e.g., Duvaucel's gecko, *Hoplodactylus duvaucelii*), native land snail species (*Amborhytida tarangaensis*)].

Interviews

Around 5,667 people affiliate to the northern coastal tribe of Ngātiwai by descent (53). We conducted interviews with 6 women (mean age: 66 years, range: 40–88 years) and 18 men (mean age: 66 years, range: 50–80 years) of Ngātiwai descent. Seven interviews were conducted with two or more participants present at each. Interview participants were

community members identified as having lived most of their lives along the coast and consequently had extensive knowledge relating to the islands and coastal environments or had management experience with the islands. Interviews were conducted in a semi-directed fashion to allow for a more open and natural conversation to occur, and for unanticipated insights to emerge (54, 55). IPLCs often illustrate their values in stories and activities, including narratives on how oneself is seen within the place (51). Questions were focused around the importance of the islands to the people, how people historically and currently engage with the islands, and future aspirations for the islands and the Ngatiwai's relationship with those islands. Since all interviewees spoke English as either a first or second language, all interviews were conducted primarily in English, took place between November 2017 and March 2018, and ranged between one and two hours in length. All interviews were recorded on digital audio and transcribed verbatim.

Interview coding

A Ngātiwai cultural values framework revised from (56) was developed (Supplementary Materials Table S1). Nine primary values served as the primary values in our coding protocol (protocol coding; [56]) and secondary values were coded under the primary values (57). For each interview, two of the co-authors (PL and CS) independently coded assemblages of secondary values to sections of narrative they perceived related to a specific theme. Biophysical elements mentioned within each section of narrative were also recorded. The two co-authors were selected for this task based on their professional and personal experience with the islands and Ngātiwai community. Prior to coding, agreement around the understanding of values and how they should be assigned to interview text was achieved between the two co-authors (58, 59). For this, a single transcript was independently coded and then a discussion between PL and CS around inconsistencies provided an opportunity to

refine the values definitions before a second transcript was coded. A second transcript was then coded by the same two co-authors. Any remaining inconsistencies were discussed until a consensus around all the codes was reached.

Network construction and analysis

Quantification of relational values allows identification of core values shared in a culture and improved communication of the values (60, 61). A network approach was chosen for studying the value system because we detected in the interview data that the values were highly interrelated. The Ngātiwai respondents frequently alluded to values in association with, and supported by, other values (in agreement [14, 56]). For example, expressing and experiencing environmental stewardship (*kaitiakitanga)* or connection with place and ancestors was enabled by having the prestige (*mana*), to make decisions about place.

We considered the frequency of values in the interview data to be the most direct indicator of which values are most recurrently associated with the islands (cf. 62). The values most commonly associated with the islands (Figure 1) thus presents the relative frequency of values in the interview data. Similarly, we used repetitive associations between the values and values and biophysical elements in the interview data to capture relationships among the values and between the values and biophysical elements. In practice, the frequency with which two elements (values, biophysical elements) were discussed together in the interviews was used as a measure of the strength of the relationship between the elements. The direction of the relationship represents dependency of one element on another. For example, the interviewee may have explained that harvesting food on the islands strengthens their sense of connectivity to ancestors and identity. We then transformed the detected assemblages of values and biophysical elements, and their relationships, into a network. The resulting socio-

ecological network is a directed, weighted two-mode co-occurrence network, in which nodes represent values or biophysical elements. Connections between biophysical nodes are not included.

The interview data resulted in a network of 110 nodes, including 22 value nodes and 41 biophysical nodes (Supplementary Materials Table S2). The weights of the links varied from one to 142 and were standardized to values 0 - 1. The coding method resulted in a highly connected network (261 links) of which some connections were acknowledged only once or few times. To study the core dependencies in the islands-related value system, we extracted a network that consisted of only the strongest 5% of co-occurrence links (hereafter, core network), and removed all the nodes that were not connected to these strongest links (Supplementary Materials Table S4). The resulting network, which was used in the structural analyses, consisted of 20 nodes, including 13 value node and seven ecosystem nodes, and 73 links. All network analyses were performed using the iGraph package in the R programming environment (63, 64). Random networks for Figure S2 were produced using Erdős-Rényi randomisation adapted to two-mode networks. That is, the probability of a link being formed is calculated by dividing the number of links in the observed network by the product of the numbers of primary and secondary nodes in the observed network (65). The binary two-mode network randomization and calculation of average path lengths for random networks and the core network was performed with the tnet package in the R programming environment (66).

Data availability

All interview data are the property of Ngātiwai, but held by Manaaki Whenua Landcare Research and Stone Consultancy. The adjacency matrix used in network analysis is available from PO'BL upon reasonable request, with permission from Ngātiwai Trust Board.

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