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Including stewardship in ecosystem health assessment

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To adapt to the ecological crises and social inequities of the Anthropocene, a new conservation paradigm is emerging that embraces people in nature and the positive roles people play in ecosystem health through land stewardship. We discuss the emergence of this new model and explore the methods needed to research and coordinate stewardship as part of conservation landscape planning through a practical case study. Updating conservation frameworks to include the positive impacts people have on ecosystems, we argue, is a powerful leverage point for catalysing more effective and equitable nature conservation and other large-scale societal transformations necessary for just sustainability.

Human systems and natural systems are inextricably intertwined. These co-evolving systems are driving rapid changes in the Earth's climate, biodiversity, functioning and composition: changes that collectively point towards a new global epoch, the Anthropocene[1], and dangerous risks and vulnerabilities for both human and non-human nature[2–5]. New scientific understandings of how humans and nature are entangled, and the unsustainability of recent trends, highlight the urgency for society and science to transform and adapt to preserve biodiversity and human well-being[6].

Nature conservation is a key societal enterprise that influences human interactions with the biosphere. It is also a discipline in need of transformation and adaptation to improve equity and effectiveness in the face of global change[7–11]. The conceptual frameworks that have long guided conservation science have at their centre one-directional relationships between humans and non-humans, namely the damaging impacts of society on nature and the positive contributions of nature to people (Fig. 1a). Although such models highlight interdependencies, they retain a categorical separation of people and nature, and gloss over the variability, the complexity and the mutually constitutive nature of culture, society and ecologies[12–14]. In particular, frameworks gloss over the positive contributions people make to ecosystem health and well-being from land stewardship, by which we mean the direct embodied interactions of people caring for land and multispecies communities (also known as tending, keeping or responsible use) (Fig. 1b).

Thus, land stewardship, whether taking care of protected areas or adjacent rural and urban lands, is an important practice that links biophysical and social systems and influences ecosystem health[6,15]. Scientists have embraced 'stewardship' as a framework for ecosystem resilience in the Anthropocene, highlighting Earth stewardship, environmental stewardship, planetary stewardship and biosphere stewardship as key practices for aligning biodiversity, sustainability, human health and well-being[4,16,17]. At the same time, stewardship as an ecosystem driver remains underexamined in conservation science[18]. We argue that for communities to become good Earth stewards, and for global conservation to support this transition, conservation science should do more to embrace and illuminate stewardship as a theory and practice on local and regional scales. Little is understood about how diverse and prevalent stewardship practices are on landscapes, or how stewardship influences ecosystem health[19,20] and intersects with social equity and justice struggles[11], or how it scales up to effect regional and global processes. Probable reasons for this gap in understanding include the longstanding western cultural worldview that conceptualizes natural and human systems as separate rather than intertwined, and people as antithetical to healthy nature. This gap also reflects environmental injustices associated with colonialism[10,21]. The result has been to minimize the role of people in enhancing and sustaining nature through direct participation in ecosystems.

Stewardship is taking on increasing importance in guiding ecosystems because so much of nature conservation today, by necessity, takes place in human-dominated landscapes[22,23]. Whether understood as anthropogenic biomes, multifunctional landscapes, urban ecosystems, cultural landscapes or social–ecological systems, conservation

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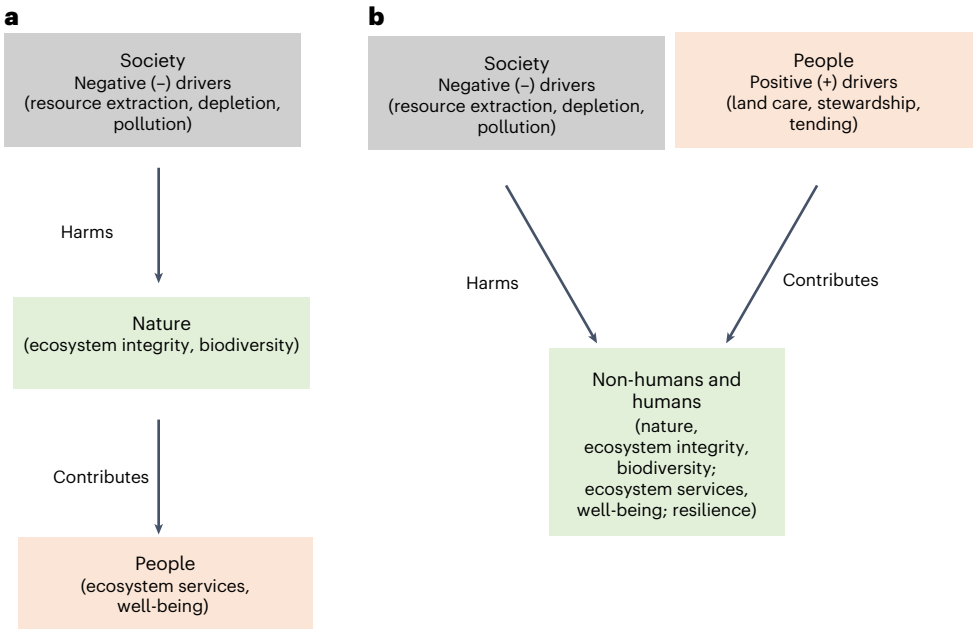

Fig. 1 | A revised conceptual framework of interactions among people and nature. a, Conceptual frameworks for conservation generally conceptualize one-directional relationships among people and nature, namely the negative impacts of society on nature and the positive contributions of nature to people. **b**, We offer a revised conceptual framework that does not separate humans from non-humans and highlights the positive contributions of people in addition to the negative harms.

success as a whole emerges through the decisions of heterogeneous individuals operating on smaller parcels, who may or may not have the same assumptions, knowledge practices or desired outcomes[15,24]. A challenge in this context is how to align the activities set within each parcel with goals for the larger landscapes in which the parcels are embedded. The inclusion of stewardship in frameworks may foster this alignment because it will serve to illuminate the labour and care of people as part of understanding ecosystem trajectories, as well as the roles that labour and care play in producing diverse values from landscapes which include clean air and water, biodiversity, carbon sequestration, local food and fibre, recreation, spirituality, cultural heritage and rights, and a sense of place, kinship and communion with non-humans.

Recognizing the fact that people are intricately embedded in nature rather than apart from it, we advocate for a revised conservation framework: one that embraces people and their stewardship as a driver of landscape and Earth system processes, and thus includes research and analysis of stewardship as an integral part of assessing ecosystem health. In this Perspective, we further explore the rationale for including stewardship as part of a social–ecological approach to assessing ecosystem health. We then illustrate an approach that is inclusive of stewardship alongside other ecosystem health metrics, and identify some benefits and challenges for advancing on this frontier through a case study of an assessment developed within a stewardship network in a major urban centre and biodiversity hotspot in the San Francisco Bay Area, California, USA.

People belong in nature

Addressing human entanglements with the more-than-human world (also known as 'nature') is a critical component of biological conservation, sustainability and human well-being. This is because people and nature are inextricably intertwined and co-dependent across multiple scales of interaction, from the cellular to the global Earth system[3,25]. Despite the profound intimacy of human and non-human worlds, conservation science has tended to treat people as antithetical to nature, that is, they do not belong. This perspective was shaped by many factors, including a dominant western cultural worldview that separates the category of people from the category nature, and the specific socio-political conditions (for example, colonial, aesthetic and religious) in which conservation science took shape[10,26–28]. This worldview structured the emerging science of conservation and its primary strategy of protected areas and parks. This mentality that land can only be enclosed or exploited has been the Achilles heel of biodiversity conservation.

Protected areas and parks have been widely critiqued because of their impacts on local people. Often, parks are analysed as a form of neocolonialism because they enclose commons, dispossess local people from land and lifeways[28–30] and impose external entities as local governance[31]. Concerns about the negative effects of protected areas on local people are among the most polarizing issues within the global conservation community[32]. Meanwhile, in the face of persistent declining biodiversity[3], the global conservation community continues to set ambitious land-protection targets, which include 30% of land cover by 2030 (www.hacfornatureandpeople.org) and 50% of land cover to be protected for nature, as advocated by the Half-Earth campaign (www.half-earthproject.org). For such efforts to be both effective and just, it will be necessary to better integrate protected area strategies into the larger social–ecological landscapes in which they are embedded[33–35].

Without doubt, the theory and practices of conservation science have been evolving to become more inclusive, involving more community participation as well as more social scientific and humanistic research, but this integration remains relatively undeveloped and is insufficiently nuanced, equitable or grounded in social theory[10,36,37]. Consequently, while scientists are calling for Earth stewardship as a framework for resilience in the Anthropocene, the people on the ground caring for the land — their labour, knowledge, values and needs — have been underappreciated[38].

Decolonization, Indigenous resurgence and environmental justice movements are drawing attention to the positive role that local ecological stewards can play in biodiversity, ecosystem health and resilience. Research has shown that the lifeways of Indigenous people, and other communities with histories of sustaining livelihoods from

the land over long tenures, are important drivers of biodiversity and resilience on landscapes[15,39–43]. The specific biocultural, place-based knowledge that people bring to stewardship not only supports lifeways and cultural diversity but also introduces patch disturbance, leading to land-cover heterogeneity, which in turn positively influences the diversity of native plants and animals[41,44]. One recent analysis found as much if not more biodiversity in Indigenous land holdings compared with protected nature parks in Brazil, Canada and Australia[45]. Another analysis showed that the legal designation of forests as protected is not predictive of forest health. Instead, the outcomes reflect more complex interactions among the park boundaries, the socioeconomic conditions in the landscape and the degree of local community involvement in governance[33]. Scientists are only beginning to understand the degree to which land stewardship by local people has structured ecosystems in the past and influences ecosystem health today. Insufficient research notwithstanding, diverse lines of evidence suggest that sustaining and reconnecting people's connection to the land is an important element of effective and just environmental governance[6,11,15,40,41,45,46].

For two additional reasons related to biodiversity protection, conservation science has been evolving to embrace people more deeply. First, as global anthropogenic change shifts the climate, and otherwise alters the composition and structure of biological communities, it has become difficult for protected areas to retain the rare species and historic conditions they were designed to protect[8,9]. In this context, human involvement is no longer viewed as antithetical to naturalness, but rather it has become essential as a means to resist extinction[47]. Second, protected areas are not functionally bounded biological entities, but instead are embedded in landscape mosaics of land use. As a result they are subject to constant fluxes of species, nutrients and pollutants across land-use boundaries, from park to farm field to city. This reality is inspiring greater attention to ecological stewardship in the 'matrix', and how working lands and urban lands can help promote population viability, dispersal and migration of plants and wildlife that are critical for their long-term survival[20,48,49].

The stewardship-conservation paradigm

A new-found appreciation of the ways that land stewards contribute to biodiversity and other dimensions of ecosystem health is contributing to a reimagined conservation paradigm. This model recognizes that land stewardship is critical to (1) the resilience of cultural diversity and place-based biocultural knowledge, (2) the resilience of biodiversity in protected areas under conditions of global change, and (3) improved landscape connectivity. In addition, this new model responds to an increasing awareness of how conservation policies and practices have, intentionally and unintentionally, disproportionately benefited a white, elite populace to the exclusion of other socioeconomic and cultural groups. This emerging paradigm embraces diverse people and their land-stewardship practices and values more holistically, including valuing the sociality, quality and reciprocity of human relationships with non-humans as a key aspect of (and resource for) adaptation to global change[9,11,21]. Such relational values are probable key pathways of transformative change for sustainability and well-being[14,50]. This paradigm aligns with multispecies, multicultural perspectives that recognize that nature conservation occurs within social–ecological systems, such that landscapes and processes are shaped by the interactions of dynamic assemblages of social actors — human and non-human — with diverse interests, knowledge and forms of agency.

Although the meaning, cultural specificity and political ideology of stewardship varies[18,51,52], the word is used by diverse groups to signal an ethical and practical alternative to technomanagerial, command-and-control approaches to ecosystem care. When people are conceptualized as ecosystem managers, they tend to be imagined as external to ecosystems, in a top-down fashion, and as interlopers engaged in science-based, ideally temporary, interventions (for example, culling invasive species) to steer systems back towards autonomous non-human wilderness[53]. By contrast, when people are conceptualized as stewards they tend to be imagined as vital participants, engaged in sustained relationships of care or responsible use, whose activities nurture ecosystems while improving human well-being. Chapin and co-authors[16] contrast 'ecosystem stewardship' with traditional 'steady state resource management' and argue that the former provides greater flexibility and adaptability to uncertainty and change in a rapidly transforming world. In contrast to literature about environmental management, literature about environmental stewardship tends to emphasize participation, cross-scale, place-based, transdisciplinary approaches, all of which lead towards coordinating multibenefit conservation outcomes and equity in our socially uneven and more-than-human world.

We argue that land stewardship is a key practice that links biophysical and social systems, but also that more analysis and specificity is needed. The diversity of stewardship types (the different ways that people and institutions take care of land and species) creates a heterogeneous mosaic on the landscape[22], and this heterogeneity is likely to be important for sustaining biodiversity and human well-being[33,43]. Without specificity, however, appeals to stewardship are not very helpful for understanding and coordinating conservation. For example, a natural-resource manager practising invasive-species control using chemicals is one type of stewardship, whereas a rancher using cattle is another, volunteers hand-pulling invasive plants is another example, and cultural burning is yet another. All may function to decrease the abundance of undesirable plants, but the broader consequences of each form of stewardship — toxicity in the landscape, erosion, connection to the land — may be quite different. Each type of stewardship produces distinct ecological and social effects, and has its own benefits, costs and vulnerabilities that need to be understood and cared for as part of coordinating conservation and sustainability. For example, despite some low-intensity farmlands in Europe being designated as 'high nature value' for biodiversity conservation, these farms and their stewards continue to decline due to global socioeconomic trends that drive agricultural intensification and farmland abandonment[54].

Stewardship and ecosystem health assessment

Network weaving for social–ecological health

This new stewardship-conservation paradigm requires novel planning and analytic tools to illuminate stewardship as part of coordinating conservation and sustaining ecosystem health in multifunctional landscapes[24,55]. Philosophically and practically, research must bridge conceptual frameworks and landscape-scale science-based assessments with the messy, complex, on-the-ground work of diverse human actors working at local-parcel scales and embedded into larger-scale regional-to-global socioeconomic and policy dynamics. Practically speaking, this is often difficult to do because communication across diverse stakeholders is complicated[24]. The development of networks that facilitate cross-parcel communication and collaboration is one approach that has worked well in bridging conceptual gaps in land governance. Here, to illuminate stewardship as part of conservation assessment, we offer a practical example of how such network activities can produce cross-parcel cooperation as well as useful approaches and tools.

The Santa Cruz Mountains Stewardship Network (SCMSN) is a collaborative made up of twenty-four organizations that own, manage or in some way steward about 80% of conservation lands in the Santa Cruz Mountains bioregion, California, USA, an area of approximately 1,036 km^2 (Fig. 2). The organizations involved include land trusts, public agencies, an Indigenous tribal band, logging companies and universities[56]. The SCMSN formed in 2014 and was motivated by a desire to build relationships among, and coordinate the activities of, diverse landowners and stewards working at parcel scales to produce a wide range of conservation outcomes identified at the landscape scale. The SCMSN has persisted in the years since then because participants

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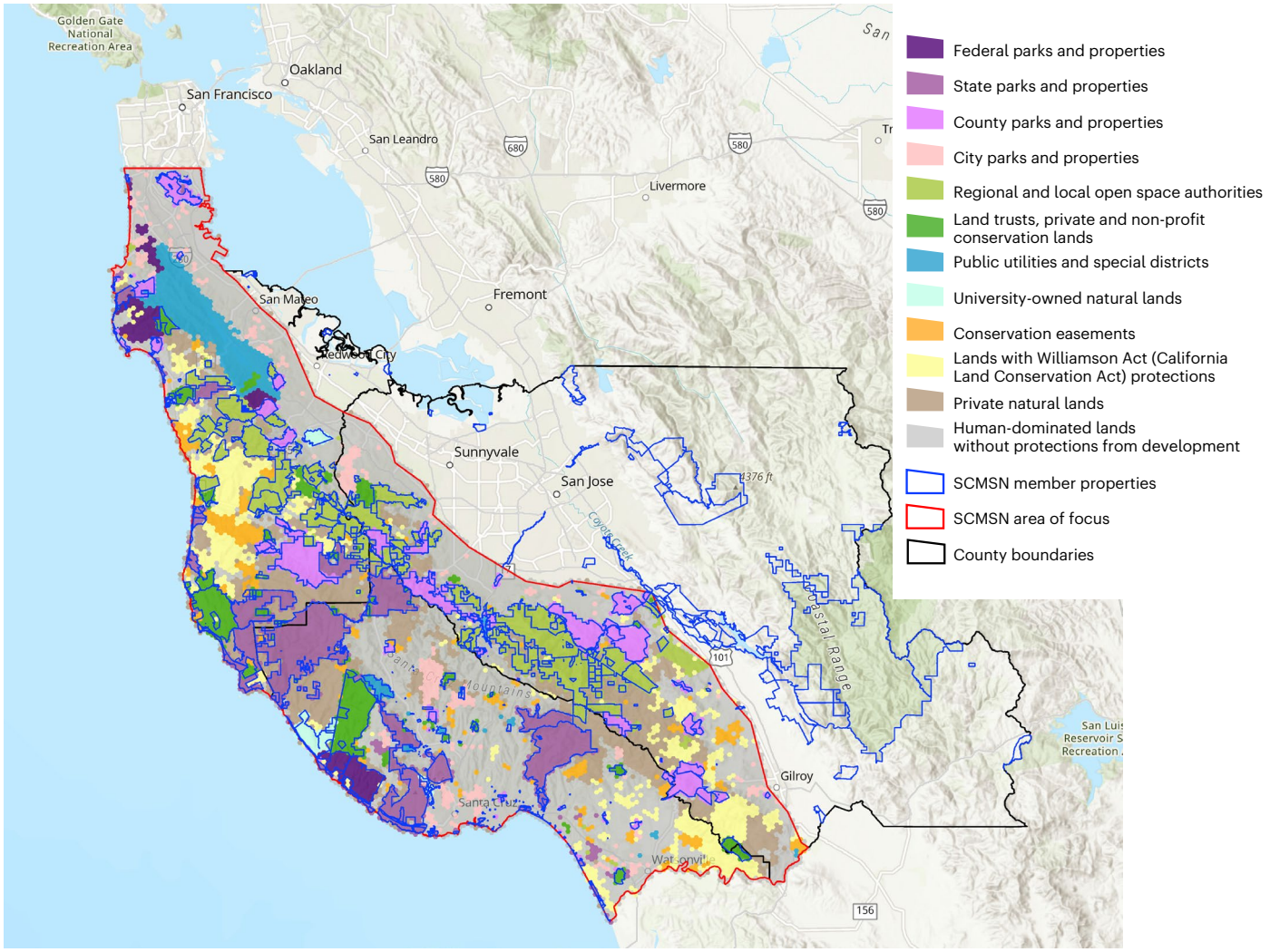

Fig. 2 | Conservation landscape is a stewardship mosaic. The stewardship mosaic of the Santa Cruz Mountains conservation landscape, defined roughly as the darkened area within the red line. Land management categories are shown. There is variation across and within the management categories in legal mandates, goals, and stewardship approach and activities. Properties stewarded by members of the SCMSN are outlined in blue. County boundaries are outlined in black.

recognize it as a valuable vehicle for collaboration in the region, aiding its members in working across jurisdictions and property lines. The diversity of membership and land use led the SCMSN to use, as a guiding concept for working together, the concept of a stewardship mosaic (Fig. 2), in which many kinds of land-use/land-care strategies, including working lands, are viewed as acceptable, and even beneficial for the landscape as a whole[57].

The history of California is important for understanding the relevance of the stewardship mosaic to contemporary conservation. California is a biodiversity hotspot that has experienced radical turnover in culture, population and governance over the past 500 years, alongside devastation of the local ecology and Indigenous population[42]. In the nineteenth century, wilderness preservation concerns grew among the United States populace, and by the mid-twentieth century, conservation groups were focused on protecting as many acres as possible from development. With land protection, it was typical for people to lose access, for land stewardship to cease and for non-native domesticated animals (for example, sheep and cows) to be removed. Often, the removal of non-native species resulted in further ecological cascades and unintended consequences that challenge long-term conservation success[58]. Today, different forms of stewardship are being re-integrated into protected lands because the activities of people, whether using fire, harvesting timber, raising animals or cultivating food[42,59], support dimensions of ecosystem health on the landscape, especially in the context of global anthropogenic change (Table 1). This appreciation of stewardship as social–ecological feedback that is relevant to ecosystem health and resilience (Fig. 3) is key to the philosophical principles and practical activities that unite the SCMSN.

Discussions within the SCMSN revealed that a piece of the conservation dialogue was missing: appreciating the diverse values people have from the land and the diverse ways that people care for the land, together with how that diversity provides resilience for the ecosystem health. Consequently, the omission of stewardship in existing regional conservation tools and ecosystem health assessments that influence conservation priorities and investments was viewed as a problem. Network dialogues revealed frustrations that stewardship was felt to be invisible, not well understood and not financially supported by the conservation community and public at large. To that end, the SCMSN collaborated on designing an assessment tool that would advance understanding of the conditions within the entire landscape encompassed by SCMSN members, and at the same time recognize that ecosystem health depends on both ecological and social components and processes. The goal was to design an assessment that both recognizes and values diverse people and cultural practices as

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Table 1 | Common land stewardship activities in California and examples of social and ecological dimensions

Habitat	Stewardship type	Environmental stress addressed	Ecological benefits	Societal benefits	Vulnerabilities
Grasslands	Low-intensity ranching	Nitrogen pollution Species invasion	Biodiversity	Local food Livelihoods	Biocultural knowledge Economics
Forests	Restoration forestry	Climate change Wildfire risk	Forest structure Redwoods	Decreased fire risk Livelihoods Timber resources	Biocultural knowledge Economics
Grasslands and Forests	Cultural burning	Climate change Habitat loss Species invasion Wildfire risk	Biodiversity Forest structure Redwoods	Equity and justice Cultural preservation Decreased fire risk Livelihoods	Access Biocultural knowledge
Lowlands and wetlands	Low-intensity agriculture	Climate change Fragmentation Habitat loss Water pollution	Anadromous fish Birds Connectivity	Local food Livelihoods	Biocultural knowledge Development Economics Food safety

integral components of all ecosystems and conservation nowadays, and helps generate more insight into how people positively contribute to ecosystem health. The outcome was the sustainable landscape health assessment (SLHA), as summarized below, which advances how stewardship can be meaningfully incorporated into ecosystem health assessments to aid in conservation planning and landscape-scale coordination.

Ecosystem health assessments emerged in the 1990s as a means to illuminate human connections to natural systems, to foster integrative and transdisciplinary conceptual understandings of the system and contribute to adaptive management[55,60]. A wide variety of frameworks have been developed, each specific to the relevant ecosystem and coordinating entity (see, for example, the 'State of the Estuary', 'One Tam' and 'State of the Great Lakes' partnerships). Most frequently, ecosystem health assessments focus on measuring indicators of the ecosystem condition, such as the abundance of endangered species, commercial fish stocks and water pollutants, or indicators related to land use, such as acres of protected lands. Although stewardship and adaptive management are identified as the key tools to address ecosystem health, the specific people and institutions that provide services and retain relevant place-based, biocultural knowledge are generally not identified as resources or indicators. Omitting stewardship from ecosystem health assessments inhibits the likelihood that a particular landscape will maintain or achieve a desired state of ecosystem health. Thus, the integration of stewardship indicators is a necessary step towards the comprehensive assessment of conservation landscapes as social–ecological systems.

The sustainable landscape health assessment

The SLHA as developed for the Santa Cruz Mountains conservation landscape is a semiquantitative geospatial evaluation of three indices: ecosystem integrity, ecosystem services and stewardship support (Fig. 4). The goal was to specify indicators and metrics that relate to important social–ecological feedbacks and to integrate the social–ecological metrics alongside biophysical and land-protection metrics more common to ecosystem assessments. Such integration enables the SLHA to be used to assess whether or not the needs required by the various inhabitants of the system — both human and non-human — are being met now and into the future. Although the example we provide is for the Santa Cruz Mountains system, the general concept is that such SLHAs can provide a decision-support framework and data that diverse land stewards can use to evaluate, coordinate and adapt the stewardship in relation to ecosystem conditions and goals, as well as to support communications with partners, funders and the general public. The details of the Santa Cruz Mountains SLHA and its findings are presently available to SCMSN members and will be published elsewhere. Here we provide a snapshot of components, and reflect on the immediate benefits and challenges towards advancing research and dialogue on this frontier.

The SLHA provides three different lenses of landscape health (Figs. 4 and 5): ecosystem integrity, ecosystem services and stewardship support. Each lens individually highlights heterogeneity on the landscape, and when combined they illuminate how the landscape works as a whole to produce dimensions of social and ecological health and resilience. The processes used to identify indicators supported SCMSN members to engage in dialogue, build trust and share practice information. Information sharing between organizations and across property lines and jurisdictions creates a generative state from which collaborative projects between different clusters of organizations emerge[56]. For example, SCMSN members collaborated on a cross-property trail map (existing and planned), which immediately revealed important synergies and opportunities for collaboration to improve community access. Effective landscape collaboration is dependent on this kind of informal collective knowledge building. Thus, building relationships and trust among SCMSN members is itself a key metric of success[57].

Critically for the Santa Cruz Mountains region, the SLHA reveals areas where greater investment and coordination will be needed to foster resiliency. For example, the southeast region of the landscape is of high value in ecosystem integrity (lower right, Fig. 5a), but low value for stewardship support (Fig. 5c). This region is an immediate priority for investment to improve stewardship capacity. In the north coastal region, we find high value in ecosystem services (upper left, Fig. 5b) but lower values in ecosystem integrity (Fig. 5a) and stewardship support (Fig. 5c). Farming and ranching are common in this region, which is also a priority area for mitigating water pollution and supporting the survival of endangered fish and amphibian populations. Farmers and ranchers are not well represented yet in the SCMSN. Our assessment highlights the need for more targeted recruitment with these groups to coordinate stewardship and improve ecosystem integrity.

Much work remains to be done to refine the assessment and to understand how it will be used and improved by the SCMSN over time. Already, the SLHA is proving useful: work is underway to incorporate it into regional planning via the Conservation Lands Network explorer tool, which serves the wider geography of the San Francisco Bay Area and motivates conservation funding (www.bayarealands.org). The addition of stewardship in spatial planning provides an additional lens through which to identify and focus conservation decisions.

Challenges of including social indicators

Although the Santa Cruz Mountains SLHA successfully integrates a wide range of social and ecological indicators into one geospatial resource, and provides an innovative model for including stewardship

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Fig. 3 | Example of social–ecological feedbacks among fire, redwoods and stewardship. Top left: Valentin Lopez, Chairman of the Amah Mutsun Tribal Band, with members Abram Lopez, Paul Lopez and Nathan Pineida, perform a fire ceremony as part of a controlled burn. Top right: local forester at the Soquel Demonstration State Forest. Bottom left: blades at Big Creek Lumber sawmill. Bottom right: burned Redwood trees after the 2020 CZU Lightning Complex wildfire. In this case, people and infrastructure provide biocultural resources that support ecosystem health. Large and severe wildfires are increasing in California, resulting in tremendous social, ecological and economic impacts. Both forest thinning and fire stewardship are used to reduce the threat of severe fire, forest-stand conversions and to improve biodiversity and ecosystem structure. Indigenous fire stewardship provides distinct knowledge, ecological and social benefits. Access to land for cultural burning enables Indigenous people to practise their heritage and spirituality while gaining livelihoods. The number of acres that are accessible for cultural burning, and the number of Indigenous stewards with the biocultural knowledge, may be indicators of social–ecological health and resilience. This is a dimension of stewardship capacity that could be quantified, and for which goals could be set and tracked over time relative to the baseline conditions today. The Big Creek Lumber sawmill, a family-owned business operating since the 1940s, provides another example of how ecological and human needs are intertwined. It is the only remaining sawmill situated in the Redwood ecosystem south of San Francisco. The sawmill is used by Big Creek for its own timber operations, which have supported generations of local foresters with specific place-based knowledge about how to practise sustainable forestry. In addition, Big Creek's foresters and sawmill services are in demand by conservation organizations in the region who are adapting more lands to restoration forestry because it improves the Redwood forest structure towards old-growth conditions. The sawmill is part of the 'conservation ecosystem', and for it to be sustained, a threshold of timber access must be retained. Acres of timberlands in production or restoration forestry, as well as the number of local foresters, are additional factors that could be measured and incorporated into assessment as part of coordinating conservation in the region.

in ecosystem health, it is only a starting point for developing such tools to their full potential. A wide gap separates what should ideally be visualized and measured and what is currently possible in practice. Perhaps not surprisingly given the state of the science, biophysical indicators were relatively straightforward to identify, access and standardize across the landscape. By contrast, indicators related to social processes were more limited and partial, frustrating efforts at inclusion in the mapping exercise. For example, the cultural services included in the ecosystem-services index of the SLHA focus exclusively on recreation, but the SCMSN recognizes the importance of many other cultural services, such as spiritual access and equity and inclusion in management decisions. Information on these variables and many others is not yet available in a way that could support geospatial quantification, so the current version of the SLHA does not adequately address social-justice concerns. This raises important concerns about how the legacies of scientific data practices may continue to hamper the ability

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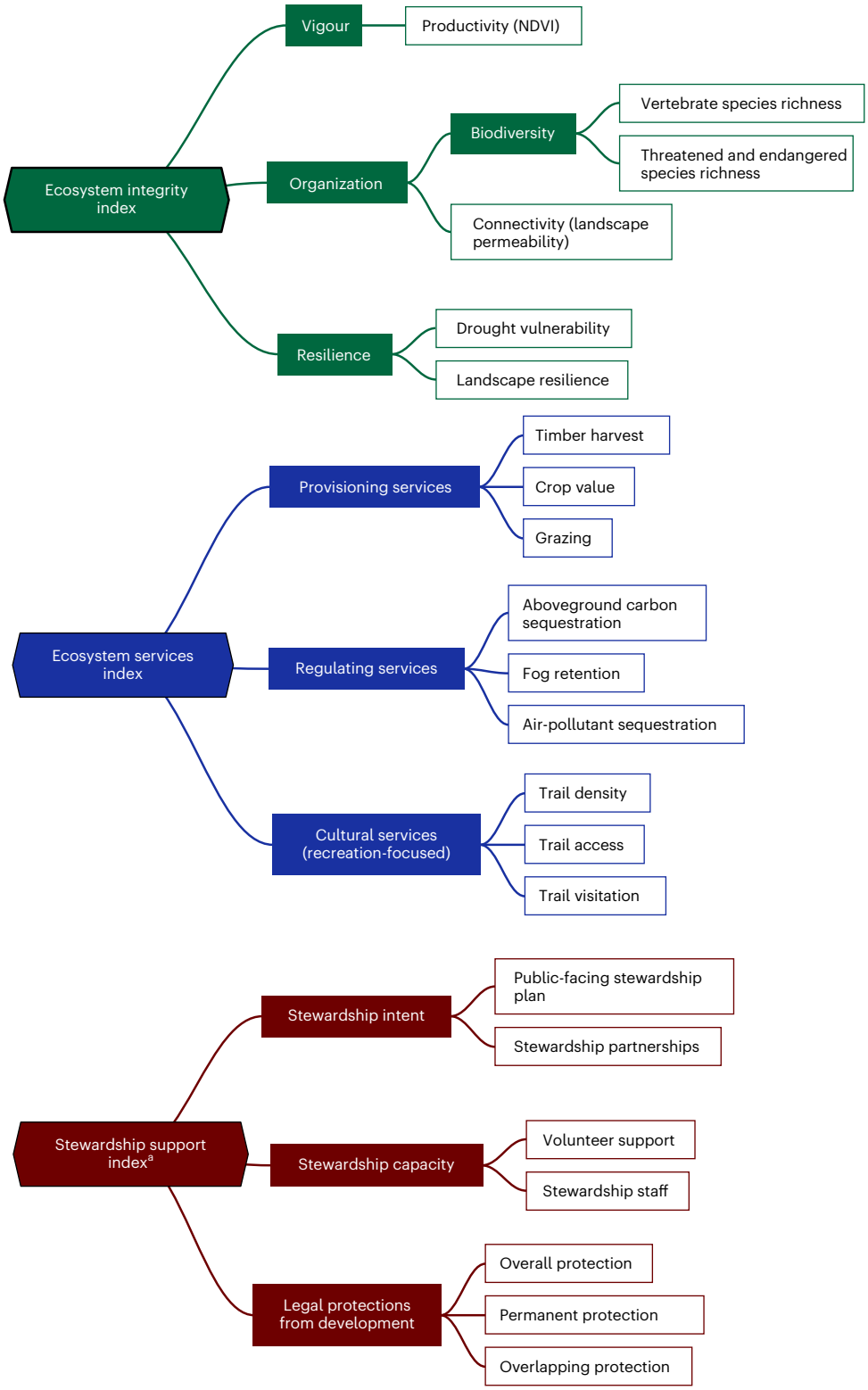

Fig. 4 | Components of the sustainable landscape health assessment. The SLHA framework represents ecosystem health through three lenses: ecosystem integrity, ecosystem services and stewardship support. Each index (far left) represents a linear combination of metrics (far right, for which all values are scaled 0–1) that are organized by subframeworks (centre). The specific metrics selected for inclusion were co-developed through a process of SCMSN engagement, literature review, expert input and data availability. Metrics were tailored to reflect (1) the specific physical and biotic potentials and constraints relevant to the landscape and (2) the desired benefits from the landscape, which ultimately are value judgements ideally arrived at by balancing the considerations of stakeholders against the biological realities of what is needed to maintain an ecosystem in a particular state. For application to other regions, metrics should be selected in consultation with local practitioners and based on the specific resources and communities (human and non-human), the governance, as well as stressors, threats and vulnerabilities that are relevant to that region. NDVI is the normalized difference vegetation index. [a]Stewardship support indicators are presently reported only for locations included in the California Protected Areas Database (v.2021b).

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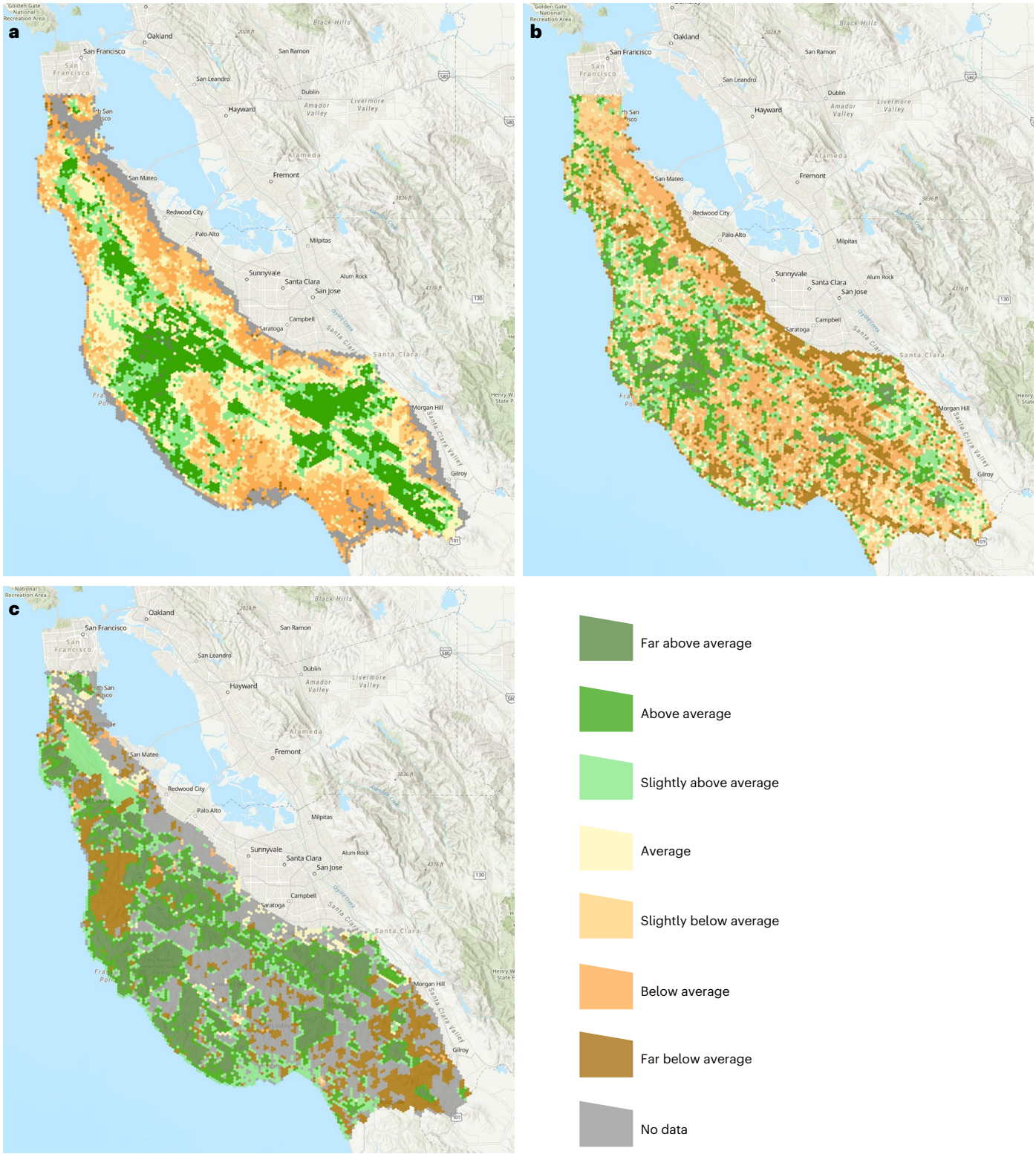

Fig. 5 | The landscape viewed from three different lenses of health. a–c, Maps from the first iteration of the SLHA represent ecosystem integrity (**a**), ecosystem services (**b**) and stewardship support (**c**). Stewardship support is only evaluated for properties within the California Protected Areas Database (v2021b).

of conservation and sustainability planning to address inequities, even when participants are aware of the biases.

The most notable limitation we identified in the SCMSN project is related to stewardship itself. Although stewardship is an increasingly popular concept in conservation and sustainability discourse, it is a challenge to develop appropriate metrics to express stewardship geospatially. This research was co-developed within an active network of practitioners carrying out stewardship in different ways, and yet these differences remained difficult to express appropriately in the context of a science-based assessment. In the process of developing the SLHA, it became apparent that stewardship is perhaps best understood as a relationship-based, place-based, emergent and dynamic activity.

It is not easily classified, mapped or quantified. Much of it occurs on private lands or in private contexts. We intended to use spatial data about stewardship practices, type and amount as metrics that could be monitored and tracked over time as a way to indicate stewardship health, but this was not feasible. Information on practices was too partial. Some SCMSN partners either do not have spatial records or were unwilling to share. Important differences such as whether a farm is organic or conventional, or whether invasive plant management efforts used biological, chemical or mechanical means were too granular for this analysis. As with spatial records, SCMSN members either were not inclined to share or did not keep records. Another source of difficulty in illuminating stewardship is that much of it is practised by third parties who do not appear on land-ownership maps and whose activities are difficult to track (for example, environmental consultants, non-governmental organizations, logging companies, volunteers and resource conservation districts).

Given these challenges, in this initial development of the SLHA, stewardship was included for lands identified in the California Protected Areas Database, and as an indicator of landowner intentions to steward the land, staff stewardship capacities, ongoing volunteer support and the degree of legal mandate for stewardship. The California Protected Areas Database includes all the public and private lands in the state that have a title-based legal mandate to restrict development, such as designated parklands, biological preserves or lands under conservation easements, both permanent and time-limited (for example, according to the Williamson Act). Information about stewardship intentions and capacities on private lands, including those under conservation easement, was not readily available. Within the SCMSN, private landholders were less likely to share information about their property boundaries and stewardship practices compared with public agencies.

Barriers to information sharing reflected a lack of time and capacity, as well as trust about how the information will be used and analysed; some stewards were also sceptical about whether or not the data could accurately capture the complexity of social–ecological systems. This hesitancy may also reflect a concern that if stewardship activities are made more public, it might result in unhelpful scrutiny. Efforts to map and classify stewardship raise the possibility for correlating stewardship with ecological conditions, but these relationships may be misleading. Stewardship is a dynamic activity, whereas ecological conditions integrate land-use activities over larger spatial scales and longer periods of time. In addition, environmental consultants or other professionals who earn their living by providing stewardship services may have a proprietary approach and little incentive to expose their techniques to external review. Landscape-scale data-based assessments risk feeling totalizing and oppressive to local stewards rather than illuminating and supportive.

Advancing stewardship science

Fostering good social relations is an essential part of advancing stewardship science and collaboration in multifunctional landscapes[24]. Such collaborations require a high level of transparency and accountability. Ultimately, the payoffs from these efforts could be substantial in terms of our scientific understanding of social–ecological systems as well as in terms of unlocking more resources, financial support and better overall outcomes in meeting conservation and sustainability goals. However, getting there will not be easy. Challenges include quantifying the metrics of stewardship with appropriate specificity in method and location, addressing incentives as well as the privacy and trust concerns of practitioners, and ensuring that data approaches can be applied equitably, all of which became apparent during the course of our work.

For the widespread incorporation of stewardship into ecosystem health assessment and conservation planning, scientists and practitioners will need to find ways to overcome these challenges. There remains the question of how to provide sufficient incentives for land stewards to provide details about their activities. Conservation funding agencies and governments could help to improve information availability by increasing public reporting requirements about stewardship activities, with the caveat that reporting requirements need to be more than unfunded mandates and balanced with respect for privacy concerns, especially on private property and where participation is voluntary.

There also remains the question of what level of granularity is relevant, or feasible, to shed light on the stewardship type and location. Research-practice collaboratives that include social scientists such as cultural anthropologists may help to advance this frontier. Through the use of ethnographic methods and other qualitative approaches that are effective at centring social risks and power inequities, practitioners may increase trust in the relevance of assessments and be willing to share details, such that the information can be extrapolated into typologies[19], for example, stewardship archetypes. Archetypes are an emerging research tool in sustainability studies that is used to identify recurrent patterns of phenomena at an intermediate level of abstraction, relevant to developing common learning across many 'messy' cases[61]. In principle, such typologies of stewardship could be mapped geospatially, analysed and tracked as a landscape metric and nested into global efforts to map human interactions in ecosystems (for example, anthropogenic biomes[22]).

Rising to these practical and philosophical challenges will be critical to fully develop robust models of ecosystem health that integrate stewardship with other metrics of ecological health.

Already, a wealth of biophysical environmental data are available at local, landscape and global scales for geospatial analysis through innovations in remote sensing[62]. The need now is for similarly detailed information about stewardship to be co-analysed with biophysical data, to unleash a powerful opportunity to improve our understanding of the relationships amongst land stewardship, ecosystem health and conservation at spatial scales from local to global. Such techniques and insights can improve the alignment of biodiversity conservation, including new protected areas, with the rights, knowledge and values of local people. As this research becomes possible, analysis and intervention into the larger socio-cultural, economic and political systems, to either promote 'good' or discourage 'bad' stewardship activities, may also become possible. In essence, if Earth stewardship is a solution to the problems of the Anthropocene, then revealing stewardship on the ground in all its complexity is a critical enterprise.

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Author contributions

N.E.H., D.S., K.M.C. and A.D.B. worked collaboratively to develop this Perspective. All authors contributed to the ideas expressed, and reviewed and edited multiple drafts. N.E.H. wrote the manuscript and prepared tables and figures. K.M.C. led the development of the SLHA and prepared figures.

Competing interests

The authors declare no competing interests.

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