SOCIAL SCIENCES

Linking the nonmaterial dimensions of human-nature relations and human well-being through cultural ecosystem services

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Nature contributes substantially to human well-being through its diverse material and nonmaterial contributions. However, despite the growing literature on the nonmaterial dimensions of human-nature relations, we lack a systematic understanding of how they are linked with human well-being. Here, we use the concept of cultural ecosystem services (CESs) as a lens to explore this interface. Through a systematic review of the peer-reviewed literature, we elicit the unique pathways and mechanisms linking individual CESs and constituents of human well-being, as well as their relative effects. Subsequently, we identify their complex interactions through latent class analysis and multiple correspondence analysis, which delineate five major assemblages that reflect synergies and trade-offs at the interface of CESs and human well-being. We critically discuss key research trends and gaps and propose directions for future research and practice to leverage the potential of the nonmaterial contributions of nature for human well-being and sustainability more broadly.

INTRODUCTION

Nature contributes manifold benefits to humans, at the individual, group, and societal levels. Beyond material and tangible contributions such as food, raw materials, clean water, and hazard regulation, among others, nature also provides a large diversity of nonmaterial contributions through opportunities for recreation and leisure, spiritual fulfillment, personal development, social relations, and aesthetic experiences (*1*, *2*). These nonmaterial contributions can have substantial effects on the well-being of humans at different scales (*3*), manifesting in very different manners (*4*, *5*).

The academic community has repeatedly emphasized the necessity to understand the complex nonmaterial dimensions of human-nature relationships and unravel how they intersect with human well-being (*1*, *6*, *7*). Understanding the underlying processes behind how the nonmaterial contributions of nature are linked to human well-being, designing appropriate interventions to leverage their contribution to human well-being, and mitigating the negative impacts of human activities on them are all essential for sustainable ecosystem management (*6*, *8*).

Up to now, a large body of literature has attempted to unravel in a coherent manner the nonmaterial dimensions of human-nature relations, using very diverse lenses and methodologies. For example, studies have come from fields as diverse as connectedness with nature, cultural ecosystem services (CESs), environmental psychology, environmental education, environmental sociology, geography, outdoor recreation studies, and even political ecology (*9*, *10*). However, despite this ever-expanding body of literature, the current evidence regarding the nonmaterial dimensions of human-nature relations is highly fragmented, particularly in terms of their actual linkages to human well-being and how they manifest. This is due to a series of reasons. First, the relevant literature tends to adopt different theoretical frameworks and terminologies (*3*, *11*–*13*), resulting in fragmented knowledge and inconsistent assessments. This is true both for the nonmaterial contributions side and for the human well-being side and is reinforced by the limited effort to synthesize cohesively this knowledge from these diverse academic fields (*4*). Second, both the provision of nonmaterial contributions and the linkages to human well-being are highly context dependent, which complicates their generalization and systematic understanding across different localities and scales (*4*, *10*).

The concept of ecosystem services, broadly defined as the benefits that humans derive directly and indirectly from nature (*1*), has emerged in the past two decades as one of the focal lenses for exploring human-nature relationships (*14*). Despite certain criticisms (*15*) and the transdisciplinary evolution of the term as nature's contributions to people (NCPs) (*16*, *17*), the concept of ecosystem services has provided one of the most popular lenses for exploring human-nature relations when considering its huge proliferation in the academic literature (*18*).

In this respect, the concept of CESs has been a major lens for exploring the nonmaterial dimensions of human-nature relations (*10*). CESs encapsulate, among others, recreation, spiritual enrichment, cognitive development, social relations, and aesthetic values (*1*, *3*, *13*). Although CESs have been used extensively in the literature (*12*), it has been exceptionally challenging to systematize concretely and comprehensively their linkages with human well-being (*11*, *12*). This is in no small part due to the fact that, as "representations" of nonmaterial human-nature relations, CESs are often intangible, subjective, socially constructed, and dependent on human perception, thus requiring very different sets of tools, metrics, and approaches for their understanding and assessment (*3*, *19*, *20*).

Here, we argue that by using CESs as a lens, it is possible to generate valuable insights of the actual interface between the nonmaterial dimensions of human-nature relations and human well-being. There

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is an extensive empirical and highly interdisciplinary literature on CESs accumulated in the past two decades (see table S6) that can be mobilized to understand these linkages. Furthermore, this CES literature tends to use a relatively consistent vocabulary of the different dimensions at this interface, which can facilitate the elicitation of linkages and related patterns.

We conduct a systematic review and analysis of the relevant peer-reviewed literature to (i) delineate the pathways and underlying mechanisms linking different CESs and constituents of human well-being; (ii) compare the effects of the different pathways underpinning these linkages; and (iii) identify possible interactions, synergies, and trade-offs in how CESs intersect with human well-being. The main outcome of this Review is a typology of the 16 individual mechanisms linking different combinations of CESs and constituents of human well-being, as well as their complex interaction in terms of synergies and trade-offs. Furthermore, we identify and critically discuss research trends and gaps at the interface of CESs and human well-being and offer recommendations for future research and practice. Collectively, the findings of this systematic review seek to systematize information that can help leverage the potential of the nonmaterial dimensions of human-nature relations for human well-being and sustainability more broadly.

RESULTS

General literature patterns

The systematic review identifies 301 studies focusing on the linkages between CESs and human well-being, including 287 empirical studies and 14 review studies. The reviewed studies span a total of 62 countries at various spatial scales, with 81.8% of the papers focusing on the local scale (n = 247 studies), 8.3% at the national scale (n = 25 studies), 6.3% at the regional scale (n = 19 studies), and 3.6% at the global scale (n = 10 studies). In terms of stakeholders' representation, almost all studies consider local communities, followed by tourists, indigenous communities, and farmers, fishers, and business owners (figs. S5 and S6).

Figure 1 shows the geographical distribution of the study sites considered in the reviewed literature and the number of publications by region and ecosystem type. Most studies focus on Europe (42.1% of articles), Asia (21.7% of articles), and North America (18.5% of articles). Only a few studies focus on Central and South America (6.5% of articles), Africa (5.8% of articles), and Oceania (5.4% of articles), despite being very biodiverse and containing many ecosystem-dependent communities. The reviewed studies mostly focus on CESs from urban and semiurban ecosystems (26.2% of articles), forests and woodlands (20.2% of articles), inland water (12.5% of articles), and coastal areas (8.9% of articles). Some of the reviewed studies also document the linkages between CESs and human well-being in relatively less studied ecosystems such as the arctic and mountain tundra, deserts and scrublands, and savannas.

Over time, we see studies from more diverse academic fields exploring the linkages between CESs and human well-being (fig. S4). Initially, relevant studies tended to represent a rather narrow disciplinary background such as environmental studies, urban studies, and geography. However, since about 2012, which coincides with the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), relevant studies tend to represent more diverse academic fields. By 2020, studies represented a quite large diversity of fields from the social sciences and humanities, cultural studies, psychology, pharmacology, medicine, and international relations, among others. Note that the reviewed studies have gradually adopted more diverse and innovative methods for data collection and analysis from different disciplines. However, a closer examination of the theoretical frameworks and research tools (see table S7) shows that knowledge integration remains still rather shallow across disciplines, despite the growing diversity of the underlying methodological portfolio.

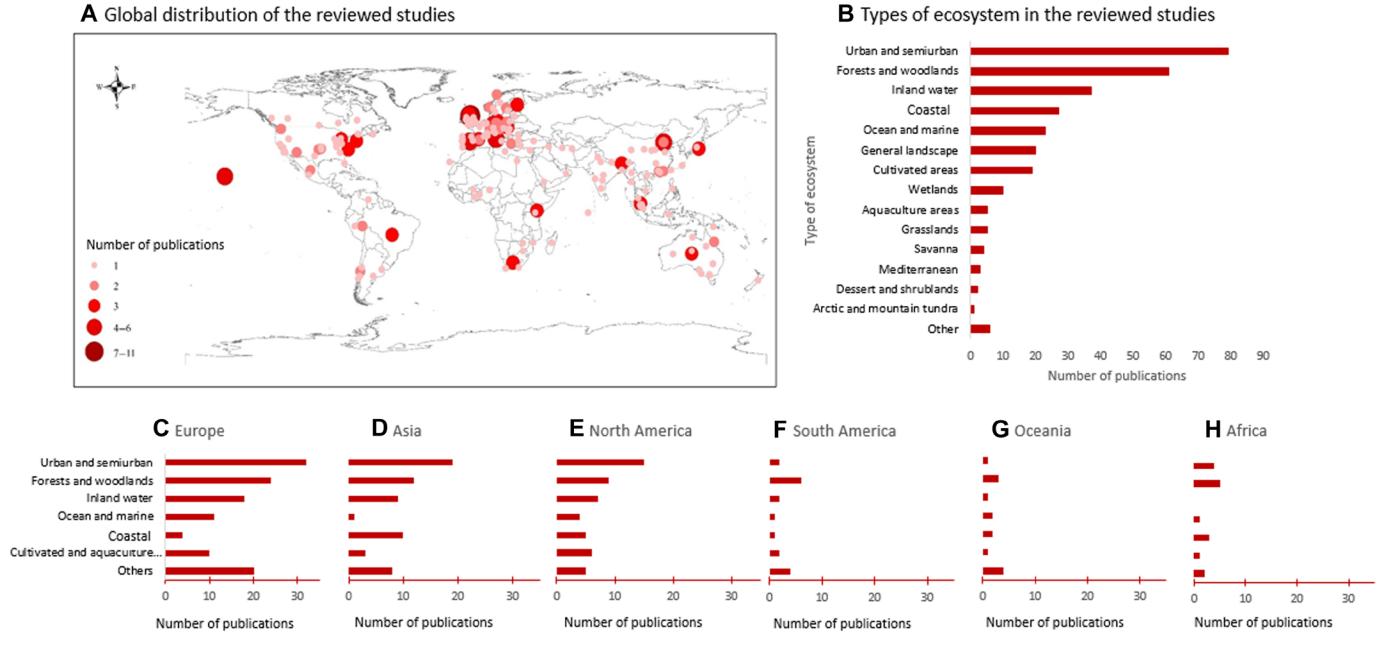

Fig. 1. Focus of the reviewed articles used in the systematic review. (**A**) Heatmap of the spatial distribution of the reviewed studies globally. (**B**) Bar chart of the total number of publications by ecosystem type. (**C** to **H**) Bar charts of the total number of publications by region for different ecosystem types.

Pathways and mechanisms linking CESs and human well-being

From the 1134 observations of the pathways linking a single CES and to a single constituent of human well-being, the 979 observations (86.3%) represent positive contributions, the 133 observations (11.7%) represent negative contributions, and the 18 observations (1.6%) represent two-way interactions. A total of four observations (0.4%) could not be categorized in terms of the direction of impact.

Our results suggest that the linkages between individual CESs and individual constituents of human well-being are very diverse and can be sorted in 227 unique pathways. Each of these pathways depicts a linkage through which the provision of (or change in) a single CES affects a single constituent of human well-being. When looking these 227 pathways more closely, it is possible to observe commonalities in terms of (i) the ways people consciously and unconsciously engage with ecosystems and experience benefits/disbenefits (i.e., channels of interaction) and (ii) the processes through which these interactions contribute to human well-being (i.e., mechanisms).

The four channels of interaction emerging from our analysis are form, cultural practices, intellectual practices, and spiritual practices. Form essentially denotes interactions with nature through the physical and tangible aspects of ecosystems. Cultural practices denote the interactions with nature that provide an opportunity for playing and exercising, creating and expressing, producing and caring, and gathering and consuming natural products. Intellectual practices denote the interactions with nature that provide an environment for learning and gaining new knowledge. Spiritual practices denote the interactions with nature that provide an opportunity for spiritual and religious activities.

The 16 types of mechanisms are (i) cognitive, (ii) cohesive, (iii) communicative, (iv) creative, (v) evolutive, (vi) formative, (vii) intuitive, (viii) regenerative, (ix) remunerative, (x) retrospective, (xi) satisfactive, (xii) transactive, (xiii) transcendentive, (xiv) apprehensive, (xv) destructive, and (xvi) irritative (Table 1). Of these, 6 mechanisms were adapted from a previous study (*5*), and 10 mechanisms were newly defined by the authors following the qualitative data analysis.

When using these four channels of interaction and 16 mechanisms, it is possible to aggregate the 227 individual pathways into 68 aggregate pathways that have similar characteristics. Of these 68 aggregate pathways, 45 denote positive contributions to human well-being, and 23 denote negative contributions to human well-being. Tables S12 to S14 provide an explanation of these 68 aggregate pathways, including specific examples from the literature.

Note that the empirical research on the linkages between different CESs and constituents of human well-being via distinct mechanisms is uneven. Figure 2 is an alluvial diagram illustrating the frequency of the documented mechanisms across the reviewed studies. Recreation and tourism and aesthetic value are the most popular CESs among the identified studies, accounting respectively for 31.9 and 17.6% of the total observations. Similarly, there seems to be an uneven representation in the reviewed literature of some mechanisms and constituents of human well-being, such as contributions to "mental health" (15.9% of observations), "physical health" (10.7% of observations), and "subjective well-being" (13% of observations) via regenerative mechanisms. Similarly, contributions to "social connectedness and belonging" (12.7% of observations) via communicative and cohesive mechanisms are also well represented in the reviewed literature. However, the empirical evidence about the influence of CESs on many other constituents of human well-being is still relatively lacking, such as the contributions of CESs to "learning and capacity," "personal identity and autonomy," and "sense of security and certainty" (Fig. 2).

We need to point here the possibility of a certain degree of overlapping between some mechanisms and channels of interaction in some contexts. This is mainly because linguistic constraints make it difficult to fully differentiate between some channels of interaction and some mechanisms. The implications and limitations of possible overlapping between some analytical categories are explored in more depth in Discussion (see the "Linkages between CESs and human well-being" section) and Materials and Methods (see the "Challenges and limitations" section).

Relative contribution of individual mechanisms

For each of the observations, we normalize the effects of CESs on human well-being through expert judgment, assigning scores from −2 to +2 (see Materials and Methods). We develop three matrix maps (Fig. 3) that represent the impact of each pathway to specific constituents of human well-being (denoted by the colors of the squares) and the overall quantity of the empirical literature (denoted by the size of the squares). Overall, there is a higher prevalence in the literature of positive and high-magnitude CES impacts on human well-being, while there is a comparatively lower prevalence of lower magnitude or negative impacts.

When looking at the positive contributions of CESs to human well-being, our results suggest that the highest such contributions are for mental health and physical health, with average scores of 1.99 (n = 150, SE = 0.014) and 1.97 (n = 108, SE = 0.02), respectively. Among individual CESs, recreation and tourism and aesthetic value exhibit the highest contributions to human health via the regenerative mechanism. "Connectedness and belonging" is the well-being constituent that receives the second highest benefits from CESs with an average score of 1.92 (n = 131, SE = 0.03). CESs can also have substantial positive effects for personal "learning and capability," with an average impact score of 1.91 (n = 114, SE = 0.04). The average scores are more moderate for other constituents of human well-being such as "certainty, sense of control, and security" (score = 1.86, SE = 0.072, n = 19), "identity and autonomy" (score = 1.84, SE = 0.042, n = 71), "spirituality" (score = 1.79, SE = 0.05, n = 81), "inspiration and fulfillment of imagination" (score = 1.72, SE = 0.03, n = 84), subjective well-being (score = 1.71, SE = 0.34, n = 125), and "economic well-being" (score = 1.58, SE = 0.09, n = 61).

The negative contributions of CESs to human well-being manifest through ecosystem disservices (table S12) and the degradation or loss of CESs (table S13) (see Materials and Methods for definitions). Among all well-being constituents, our results suggest that the highest negative effects are linked to mental health (score = −1.98, SE = 0.02, n = 25) via the destructive mechanism. Some disservices also profoundly affect certainty, sense of control, and security (score = −1.88, SE = 0.44, n = 14) via the apprehensive mechanism. These are mainly associated with aesthetic value and recreation and tourism, with a common underlying concern over safety, which is directly associated with how some natural elements are perceived. CES degradation sometimes also has negative effects on spirituality via the destructive mechanism (score = −1.94, SE = 0.06, n = 10). Economic well-being can be also affected negatively via the remunerative mechanism from financial loss caused by the degradation of CESs (score = −1.94, SE = 0.08, n = 16).

Table 1. Mechanisms linking CESs and human well-being. The 6 mechanisms indicated with an asterisk (*) are adapted from a previous study (*5*), while the other 10 mechanisms are defined by the authors. For each of the mechanisms, we provide as an example a unique pathway of CES mechanism–constituent of human well-being. Note that some mechanisms mediate more connections of individual CESs and human well-being constituents. A comprehensive explanation of the different pathways for each mechanism can be found in tables S12 to S14. The table presents in alphabetical order the positive (nos. 1 to 13) and negative (nos. 14 to 16) mechanisms.

No.	Type of mechanism	Definition	Example			
			Sample CES	Channel of interaction	Sample constituent of human well-being	Description
1	Cognitive*	The development of knowledge and understanding via interaction with nature	Education	Intellectual practice	Learning and capability	Ecosystems are a source of learning and knowledge about the environment, history, culture, and human relationship. Ecosystems provide opportunities for scientific research, environmental education, and learning from older generations. The education of children within/through the natural environment can assist in the development of knowledge, skillsets, and a sense of wonder for the world (*24*, *41*).
2	Cohesive	The development of meaningful relationships between people via interaction with nature	Social relation	Cultural practice	Connectedness and belonging	People can develop bonds with family members, friends, and other individuals through the interaction with nature. Social interactions and activities in natural settings such as camping trips and social events in natural settings can strengthen ties, reinforce fundamental values, and inspire respect, responsibility, solidarity, and caring for others, broader communities, and the environment (*69*).
3	Communicative*	The development of social communication and conversation via interaction with nature	Knowledge system	Intellectual practice	Learning and capability	In some cultural contexts, the knowledge of the culture and the practices needed for survival are part of the people' capacity for self-determination and personal development. These are often transmitted via communication between elderly people and young people at cultural events in natural settings, which are essential in this process. For example, indigenous communities transmit via communication in natural settings knowledge systems that are important for their personal development and livelihoods (*119*).
4	Creative*	The experience of new and original situations that inspire artistic work, aesthetic appreciation, creativity, and freedom (among others) via interaction with nature	Inspiration value	Cultural practice	Inspiration and fulfillment of imagination	Nature has inspired people throughout the history of humanity for artistic expression. These examples can be inspiration to paint, draw, take photos, be active/get out, conserve, manage, protect, discover, explore, and generally think about things (*5*).
5	Evolutive	The gradual change of individuals' personality, mood, feelings, attitude, perception, behavior, values, and belief systems over time (more often internal change) via interaction with nature	Recreation and tourism	Cultural practice	Learning and capability	On many occasions, the natural environment tends to make people more friendly, playful, elated, and affectionate over time (*24*). In some cases, nature-based recreation activities are gratifying and gradually increase courage or self-esteem (*41*).
6	Formative	The change of individuals' moods, feelings, attitudes, perception, behaviors, and values that is relatively instant or over short periods of time (more often internal change) via interaction with nature	Aesthetic value	Form	Identity and autonomy	Ecosystems offer spaces for individuals to instantly express their personal distinctiveness and identity without feeling constrained by external factors such as the norms and values imposed by society. In some cases, being in nature immediately enables achieving a personal sense of freedom and escapism from the social boundaries created by extrinsic factors of society. The sense of freedom and autonomy inspired by wild nature in that moment can allow individuals to strengthen their own intrinsic values and beliefs and to feel they can be free and make their own choices in lives (*120*).

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No.	Type of mechanism	Definition	Example			
			Sample CES	Channel of interaction	Sample constituent of human well-being	Description
7	Intuitive*	The sensual experiences, human instincts, and feelings (often of a spiritual and religious nature) via interaction with nature	Spiritual value	Spiritual practice	Spirituality	Many people experience something deeply spiritual when they interact with nature. In some geographical contexts, people find meanings in nature from the time they are born to the time they die, while the sense of spirituality attached to nature can bring hope, faith, personal beliefs/values, and empowerment (*49*).
8	Regenerative*	The generation of restorative outcomes (e.g., alleviation of fatigue and emotional stress) through recreation, leisure, tourism, escapism, and therapy via interaction with nature	Recreation and tourism	Cultural practice	Mental health Physical health Subjective well-being	Interaction with nature can improve mental health by helping to (i) reduce stress, anxiety, and depression; (ii) reduce visits to psychologists; (iii) improve sleeping quality; (iv) reduce the use of antidepressants, sleeping medicine, and sedatives; (v) increase vitality; (vi) decrease cognitive decline; (vii) increase ability of recovery and healing from crisis; and (viii) reduce mental fatigue and illness (*4*, *34*). Benefits to physical health through interaction with nature include (i) lower body mass index; (ii) reduced prevalence of disease; (iii) reduced obesity; (iv) lower somatization level; (v) decreased cognitive decline; (vi) reduced blood pressure, heart rate, and muscle tensions; (vi) improved immune system; (vii) increased restoration and healing; and (viii) lower mortality risk (*4*).
9	Remunerative	The economic benefits people obtain from ecosystems through nonmaterial benefits in cash or other monetary forms	Recreation and tourism	Cultural practice	Economic well-being	Nature-based tourism can directly or indirectly contribute to the livelihoods of local communities and broader economic growth. Examples include the direct generation of revenue from accommodation, transportation, guided tours, and food and beverage sales. Broader indirect contributions include poverty alleviation and employment generation (*121*, *122*).
10	Retrospective*	The personal memories and reflections of the past via prior interaction with nature	Sense of place	Form	Identity and autonomy	Natural landscapes are important to some people as they have evolved emotional and cognitive bonds, becoming parts of their personal and collective memory and their life stories (*123*).
11	Satisfactive	The feeling of satisfaction and fulfillment of expectations and needs associated with interaction with nature	Cultural heritage value	Cultural practice	Subjective well-being	Engaging in ecosystem-related livelihood activities can instill pride and sense of satisfaction. In many cases, farmers through their livelihood engagement with nature feel fulfilled have pride for their lives and a sense of purpose in life when putting a good day at work (*120*).
12	Transactive	The social benefits people obtain by bartering or trading the products of ecosystems	Cultural heritage value	Cultural practice	Economic well-being Connectedness and belonging	For many indigenous communities, particular species carry a special cultural heritage value that can be used for exchange and trades among kins to sustain the reciprocal relationships essential to their functioning (*124*).
13	Transcendentive	The benefits that lie beyond the ordinary experiences and the regular physical realm, more often associated with religious or spiritual values via interaction with nature	Spiritual value	Spiritual practice	Spirituality	Many people and communities experience ecosystem-inspired feelings related to "entities larger than themselves" (*125*). For some people, being in natural settings makes them appreciate people's connection to all things in the universe (*24*).
14	Apprehensive	The anxious and fearful feeling generated via interaction with nature	Aesthetic	Form	Certainty, sense of control, and security	Some people are afraid of their safety when encountering certain natural features via visual or auditory interactions, such as scary animals, dangerous predators, animal blood, and areas that are dark with high tree cover, among others (*4*, *22*, *46*).
15	Destructive	The direct damages caused to health, relationships, finance, and capability (among other constituents of human well-being) via the loss/degradation of CESs	Aesthetic	Form	Economic well-being	Some ecosystem disservices associated with CESs can increase the direct cost for repairs and maintenance, control, or remove unwanted species. For example, damage to physical structures can be caused by accelerating corrosion due to bird excrements or the destruction of pavements due to tree roots or animals digging nesting holes (*50*).
16	Irritative	The unpleasant and annoying feelings people obtain via their interaction with nature	Aesthetic	Form	Mental health	Some ecosystem disservices associated with CESs cause negative feelings such as annoyance and discomfort, e.g., annoyance or disgust wildlife noise, animal excrements, or plant litter (*46*, *50*).

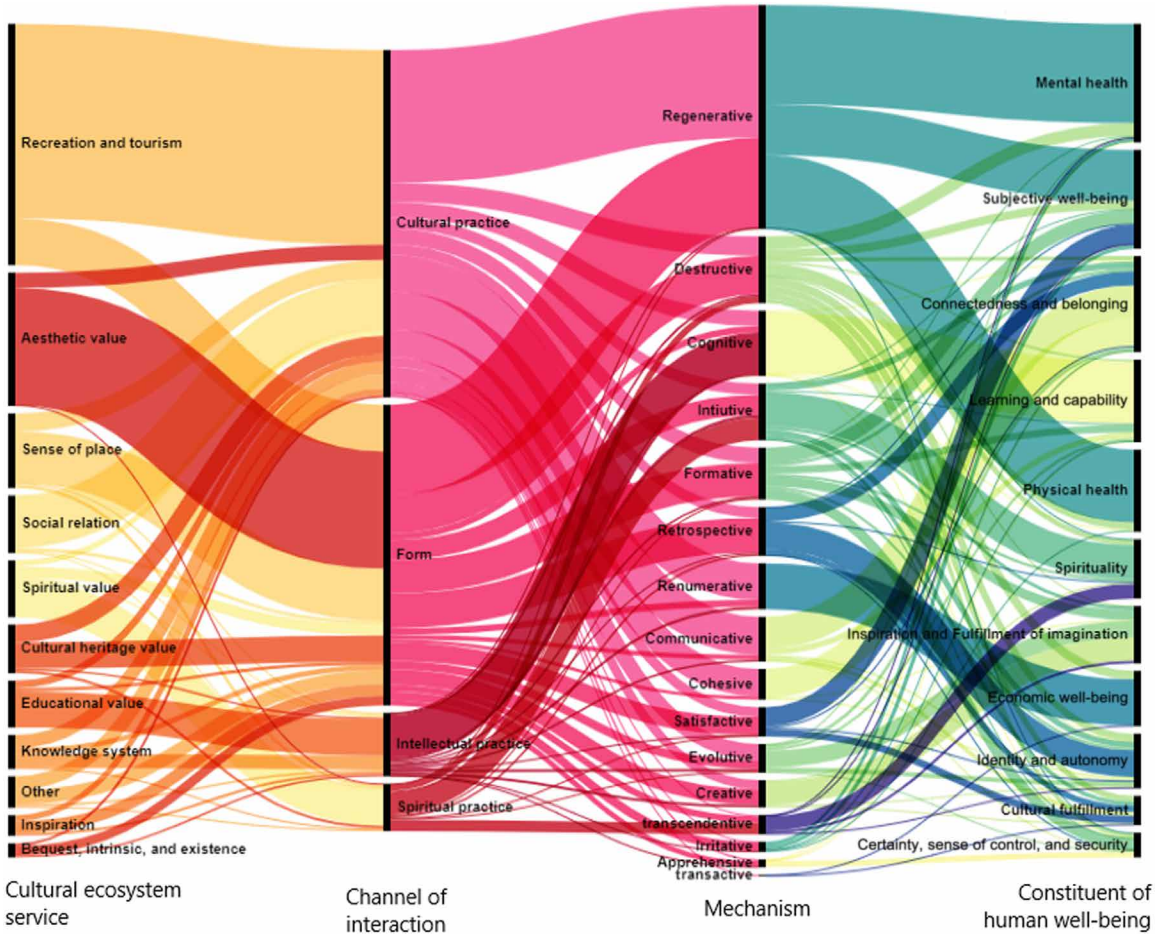

Fig. 2. Frequency of the CESs, mechanisms, and constituents of human well-being documented in the reviewed studies. The width of each line linking any two elements in the alluvial diagram represents the number of relevant observations (of the unique 1134 total observations). This essentially represents the popularity/visibility of each element in the reviewed literature and should not be perceived as a metric of importance or weight linking any two components.

Interactions, synergies, and trade-offs

Often, CESs and the pathways through which they are linked to human well-being via channels of interaction and mechanisms also tend to interact with each other in complex ways. For example, pathways associated with developing caring for nature via nature-based recreation could be related to both the "cultural practices" and the "intellectual practices" channels of interaction, via both evolutive and cognitive mechanisms (see tables S12 to S14). Inherently, there are interactions between these pathways and possible synergies and trade-offs between them when these pathways manifest in reality.

To identify these interactions, we conduct latent class analysis (LCA) and multiple correspondence analysis (MCA) to identify and define "assemblages," which encompass collections of pathways linking CESs and well-being that appear significantly related (see Materials and Methods for definitions and analytical approach). Through this concept, we emphasize how the interactions among individual CESs, constituents of human well-being, and pathways go beyond influencing autonomously human well-being (i.e., one pathway linking a single CES to a single constituent of human well-being), to create synergies, trade-offs, and dynamic wholes.

Overall, we identify five assemblages that contain interacting pathways and relate to (i) sensory affection, (ii) learning and development, (iii) health and leisure fulfillment, (iv) social vibrancy, and (v) spiritual and heritage resources. Table 2 summarizes the main features and interactions within these assemblages, the relevant constituents of human well-being, and the underlying mechanisms and affected groups.

Subsequently, we identify trade-offs and synergies between these assemblages through MCA. In terms of the associations among CESs, well-being constituents, and affected groups, the significant associations of CESs account for 6.9% of the first dimension (x axis) and 7.1% of the second dimension (y axis) (Fig. 4). Trade-offs and synergies occur among four assemblages, namely, "health and leisure fulfillment," "spiritual and heritage resources," "social vibrancy," and "learning and development." On the first dimension, health and leisure fulfillment has trade-offs to three other assemblages. On the second dimension, learning and development has trade-offs to both "spirituality and heritage resources" and social vibrancy (Fig. 4). These trade-offs are mainly associated with traditional and indigenous communities. Conversely, synergies are found between spirituality and heritage resources and social vibrancy (Fig. 4).

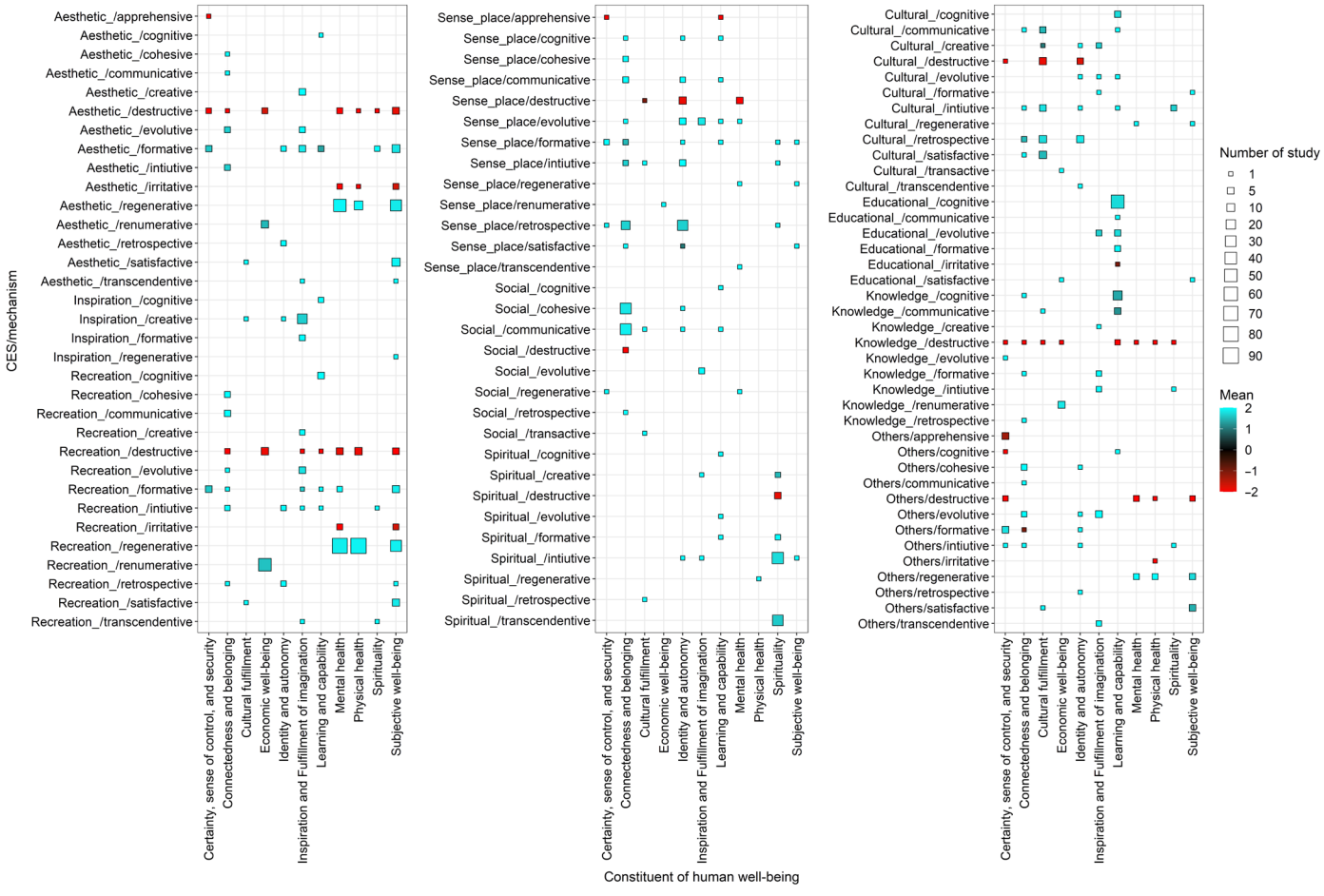

Fig. 3. Relative contribution of individual pathways to human well-being. Each box or empty space represents a unique pathway of a single CES to a single constituent of human well-being via a single mechanism. For simplicity, we list all 16 mechanisms explained in Table 1 for each CES (*y* axis) and cross map them to each constituent of human well-being (*x* axis). Essentially, each box indicates a unique combination of CES mechanism–human well-being found in the literature (i.e., in the 1134 observations divided into 227 unique pathways during the first iteration of the coding; see the "Elicitation of pathways and mechanisms" section), while each blank space indicates a unique combination not found in the literature. The size of each box represents the number of studies that captured the specific pathway. The color of each box represents the average effect of the specific CES on the specific constituent of human well-being via the specific mechanism after normalizing each relevant observation with a score of −2 to +2 (see the "Quantification of CES effects on human well-being" section).

DISCUSSION

Linkages between CESs and human well-being

The critical analysis and synthesis of the 287 empirical case studies and their 1134 observations suggest that the nonmaterial dimensions of human-nature relations (conceptualized as CESs in this systematic review) are linked to human well-being through very different pathways. In total, we identify 227 unique pathways linking a single CES to a single constituent of human well-being. The iterative qualitative analysis identifies that some pathways share commonalities in terms of (i) the ways in which people consciously and unconsciously engage with nature (i.e., four channels of interaction) and (ii) their format and approach as to how they affect human well-being (i.e., 16 mechanisms).

The four broad channels of interaction are form, cultural practices, intellectual practices, and spiritual practices. Form essentially reflects human-nature relations emerging via appreciating the physical aspects of the natural world, including the multiple qualities that affect sensory experiences, such as interactions from looking at the shape of the cliffs, feeling the sea breeze, or smelling the flowers' scent, among others (*5*, *21*, *22*). Cultural practices reflect human-nature relations that emerge via opportunities for playing and exercising, creating and expressing, producing and caring, or gathering and consuming natural products (*20*, *23*). Intellectual practices reflect the human-nature relations emerging via learning and gaining new knowledge, including, for example, interactions emerging from researching, learning, and thinking about or knowing about ecosystems and/or their components (*4*, *24*). Spiritual practices reflect the human-nature relations that emerge through opportunities for spiritual and religious activities, such as rituals and religious activities in sacred natural places or using plants and animals in ceremonies (*25*, *26*).

The 16 distinct mechanisms that mediate the linkages between CESs and constituents of human well-being (Table 1) reflect in more concrete terms similarities in how the nonmaterial dimensions of human-nature relations affect human well-being. Six of these mechanisms were adapted from the literature (*5*), while the remaining 10 were systematized by the authors following an iterative review and coding process. We discuss these mechanisms in greater depth in the next section.

Table 2. Characteristics of assemblages. We follow the definition and classification of "Indigenous community" adopted by the United Nations (*126*) as "Indigenous peoples are inheritors and practitioners of unique cultures and ways of relating to people and the environment. They have retained social, cultural, economic, and political characteristics that are distinct from those of the dominant societies in which they live." Similarly, "local community" refers to the local people in a specific context but not including the indigenous people.

Assemblage	CESs	Well-being constituents	Mechanisms	Ecosystems	Beneficiaries
Sensory affection	Recreation and tourism	Certainty, sense of control, and security	Apprehensive	Inland water	Tourists
	Aesthetic value	Economic well-being	Irritative	Ocean and marine	Local community
	Sense of place	Mental health	Destructive	Urban and semiurban	
	Authentic wilderness	Subjective well-being	Regenerative		
Learning and development	Education value	Learning and capability	Cognitive	Forest and woodland	Indigenous community
	Knowledge system		Communicative	Cultivated areas	Local community
	Cultural heritage/ cultural diversity value		Formative	Ocean and marine	Farmers and fishers
Health and leisure fulfillment	Recreation and tourism	Mental health	Regenerative	Urban and semiurban	Tourists
	Aesthetic value	Physical health	Satisfactive	Inland water	Local community
		Subjective well-being	Remunerative		
		Economic well-being			
Social vibrancy	Recreation and tourism	Connectedness and belonging	Cohesive	Urban and semiurban	Tourists
	Aesthetic value	Economic well-being	Communicative	Forest and woodland	Local community
	Social relations	Identity and autonomy	Retrospective		Farmers and fishers
	Sense of place				Business owners
Spiritual and heritage resources	Spiritual value	Spirituality	Intuitive	Forest and woodland	Local community
	Cultural heritage/ cultural diversity	Identity and autonomy	Retrospective	Ocean and marine	Indigenous community
	Inspiration value	Inspiration and fulfillment of imagination	Creative	Urban and semiurban	Tourists
	Aesthetic value		Evolutive	Coastal areas	

The four channels of interaction and the 16 mechanisms provide a comprehensive mapping of the interface between the nonmaterial dimensions of human-nature relations and human well-being through an ecosystem services lens. In this sense, they constitute a conceptual advancement that can have both theoretical and practical application.

In terms of theoretical application, these mechanisms and channels of interaction can influence the development of conceptual frameworks that explore the interface between the nonmaterial dimensions of human-nature relations and human well-being in more nuanced ways, especially when using CESs or NCPs as the lens (see the "Future research directions" section). The conceptual contributions here lie on the multidimensional view of human well-being that allows for a shift from a narrow perspective focusing on a single start-point CES or end-point well-being constituent, toward understanding the actual nature of their linkages and what mediates the actual well-being outcomes (and how). For example, this can help refine the links between human well-being and the nonmaterial human-nature relations in conceptual frameworks proposed by large-scale assessments (*1*, *6*, *7*), international initiatives (*27*), and individual studies (*3*, *12*, *13*, *19*) or inform empirical studies using these frameworks to explore nonmaterial human-nature relations using CESs or NCPs as lenses (see the "Future research directions" section).

In terms of practical applications, our findings can guide future studies seeking to explain better how these mechanisms unfold in different real-life contexts and inform the design of appropriate interventions seeking to enhance human well-being through the provision of CESs (see the "Implications for policy and practice" section). This latter point echoes the extensive literature arguing for the need to capitalize on the intangible benefits provided by green spaces for enhancing human well-being, especially in urban contexts (*28*–*31*).

Relative effects of mechanisms

Figure 3 strongly suggests that the different mechanisms mediate quite different effects on human well-being. To the authors' best knowledge, this is the first comprehensive attempt to systematically quantify the impacts of CESs on human well-being through a global systematic review. The main challenge here is that as the value and contribution of many CESs are subjective and intangible, the different studies tend to adopt different descriptive and qualitative approaches, making it difficult to undertake a systematic analysis across studies (*3*, *12*, *20*).

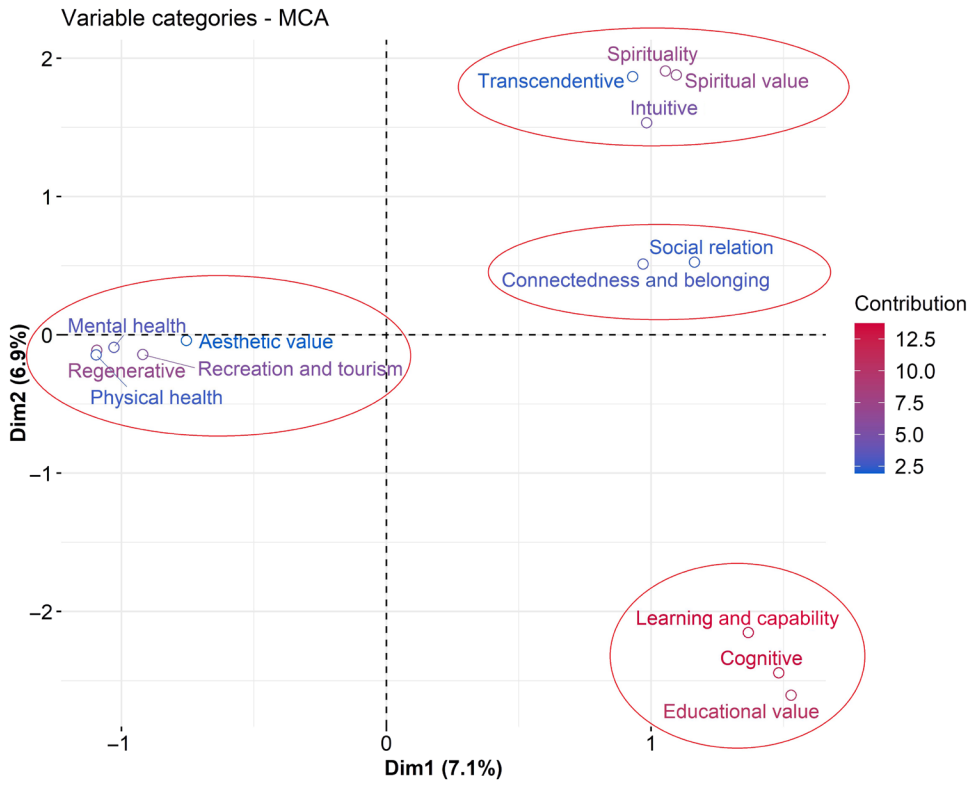

Fig. 4. Interactions, trade-offs, and synergies among CESs, constituents of human well-being, and mediating mechanisms. Each of the 1134 individual observations is assigned with various variables, and the clusters are identified through MCA (see the "Identification of assemblages" section). The significant associations account for 6.9% of the variance of the first dimension (*x* axis) and 7.1% of the variance of the second dimension (*y* axis). Variables within the same bubbles and/or sides of each axis represent synergies and positive associations, while variables on opposite sides of each axis represent trade-offs and negative associations.

Our results suggest that CESs tend to have the highest positive contributions to constituents of human well-being such as physical health and mental health via regenerative mechanisms (Fig. 3). These pathways denote interactions with nature that create positive restorative outcomes related to stress reduction, relaxation, tranquility, escapism, physical exercises, increased longevity, and recovery from sickness (*4*, *32*–*35*).

Strong positive effects are also observed for connectedness and belonging via the cohesive mechanism (Fig. 3). This reflects instances of people communicating and developing meaningful personal relationships through interactions with ecosystems (*5*, *36*–*38*). For example, very diverse nature-based activities such as recreation, hiking, and camping foster social cohesion via socially healthy behaviors and stewardship (*36*). Studies have consistently pointed that the social bonding mediated by interactions with nature can create networks that emerge beyond the physical boundaries of the sites where nature-based activities occur and reinforce the existing relationship at both personal and collective levels (*39*).

Strong positive effects are also observed for learning and capability through cognitive and evolutive mechanisms (Fig. 3). For example, via the evolutive mechanism, nature-based recreation has a positive effect on childhood growth and gradually equips children with knowledge and skillsets that can be beneficial in the future (*24*, *40*–*42*). These contributions can also manifest via the cognitive mechanism through which nature acts as a source of learning about history, culture, the natural world and social relationships (*43*), or an opportunity for scientific development, outdoor education, and learning from previous generations (*44*, *45*). It is worth noticing here that learning and capability is one of the constituents of human well-being that has been limitedly associated with discussions over "educational value" and "knowledge system" in the CES research landscape, as following the conceptual framework of the Millennium Ecosystem Assessment (MA) (*1*). However, here, we find the centrality of this human well-being constituent as almost all CESs can provide benefits to it via various mechanisms.

When it comes to negative outcomes to human well-being, mental health, and certainty, sense of control and security are the constituents mostly affected via apprehensive (*22*, *46*) and destructive (*47*–*49*) mechanisms (Fig. 3).In terms of apprehensive mechanism, it is well documented that ecosystem disservices such as noise from wildlife, wild and messy landscapes, and the presence and movement of pests can cause perceptions of disorder, while animal waste and plant litter may cause disgust (*46*, *50*). For example, some studies have recorded that obsessive fear can be triggered by some natural features via visual (or sometimes auditory) interactions, such as scary animals, dangerous predators, animal blood, and areas that are dark and covered by high trees (*4*, *22*, *46*). Some people may have a limited frame of reference for recognizing and construing these unfamiliar sensory experiences, developing in the process a sense of overwhelming "cognitive chaos" and alienation toward nature (*4*). Landscape planning, eco-tourism development, socioeconomic background, and childhood interactions with nature are some of the external factors that tend to mediate these mechanisms (*50*, *51*).

When it comes to destructive mechanisms, a key point of departure is the benefits that nature provides to many people through spiritually transcendental experiences, which transform something from within (*48*, *49*). These are closely linked with religious activities and places for customary rituals and worship (*25*). Environmental degradation, urbanization, and/or overexploitation of certain species with cultural significance can often cause the gradual loss of spiritually important landscapes (*52*, *53*) or plants/animals of religious/spiritual importance (*54*). This can in turn trigger the decline or even the loss of ritual activities and related spiritual well-being for some people or groups (*55*).

Note that although many people might not be well aware of the benefits offered by ecosystems, they can be substantially affected by the financial loss caused by CES degradation via the remunerative mechanism (Fig. 3). For example, climate change or environmental degradation can cause notable loss in tourism revenue linked to CESs, thereby reducing the incomes of people or groups working in these sectors, eventually hindering their capability to meet basic needs (*56*, *57*). Some of the reviewed studies suggest that when money enters the picture, it can sometimes shift how people frame their well-being, appreciation of nature, and motivations behind their interactions with nature (*58*, *59*). The extent of how these changes manifest varies between cases and between social groups. Thus, although it is not possible to elicit a universal conclusion here, the usefulness of money to meet several well-being needs remains elusive in the current discussion about CESs and human well-being (*60*).

Overall, there seems to be a dominance of studies about the positive contribution of CESs on human well-being (Fig. 3). Furthermore, these studies tend to report transient, immediate, and substantial impacts on the different constituents of human well-being. Conversely, much fewer studies have focused on possibly negative or low-magnitude impacts on human well-being.

When looking more critically at the results, we can appreciate better the large heterogeneity and diversity of the pathways linking CESs and human well-being, including many that have been overlooked in the current conceptual frameworks and empirical studies (Figs. 2 and 3). We note that there are some dominant pathways linking a specific CES (starting point of a pathway) to a specific constituent of human well-being (end point of a pathway) that are rather well explored in the literature. Some examples include (i) 72.8% of the pathways contributing to the human well-being constituent learning and development originate from the CES educational value and knowledge system and (ii) 60.5% of the pathways contributing to the human well-being constituent connectedness and belonging originate from the CES "social relations." However, beyond these obvious dominant pathways, there are many more that contribute to these exact constituents of human well-being. For example, among the pathways contributing to connectedness and belonging, beyond social relations, 20.4% of the pathways originate from the CES "sense of place," 9.2% from "recreation and tourism," 5% from "aesthetic value," and 3% from knowledge system via communicative, cohesive, retrospective, and evolutive mechanisms (Fig. 2). Similarly, pathways to the human well-being constituent learning and development can originate, among others, from the CES social relations via communicative mechanism (8%) or the CES "cultural heritage value" via the evolutive mechanism (5.6%) (Fig. 2).

In this sense, rather than implying problems of tautology in our conceptual framework, these findings arguably illustrate the comprehensiveness of this review that brings attention to these less visible pathways. Note that some of these pathways have been overlooked in the current research landscape but can have large impact on certain human well-being constituents (Fig. 3).

Beyond that, it is possible to observe many blank areas in Fig. 3. This suggests possible research/knowledge gaps for many pathways between CESs and constituents of human well-being via specific mechanisms. We believe that these imbalances and missing pathways could be due to three possible reasons. The first could be publication bias, which refers to the selective publication of studies based on the magnitude and direction of the results and/or the areas of interest of the authors (*61*). However, because of the inconsistent type of data and analytical procedure in the reviewed literature, it is not possible to formally test for publication bias, as is common in meta-analyses (*62*) (see the "Challenges and limitations" section). Second, the missing pathways in Fig. 3 linking a single CES to a single human well-being constituent via a specific mechanism might not exist in reality. Third, these pathways might exist but have not been empirically identified in empirical studies.

Considering the above, this systematic review provides a level of evidence and possibilities to inform future research and practice at the interface of CESs and human well-being. This can reduce the biases in the areas that "we know," fill in the knowledge gaps in the areas that "we do not know," and hint to explore the areas that "we do not know we do not know" (see the "Implications for policy and practice" and "Future research directions" sections).

Synergies and trade-offs

Following the quantitative analysis, we identify five assemblages that reflect some consistent associations and interactions among the pathways and mechanisms linking CESs and human well-being. Overall, our results seem to confirm that different mechanisms are more relevant to certain CES types and affect specific sets of human well-being constituents. This points to that it might be practical and beneficial to identify these synergistic and antagonistic relationships to inform landscape and urban planning, natural resource management, and biodiversity conservation.

The first assemblage is "sensory affection," where CESs related to recreation and tourism, aesthetic value, and sense of place tend to be bundled together and have synergistic effects on certainty, sense of control, and security, economic well-being, mental health, and subjective well-being (Table 2). These synergistic effects are observed in many studies of inland water, ocean and marine, and urban and semiurban landscapes and seascapes (Table 2). While aesthetic values can enhance subjective well-being (*4*, *63*), authentic wilderness with disordered and frightening landscapes can also cause fear and negative feelings to some people (*22*, *46*). This assemblage brings attention to the synergistic functions brought by landscape elements that could create deep internal changes to well-being via affecting human senses. This could have some interesting practical implications for landscape designs, e.g., related to the debate about the promotion of "authentic" natural landscapes or planning "false wilderness" to reconnect people to nature (*64*).

Second, the learning and development assemblage implies the synergistic associations among the CES educational value, knowledge system, and "cultural heritage/cultural diversity value" to the learning and capability human well-being constituent via cognitive, communicative, and formative mechanisms (Table 2). These synergistic effects are identified in studies in forests, woodlands, and

cultivated landscapes, and mostly for indigenous communities, local communities, and farmers and fishers. These studies tend to show many similarities in how ecosystems shape the way people think (*65*), their choices in life (*21*), and the development of their worldview and cultural significance between indigenous people and modern communities (*4*). Regardless of culture and level of livelihood dependence on ecosystems, these synergistic effects point to the longstanding associations between ecosystems and the personal lives of people through intimate knowledge of (and adaptive integrity with) the local environment, which contributes notably to personal growth (*65*). Arguably, these synergistic effects deserve attention in ecosystem management initiatives.

Third, in health and leisure fulfillment assemblage, the CES recreation and tourism and aesthetic value tend to create synergistic effects on the "health," subjective well-being, and economic well-being constituents of human well-being (Table 2). This is the most dominant assemblage among the five containing 35.3% of all observations. The fourth assemblage is social vibrancy that refers to the synergistic contributions of the CES recreation and tourism, aesthetic value, and social relation to the connectedness and belonging constituent of human well-being (Table 2). Both these assemblages tend to be more prevalent in studies of human-dominated landscapes such as urban green spaces (Table 2), pointing to the multiple positive contributions and cost-effectiveness of urban green and blue infrastructure for meeting multiple needs of urban residents, e.g., mental health, physical health, social relations, leisure, and improved quality of life (*22*, *66*, *67*).

Fifth, the spiritual and heritage resources assemblage suggests the synergistic effects of the CES "spiritual value," cultural heritage/cultural diversity value, and "inspiration value" to the human well-being constituent spirituality and identity and autonomy (Table 2). Here, identity appears to be the core determinant of these synergistic effects (*68*, *69*). Thus, the inclusion of local communities' identities and cultural practices can create substantial benefits for ecosystem management in areas that these associations are visible (*70*).

We identify a series of trade-offs among four assemblages, namely, learning and development, health and leisure fulfillment, spiritual and heritage resources, and social vibrancy (Fig. 4). For example, the trade-offs between the spiritual and heritage resources and learning and development assemblages seem to be observed in religious or sacred landscapes. In particular, in some of the reviewed studies, traditional and indigenous communities are often skeptical about the research potential and educational value of these areas (*71*). This is often due to the diverse challenges and barriers (e.g., technical, perception, and communication), as well as differences in values, which have sometimes alienated the active engagement of indigenous communities in the formulation of ecosystem management plans in such areas (*71*–*73*).

Another common trade-off in the reviewed literature is between the spiritual and heritage resources and health and leisure fulfillment assemblages (Fig. 4). Similar to above, these trade-offs are mainly observed in traditional and indigenous communities for which ecosystems (and nature more broadly) invoke spiritual experiences, e.g., Earth and its elements are perceived as living entities valued for their own sake (*24*, *48*). In this context, tourism and recreational activities that offer leisure and improve in the process health and subjective well-being of tourists are sometimes perceived as violating sacred places (*74*). Some studies have suggested that tourism-related activities sacrifice spiritual and intrinsic values (e.g., sacredness and spiritual connections between the sites and people) for instrumental benefits (e.g., tourism revenue) (*75*).

We also observe trade-offs between the health and leisure fulfillment and learning and development assemblages (Fig. 4). This trade-off is usually associated with the fact that some tourism-related and recreational activities can alter local livelihoods at community level and encourage young people to leave their traditional livelihoods (*43*, *76*). In some contexts, the environmental degradation associated with intensive tourism combined with the risks of changing livelihood structure may result in the substantial loss of local knowledge systems and skills related to nature, e.g., derived from long-term engagement with ecosystems and/or used for sustainable ecosystem management (*77*). In other cases, the inappropriate planning of tourism-related activities can obscure the educational value of historically, culturally, and ecologically important areas (*75*, *78*).

Arguably, knowledge about these synergies and trade-offs can inform practice and decision-making processes to anticipate what types of human well-being trade-offs/synergies are to be expected in areas where these CESs are provided, for example, because of tourism (*79*–*81*) or economic development (*82*, *83*). This can guide the identification of possible context-specific options for preventing or mitigating CES-driven trade-offs or synergies for human well-being (see the next section for a more in-depth discussion).

Overall, the synergies and trade-offs reflected in these assemblages emphasize that when exploring the contribution of the nonmaterial human-nature relations on human well-being, it is important to consider CESs (and their changes) not individually but as a whole. This resonates well with the literature on "ecosystem services bundles," "landscape multifunctionality," and "landscape connectivity" (*84*–*86*). Nevertheless, the concept of assemblages was used here although loosely adopted from philosophy (*87*), and it encapsulates the wider notion of the whole in that it does reflect the simultaneous provision of multiple CESs not only in a given social-ecological system but also in the associations between the pathways linking these CESs to human well-being.

Implications for policy and practice

The findings of this systematic review can have implications for policy and practice. Here, we draw from the concepts of landscape multifunctionality (*84*) and "reconnecting people to nature" (*88*) to show how the linkages between human well-being and the nonmaterial human-nature relations identified in this systematic review (and conceptualized as CESs) can inform policies and practical applications. In particular, by being the distillation of the rich literature of the human well-being outcomes of CESs, our findings can inform policies and practical applications seeking to enhance human well-being via nonmaterial ecosystem contributions, and vice versa (i.e., avoid compromising their provision).

First, the results of the pathways, assemblages, synergies, and trade-offs outlined in the previous section support the view of landscape multifunctionality and the possible value addition of policies and practical applications that promote the interactive and simultaneous provision of multiple nonmaterial benefits. More specifically, the comprehensive systematization of the linkages between nonmaterial human-nature relations to human well-being via 68 aggregate pathways (tables S12 to S14) and the trade-offs and synergies of these linkages through five assemblages can assist practitioners and decision-makers in anticipating the likely outcomes of related policies and practical applications. Strengthening human-nature

relations (including nonmaterial ones) has been strongly proposed in multiple past and ongoing assessment and academic outputs of the IPBES, which have outlined related policy options (*16*, *17*).

For example, in our case, if practitioners or policy-makers have set initial goals for enhancing specific aspects of human well-being in a given locality via interaction with nature (e.g., objective to enhance physical and mental health in a city or neighborhood through green spaces), then it could be possible to track back the pathways linking the designated set of well-being constituents to the CESs that would be needed to achieve this (e.g., tailor green spaces for exercise or promote landscape elements with aesthetic values associated with stress alleviation and escapism). By knowing the mechanisms permeating these pathways (e.g., regenerative, satisfactive, and transcendentive) and an understanding of the most likely beneficiaries, landscapes, and landscape elements that can deliver them, it could be possible to inform the development of specific interventions that meet these objectives. Similarly, it could be possible to develop interventions that avoid to the extent possible pathways associated with negative effects on human well-being via apprehensive, irritative, and destructive pathways. This can prevent not only negative human well-being outcomes but also possible opposition from groups that are affected negatively.

However, further to "creating" or strengthening such individual pathways, the five assemblages can provide a more holistic lens to decision-makers at the early stages to approach the management of these nonmaterial dimensions as a whole, as a means of obtaining multiple benefits while avoiding trade-offs to the extent possible. In this sense, the assemblages could be used as a coarse preliminary lens to anticipate what synergies (i.e., value addition) or trade-offs could be expected in a given context via proposed interventions. For example, by knowing the synergies and trade-offs within and between the assemblages (i.e., health and leisure fulfillment, social vibrancy, and spiritual and heritage resources assemblages), decision-makers can anticipate that certain tourism interventions may simultaneously catalyze synergistic effects on multiple well-being constituents (e.g., promote leisure, social relationships, and health outcomes) while being aware of possible trade-offs (e.g., damage to spiritual and cultural connections between people and the site). Ideally, decision-makers should seek to develop policies and design interventions that promote these synergistic effects while reducing the trade-offs among the different pathways. This type of information can be useful across different stages, from planning to implementation. Of course, final decisions and approaches should be guided by the local context, including the specific policy goals and constraints, possible users/beneficiaries, and socioecological context, among others.

Second, while there is a consensus that policies and practical applications seeking to reconnect people to nature can have multiple benefits to human well-being and sustainability (*88*), it is not always clear how this can be achieved. By using the notion of "leverage points," which is defined as points in a complex system where interventions can alter the overall system behavior (*88*), we argue that incorporating in the decision-making process "what really matters to people" and "what really harms people" in terms of the nonmaterial dimensions of human-nature interactions can create these deep leverage points and bring about more effective and meaningful "reconnections." These points have been made in several IPBES outputs (*9*, *16*, *17*). Specifically, our results indicate that "inner" connections such as cognitive connections to enhance learning and capability (mean = 1.91, SD = 0.044), cohesive and emotional connections to promote connectedness and belonging (mean = 1.92, SD = 0.03), and psychological connections to enhance mental health (mean = 1.99, SD = 0.014) are more likely to have a stronger effect on human well-being outcomes rather than the "outer" connections such as remunerative connections to enhance economic well-being (mean = 1.58, SD = 0.09) (Fig. 3 and tables S8 and S9). As the nonmaterial contributions of nature have often received less attention in decision-making processes compared to more tangible contributions (*19*, *89*), here, we emphasize the necessity of reconnection strategies that aim to influence the behavior of individuals and alter the paradigms that underpin the actions and decision-making for ecosystem management.

Future research directions

Despite the wealth of studies exploring the interface of the nonmaterial dimensions of human-nature relations and human well-being, through our review, we identify several knowledge gaps for future research. First, the research at this interface tends to focus disproportionately more on individuals, rather than groups. While understanding how nonmaterial human-nature relations affect the human well-being of individual is undoubtedly important, the fact remains that the reviewed studies have focused less on understanding effects on collective well-being. However, several studies have suggested that trade-offs in the provision of CESs has improved the well-being of individuals but reduced collective well-being, and vice versa. Such an example is that extremely high levels of place attachment, place dependency, and local identity (individual well-being) might trigger extreme attitudes toward managing ecosystems, in turn hindering the effectiveness of ecosystem management, creating social conflicts, and ultimately affecting negatively social cohesion (collective well-being) (*90*). Although these interactions between individual and collective well-being have been recognized in a few studies, there is a lack of broader multilevel well-being assessments that could better explain relevant well-being trade-offs and synergies.

Second, there are notable imbalances in the available evidence for different pathways (Fig. 2) and a lack of evidence for large number of theoretically possible pathways (Fig. 3). In this sense, there is a need to fill in the substantial knowledge gaps in the areas that (i) we know, (ii) we do not know, and (iii) we do not know we do not know (see the "Relative effects of mechanisms" section). For (i), there is a need to both advance the currently available knowledge and address possible publication biases (see the "Challenges and limitations" section). For the former, research should explore in-depth how these pathways and mechanisms manifest in less studied ecosystems and understand their differentiated effects to various stakeholders. The underlying factors mediating changes in the provision of nonmaterial contributions and their impact for human well-being would also need more dedicated attention. For reducing publication bias, scholars should be able to publish high quality research regardless of "uninteresting" results or novelty. Low-magnitude, negative, or incremental impacts on human well-being should also be captured and reported to gain a fuller understanding of the interface of nonmaterial contributions of nature to human well-being. For (ii), our work could be used as a high-level summary of the current research landscape and highlight the many missing pieces that need to be found. In particular, the blank areas in Fig. 3 could offer some starting points to explore whether the missing pathways exist or not in reality, as well as what is their relative effect on human

well-being. For (iii), we should point out that there might be more mechanisms linking human well-being and the nonmaterial dimensions of human-nature relations. This is quite likely the case considering the large biological and cultural diversity around the globe and the often very tight human-nature relations in many geographical contexts. In this sense, there is a need to move beyond the conventional way of thinking and collectively upgrade our research approaches and framings to unravel the unknown unknowns in human-nature relationships. We hypothesize that missing mechanisms could be present in ecosystem-dependent communities and especially traditional and indigenous communities, considering their very unique relations with nature. Thus, there would be a need to enhance even more the current efforts to promote the collaboration between scientists and indigenous and local knowledge holders (*91*), which reflects rather well the current efforts to evolve the discussion from CESs to the nonmaterial contributions of nature to people spearheaded by the IPBES (*17*).

Third, and related to the above conceptual evolution from CESs toward nonmaterial NCPs, although this systematic review essentially systematized the literature using CESs as the lens (see Material and Methods for justification), it can provide valuable insights for future studies dealing with the nonmaterial contributions of nature. Despite some challenges in operationalizing CESs (as well as capturing the underlying cultural values), our critical analysis indicates that the relevant literature has been very interdisciplinary (although not always integrative), advancing well beyond the MA framework and simple conceptions of CESs. This observation reflects very well the findings of a recent systematic review about convergences and divergences in the ecosystem services and NCP literature (*18*). Looking at the current efforts toward operationalizing NCPs in empirical research and ecosystem assessments, there is a clear need to integrate effectively this accumulated knowledge base in the CES literature to these emerging research frontiers. If anything, our research shows the very intricate linkages between the nonmaterial contributions of nature and human well-being. We believe that research in this interface should now move beyond defining the start point (i.e., CESs or NCPs) and the end point (i.e., constituents of human well-being and quality of life) to actually explaining the ways that these connections unfold in reality. This will undoubtedly open up synergistic opportunities in understanding the human well-being outcomes of the nonmaterial dimensions of human-nature relations. In this sense, the mechanisms and pathways distilled in this study may bring value to future research efforts seeking to empirically unravel how these relations emerge and operate in different parts of the world.

MATERIALS AND METHODS

Conceptual framework and key concepts

Methodologically, this paper aims to synthesize the literature about the linkages between CESs and human well-being. Many assessment reports (*1*, *6*, *7*), international initiatives (*92*), and individual studies (*3*, *13*) have developed or refined different conceptualizations and typologies of CESs, including the recent evolution of the term as nonmaterial NCPs (*17*). Similarly, many studies have delineated the different constituents of human well-being in relation to the ecosystem services (including CESs) and the benefits people derive from nature (*4*, *93*).

Acknowledging this large diversity of relevant typologies, here, we adopt (and expand) the conceptualizations and typologies of (i) CESs from the MA (*1*) and (ii) constituents of human well-being proposed by Russell *et al.* (*4*). In this sense, the main building blocks of the conceptual framework used in this study are CESs and constituents of human well-being. A pathway is the main analytical category in the qualitative and quantitative analysis outlined below and denotes a connection from a single CES to a single constituent of human well-being. Table 3 defines the concepts, and Fig. 5 provides a conceptual figure.

We adopt the MA's conceptualization and typology of CESs, as, despite its criticisms (*94*, *95*), it has a long history shaping much of the academic literature on human-nature relationships, and especially its nonmaterial dimensions (*10*), allowing, at the same time, the integration of knowledge from multiple disciplines. For the purpose of this systematic review, we adopt the full list of CESs included in the MA (*1*), namely, (i) recreation and tourism, (ii) aesthetic value, (iii) religious value, (iv) educational value, (v) cultural heritage value and cultural diversity, (vi) inspiration, (vii) sense of place, (viii) knowledge system, and (ix) social relations. We then complement this initial list with other CESs found in the reviewed documents that are not explicitly delineated in the MA framework but identified as such in the source literature. These fall under the added CES category "others," which includes CESs related to "bequest, intrinsic, and existence value," "biophilia," and "authentic wilderness." Table S2 provides the full list of CESs (and their definitions) considered in this study. Beyond the MA framework, these CES categories reflect very well the main examples provided for nonmaterial contributions of nature in the IPBES conceptual framework (*96*).

Similar to CESs, human well-being is a broad and contested term that has been interpreted in various ways without a commonly agreed definition (*4*, *93*). At a generalized level, human well-being can be perceived as a synergistic and multidimensional concept that encapsulates multiple constituents, which, when combined, characterize the positive state of individuals (see Table 3) (*4*). Although the concept of human well-being has drawn the attention of policy-makers, researchers, and practitioners globally, there is insufficient and very fragmented knowledge within the literature on how it is linked with the natural environment and the ecosystem services it provides (*93*).

In our systematic review, we use 11 constituents of human well-being, most of which are adopted from Russel *et al.* (*4*). The constituents of human well-being considered in this study include (i) physical health; (ii) mental health; (iii) spirituality; (iv) certainty, sense of control, and security; (v) learning and capacity; (vi) inspiration and fulfillment of imagination; (vii) identity and autonomy; (viii) connectedness and belonging; (ix) subjective well-being; (x) cultural fulfillment; and (xi) economic well-being.

We need to point that although we have used these conceptualizations and typologies of CESs and constituents of human well-being to develop the conceptual framework of the systematic review (Fig. 5), we have not limited the review to the studies that only used these explicitly. For example, for CESs, we do not only review studies using the MA terminology/typology but include studies that have adopted different terminologies/typologies, e.g., IPBES, Common International Classification of Ecosystem Services (CICES), and The Economics of Ecosystems and Biodiversity (TEEB) (see the "Literature identification and selection" section below). Acknowledging the slight differences among terminologies (i.e., nonmaterial NCPs for the IPBES versus CESs for the MA) (*17*), we choose the framing of CESs over other terms such as NCPs. This is because the overwhelming majority of the publications considered in this

systematic review have used the CES terminology. This facilitates data extraction and reduces judgments from the side of the authors, increasing the accuracy of data elicitation and coding (see below). Similarly, we acknowledge that the current frameworks of the constituents of human well-being are imperfect and that there are some blurry distinctions among them (*4*).

Considering the above, this review does not seek to present an argument on the accuracy of the adopted typologies but instead focuses on covering all relevant studies using different terminologies/typologies. This is consciously done to ensure the widest possible capture of studies to elicit the linkages between CESs and human well-being. In this regard, our adoption of certain conceptual frameworks does not seek to imply the superiority of the one over the other but their functionality for data elicitation within this review.

Literature identification and selection

For this systematic review, we identified peer-reviewed literature that reports how CESs contribute to human well-being, both in quantitative or qualitative terms. We identified the literature though Elsevier Scopus and ISI web of Science Core Collection. We used three categories of search words that were guided by the conceptual framework presented above. The three levels reflected (i) ecosystems or ecosystem services, (ii) specific CESs, and (iii) human well-being or quality of life. The specific keywords are ("Ecosystem*" OR "Ecosystem service*" OR "social-ecological system*" OR "Nature's contribution*") AND ("cultural ecosystem service*" OR "aesthetic*" OR "recreation*" OR "spiritual*" OR "inspiration*" OR "place attachment" OR "social relation*" OR "knowledge system" OR "sense of place" OR "educational value*" OR "Nonmaterial nature's contribution*") AND ("Quality of life" OR "wellbeing" OR "human needs" OR "well-being").

The literature search was conducted for the study title, abstract, and keywords and was limited to peer-reviewed journal articles in English. The search was performed in July 2020 with no restriction on the publication time frame. To ensure the quality, we followed the PRISMA principles for systematic reviews (*97*).

In total, 463 articles were found in Elsevier Scopus, and 251 documents were found in ISI web of Science Core Collection. We then removed duplicates, leaving 502 articles for further screening. Subsequently, two filters were applied. For the first round, the first author read the studies' titles and abstracts to remove nonrelevant literature. For the second round, the remaining articles were downloaded and read by the first author in full to determine whether they met the inclusion criteria below:

1) The study should report cultural services provided by nature or ecosystems (i.e., nonecosystem-related cultural services were excluded).
2) The study should report CES or nonmaterial contributions of nature (i.e., other ecosystem services or material contributions were excluded).
3) The study should be empirical or a review of empirical studies (i.e., conceptual, theoretical, and simulation studies were excluded).
4) The study should report observed changes in human well-being (i.e., studies not mentioning change in well-being were excluded).
5) The study documents should be articles or reviews (i.e., editorials, books, and the proceedings of conferences and meetings were excluded).

Among the 502 documents identified after the search, a total of 356 documents appeared to match the inclusion criteria mentioned above after the first screening round. The first author then read the full text of these 356 documents and identified 302 documents (288 empirical studies and 14 review papers) that were deemed eligible for further analysis. Figure S1 contains the different stages of study selection.

Critical appraisal of the reviewed studies

As systematic reviews draw conclusions based on multiple individual studies, it is necessary to evaluate the reliability of evidence at the level of the individual study (*98*). Here, we adopted a generalized set of appraisal guidelines for ecosystem services and conservation studies (*98*) and created a checklist for assessing the reliability of the evidence contained in each reviewed study. The checklist includes questions related to internal validity in terms of the research aim, data collection, data analysis, results and conclusions, and design-specific aspects (table S3). Each study is then categorized as having "very strong evidence" (score: >75%), "strong evidence" (score: 50 to 74%), "moderate evidence" (score: 25 to 49%), or "weak evidence" (score: <25%). Among the 302 articles, there were 288 empirical studies and 14 review papers. To avoid duplication, we used only the empirical studies for data extraction; thus, the quality appraisal was conducted only for the empirical studies.

Overall, the quality appraisal indicated that 94.4% of all studies included in this systematic review (272 of 288 empirical studies) have very strong evidence, 3.5% (10 studies) have strong evidence, and only one study has weak evidence. The mean value of the quality score across all studies is 83.5%.

To ensure the high quality of the database, while, at the same time, highlighting the diversity of the research landscape, we include in this systematic review the broadest possible range of the studies. Thus, we only removed the single study with weak evidence, with the final database used for the data extraction including 301 studies (of which 287 were empirical studies and 14 review papers). All the papers reviewed in this study were included in Dataset found in the Supplementary Materials.

Coding and metadata extraction

Three broad categories of metadata were extracted from each paper and subsequently used for qualitative and quantitative analysis and visualization. Table S1 shows the variables and coding for metadata extraction.

The first type of metadata reflected the general study characteristics and includes the (i) site location, (ii) publication year, (iii) spatial and temporal scale, (iv) research types and objectives, and (v) the types of stakeholder engagement. For those studies that did not provide actual coordinates, we used Google Maps to extract the longitude and latitude coordinates of the studied sites. We created a heatmap using ArcGIS version 10.5, illustrating the geographical distribution of the study sample.

The second type of metadata focused on the study methodologies and includes information related to (i) data collection tools, (ii) data analysis methods, (iii) research framework, and (iv) the broad academic field. These metadata were used to understand the degree of interdisciplinarity and the evolution of research methodologies over time using visualization tools that illustrate the diversity of the disciplines and fields represented in the reviewed studies.

The third type of metadata formed essentially the central part of the qualitative and quantitative analysis outlined below and relates

Table 3. Definitions of the main concepts and their functionality in the conceptual framework.

Concept	Description	Functionality
CES	The diverse nonmaterial contributions of nature to humans, such as, among others, recreation, spiritual enrichment, cognitive development, social relations, and aesthetic experiences. The conceptual framework contains 10 CESs.	Main concept. CESs follow the MA (*1*) framework expanded through the literature review.
Human well-being	A synergistic and multidimensional concept consisting of multiple constituents, which, when combined, characterize the positive state of individuals. The conceptual framework contains 11 constituents of human well-being.	Main concept. Basis is the MA (*1*) framework and Russel *et al.* (*4*).
Pathway	The linkage through which the provision or change in a single CES affects a single constituent of human well-being. We find 227 individual pathways that, because of similarity, are subsequently grouped to 68 aggregated pathways following qualitative analysis.	Main unit of analysis. Outcome of iterative qualitative analysis.
Channel of interaction	The different ways in which people consciously and unconsciously engage with ecosystems and experience their benefits/disbenefits. We identify four channels of interaction following qualitative analysis.	Analytical construct. Outcome of qualitative analysis.
Mechanism	Some of the pathways linking different CESs with different human well-being constituents manifest in relatively similar ways in how they affect human well-being (i.e. nature and functions of pathways). We identify 16 types of mechanisms following qualitative analysis.	Analytical construct. Outcome of qualitative analysis.
Assemblage	Some pathways tend to interact and link a specific set of CESs and contribute to a specific set of human well-being constituents via some explicit combination of mechanisms. Inherent in assemblages are potential synergies and trade-offs that move beyond the individual effects of single CES via single pathways to a single constituent of human well-being. We identify five assemblages following quantitative analysis.	Analytical construct. Outcome of quantitative analysis.

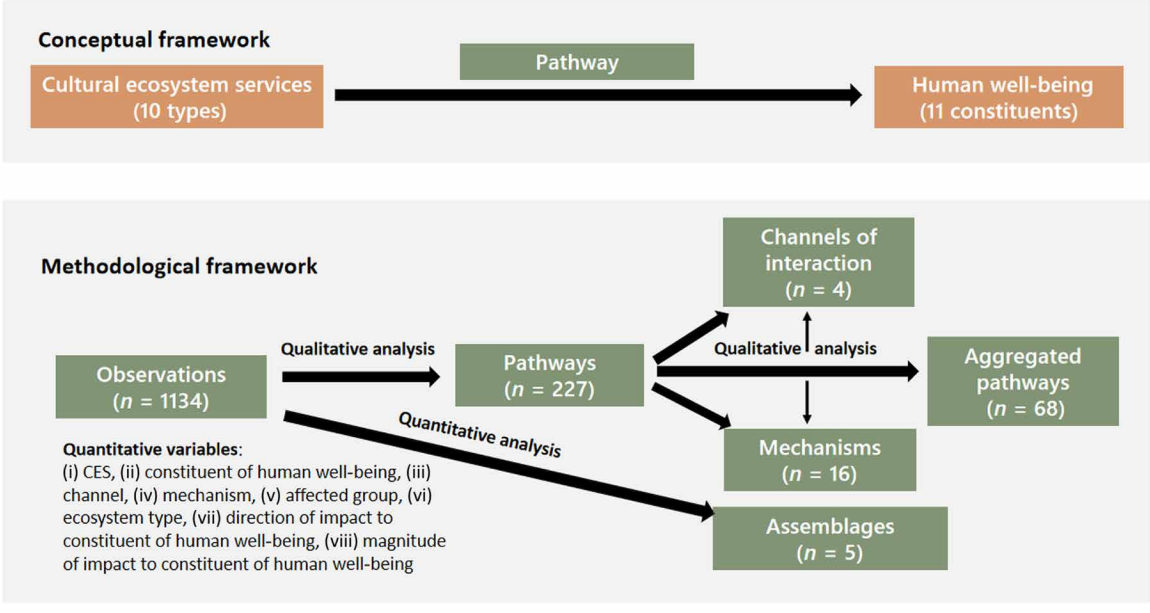

Fig. 5. Connections of the main elements used in this systematic review.

to the linkages between CESs and human well-being (see Fig. 5). Data extraction was guided by various considerations related to (i) type of ecosystem, (ii) type of CESs, (iii) observed changes in CES provision, (iv) reason for change in CES provision, (v) affected group(s), (vi) constituents of human well-being, (vii) direction of the impact on human well-being, (viii) magnitude of the impact on human well-being, (ix) outcome of the impact, and (x) description of the linkage in open text.

The study variables are both closed-ended (i.e., using coded ranges) and open-ended (i.e., using narrative answers). The former

facilitates quantitative categorical analysis, while the latter facilitates the narrative for qualitative content analysis (Fig. 5). Observations of the linkages between CESs and human well-being were extracted only from the empirical studies and not from the review papers in the authors' database (see above). The review studies were only used to facilitate a better understanding of the linkages between CESs and human well-being and for improving the conceptual framework. They were not used for extracting empirical data for the analysis.

From the 287 empirical studies contenting very strong or strong evidence (see above), the authors identified 1134 observations linking a single CES to a single constituent of human well-being. These observations were categorized following the approach outlined in the next section. The elicitation of the metadata was performed by the first author, in close consultation with the second author on a case-by-case basis in case of inconsistencies or emerging new categories. This was to allow for the consistent elicitation of the metadata while, at the same time, ensuring an added lens for challenging cases.

Elicitation of pathways and mechanisms

A relational content analysis was conducted for the 1134 observations to identify the characteristics of the linkages between different CESs and constituents of human well-being. The relational analysis enabled us explore the relationships between the concepts and identify major themes and patterns in the reviewed literature (*99*). Inductive coding was applied to allow us capture new concepts and narratives as emerging from the data itself. Figure S2 shows the flowchart of data analysis. Overall, we conducted two coding iterations to ensure that all emergent themes were consistently captured and reflected in the final dataset.

During the first coding, the 1134 observations were systematized in 227 pathways each of which denotes a connection between a single CES and a single constituent of human well-being (Fig. 5 and Table 3). When looking critically these 227 unique pathways, we observed some commonalities among them in terms of (i) the ways people consciously and unconsciously engage with ecosystems and experience their benefits/disbenefits and (ii) the processes through which these interactions contribute to human well-being. The former we call "channels of interaction," and we identified four in total, while the latter we call "mechanisms" and we identified 16 in total (Fig. 5 and Table 3). In this sense, channels of interaction and mechanisms are two different analytical categories/constructs emerging from the critical analysis of the 227 unique pathways. Of the two, the concept of the mechanism is the most important outcome of the qualitative analysis and is thus the main focus in Results and Discussion. Of the 16 identified mechanisms, 6 were adapted from another study (*5*), and 10 were defined by the authors following the qualitative analysis outlined above.

We acknowledge that some individual pathways can be mediated by different channels of interaction and mechanisms, as they have strong cultural and well-being undertones in specific contexts. Anticipating the possibility of these interactions and to avoid extracting the data in the wrong manner, we coded and treated these pathways as separate observations if there was such evidence in the underlying literature. This required an iterative coding process, which, beyond capturing these interactions, also tried to avoid overlapping to the extent possible.

During the second coding, we used these four channels of interaction and 16 mechanisms to regroup the 227 initial individual pathways into 68 aggregate pathways that share similar characteristics in how they manifest and affect human well-being. These 68 pathways are explained in tables S12 to 14 and include 45 pathways that have a positive effect on human well-being and 23 that have a negative effect. Of the 23 pathways with negative effect, 17 are associated with CES degradation/loss and 6 are associated with ecosystem disservices.

We view CES degradation as the process through which natural and anthropogenic drivers of ecosystem change disrupt the provision of individual or multiple CESs, having detrimental impact on human well-being (*21*, *52*, *100*–*103*). Conversely, the disservices reflect the negative human well-being outcomes from landscape elements developed/managed either solely or partly for the provision of CESs. The negative outcomes can be related to (i) the function of the landscape element itself (e.g., aggressive behavior of some species finding habitat in landscape elements in urban parks used for recreation) (*50*) or (ii) the mismanagement of the landscape element (e.g., feeling of anxiety that some people get from unruly natural elements such as thick trees in urban parks that might be used, among others, for illegal activities) (*22*). Although, to the best of our knowledge, there is no clear definition of disservices in the context of CESs (*20*), the abovementioned definition reflects rather well that of ecosystem disservices (*104*).

Last, we used this typology of mechanisms and channels of interaction to recode the entire dataset of the 1134 observations. The final dataset contained only categorical variables, which were then used for further quantitative data analysis and visualization (see the "Identification of assemblages" section below). We used alluvial diagrams to visualize the frequency of the mechanisms documented in the reviewed studies.

Quantification of CES effects on human well-being

The different studies included in this meta-analysis used rather different quantitative and qualitative measures to convey the contribution of CESs (or their change) to human well-being. Thus, it was not possible to conduct a proper meta-analysis. Instead, we used a semiquantitative normalization approach to enabling us to compare the contribution of CESs to human well-being between studies. This normalization approach relied on expert judgment and followed the process proposed in a recent meta-analysis on climate change adaptation (*105*).

In summary, the criteria used for the normalization were the magnitude and direction of the impacts. The direction of impact was coded as (i) positive, (ii) two-way, (iii) negative, and (iv) not concluded. The magnitude was designated as (i) high negative impact (score = −2), (ii) low negative impact (score = −1), (iii) no substantial effect (score = 0), (iv) low positive impact (score = +1), and (v) high positive impact (score = +2).

The data for the magnitude of impact (score of −2 to +2) were extracted in two steps. First, this came from the text of each study if it was explicitly indicated whether the impacts are high or low as perceived by study participants. Second, for the studies that did not clearly articulate the impact magnitude, we used expert judgment to provide the scores using a series of criteria, namely, depth, scale, and speed (table S11) (*105*). Any observation that met at least one of the conditions for high depth, scope or speed was classified as a high-magnitude impact.

After calculating the impact score for each observation, we grouped together the observations belonging to the same pathway linking a particular CES to a particular constituent of well-being.

Three matrix heatmaps were produced to show (i) the average impact scores for these mechanisms and (ii) the frequency of their presence in the reviewed studies.

Identification of assemblages

We performed LCA to identify possible interactions between analytical categories. LCA is a statistical tool that allows for the analysis of multivariate categorical data to identify the latent classes based on similar patterns (*106*). In this study, we used LCA to identify the assemblages through unobserved or "latent" classes (*107*). For each of the 1134 observations, we used eight unweighted variables as elicited from the review and qualitative analysis outlined above. These included the (i) type of ecosystem, (ii) type of CESs, (iii) channel of interaction, (iv) affected group, (v) constituent of human well-being, (vi) type of mechanism, (vii) direction of impact to the constituent of human well-being, and (viii) magnitude of impact to the constituent of human well-being. Table S1 provides the actual codes of these variables.

For the analysis, we used the open access PoLCA R package. We conducted the analysis for up to six classes, re-estimating the model until identifying the maximum likelihood solution. The Bayesian information criteria (BIC) were used to determine the appropriate number of classes to select. Detailed information of the BIC, sensitivity, specificity, and accuracy tests can be found in table S8. The general patterns and characteristics of each class were drawn to characterize the underlying assemblages, denoting interactions between analytical categories in terms of synergies and trade-offs.

We must point here that we introduce this notion of assemblages, as CESs (and the pathways through which they contribute to human well-being) also tend to interact with each other in complex ways (Fig. 5). With the term assemblages, we refer to subsets of the 227 identified pathways linking CESs and well-being that appear significantly related and interactive. Each assemblage tends to contain a set of pathways that likely link a specific set of CESs and contribute to a specific set of human well-being constituents via some explicit mechanisms with some potential synergies or trade-offs. Synergies refer to situations where the delivery of multiple CESs is enhanced simultaneously having reinforcing effects to multiple constituents of human well-being (*108*). Trade-offs refer to situations where the delivery of one CES comes at the cost of another CES, which consequently affects positively some constituents of human well-being while affecting negatively others (*108*, *109*). We loosely adopt this concept of assemblages from philosophy (*87*) to emphasize the complexity and the relationship between the part (i.e., single CES, constituent of human well-being, and pathway) and the whole (i.e., assemblage of CES, human well-being, and pathways). This is rooted in our understanding that while a single CES via a single pathway can influence autonomously human well-being, when these interact in the assembled whole, they create synergies, trade-offs, and a dynamic whole that should be understood if we are to shed light at the interface of CESs and human well-being.

We performed an MCA to supplement the results of the LCA and to explore further the trade-offs and synergies among specific sets of variables. The MCA method could be seen as a generalization of the principle components analysis when the analyzed variables are categorical rather than quantitative (*110*), as is the case for our dataset. Through the MCA, we produced plots that summarize and display the relationships between categorical variables by calculating the chi-square distance between the categories of the variables and individuals (*111*). We conducted the MCA with subsets of variables to investigate a more explicit correspondence among ecosystems, users, and their well-being.

For all analyses, we presented and interpreted the first two dimensions as the eigenvalues decrease regularly with small difference after the third dimension (*110*). We filtered results by selecting variable categories with higher contributions to a given dimension, which exceeded the expected average value. The MCA and related visualizations were performed with the FactoMineR packages in R software (*112*).

Challenges and limitations

Despite its extensive focus and multidimensional understanding of the human well-being and the nonmaterial dimensions of nature-human relations, our systematic review has a series of limitations. These include the (i) omission of evidence from grey literature, (ii) keyword selection, (iii) possible overlapping between some analytical categories, (iv) quantification method and analysis of synergies/trade-offs, and (v) publication bias.

Regarding (i), our systematic review only included peer-reviewed literature and excluded gray literature. The authors consciously made this decision to ensure the reliability and reproducibility of the results. We are aware that a large fraction of the documents reporting the benefits that people obtain from ecosystems are not peer-reviewed journal papers. This is partly because practitioners and government agencies that implement relevant projects are less likely to write academic papers about their actions. Furthermore, most of the relevant knowledge linking CESs and human well-being from indigenous and local communities is not found in peer-reviewed papers (*12*) despite its importance for understanding human-nature relations (*89*). Thus, while this systematic review can indicate the current scientific evidence about the multidimension linkages between CESs and human well-being, it should not be taken as the totality of the evidence about these linkages.

Regarding (ii), although this review uses a wide range of keywords, these terms were confined to reflect the concepts of CESs and human well-being as found in the broad fields of ecosystem services and biodiversity conservation. Thus, it was not possible to include all possible keywords related to possible constituents of human well-being or the interaction between humans and nature as used in other fields and disciplines such as sociology (*113*) and psychology (*114*). With that in mind, the authors carefully considered and refined all search terms based on the prevailing terminologies in the field. Although we believe that the search terms allow for the very good identification of the research landscape and related trends at the interface of CESs and human well-being, we also acknowledge that the keyword selection might have possibly underrepresented literature outside the fields of ecosystem services and biodiversity conservation.

Regarding (iii), we acknowledge the possible overlapping in the definitions of some of the mechanisms and channels of interaction mediating the linkages between CESs and human well-being (Table 1). Such an example is the possible overlapping among the cognitive, creative, and evolutive mechanisms. The core component of the cognitive mechanism in relation to human well-being is the benefits obtained through knowledge generation via engagement with nature (Table 1). However, arguably, knowledge can also be linked to some parts of the creative mechanism that generates human well-being benefits through the experience of new and original situations that inspire artistic work, aesthetic appreciation, creativity,

and freedom via interactions with nature (Table 1). Similarly, knowledge can relate to the evolutive mechanism that denotes human well-being benefits through the gradual change of people's personality, moods, feelings, perceptions, behavior, values, and belief system over time via interactions with nature (Table 1). There are some possibilities of overlapping among the four channels of interaction. For example, via the form channel, the visual features of nature (e.g., sea, cliffs, and trees) can inspire spiritual meanings and enlightenment to people. However, arguably, this can also be part of the spiritual practices channel. We have attempted to avoid such overlapping to the extent possible through the delineation of these analytical categories through an iterative process that sometimes divided or joined analytical categories subject to overlapping. We selected very carefully the language in the definitions of the channels of interaction and mechanism to ensure that their distinctions are generally clear and rational. However, we believe that some overlapping might occur as some of these analytical categories reflect human feelings, emotions, and inner processes, which cannot be delineate fully, as a rich literature in the fields of psychology (*115*) and environmental psychology (*116*) has shown.

Regarding (iv), there are some limitations in the normalization approach and the statistical methods used for the quantitative analysis. The quantification of the impacts of CESs (and their change) on human well-being may oversimplify the relationship between humans and nature. We only focused on the positive and negative contributions of CESs to human well-being but did not consider complex two-way impacts or feedback loops. Some studies have depicted these positive or negative human-nature feedback loops that reinforce or balance the impacts of nature on humans, and vice versa (*117*, *118*). For example, there is evidence suggesting that people with stronger inclination toward nature interact with green spaces and biodiversity more intensively, which, in turn, increases their attachment and inclination toward nature (*40*). Because of the complexity of the quantification, these feedback loops were not captured in our analysis. Last, the normalization approach used for quantifying the effects of CESs on human well-being was based on expert judgment. Although we followed an established approach (*105*) and very clear criteria (table S11), the fact remains that this expert approach may introduce certain uncertainties and biases, which should be kept in mind when reading and generalizing our findings.

Regarding (v), we acknowledge the possibility of publication bias in the reviewed studies. This refers to the selective publication of studies based on the magnitude and direction of the results and/or the areas of interest of the authors (*61*). In qualitative research, factors that may lead to publication bias include findings that are against current belief and prevailing value systems, findings that are not in line with research funding, or findings that are perceived to be unpopular among decision-makers (*62*). However, unlike the meta-analyses of quantitative research where publication bias can be formally tested, to the best of our knowledge, there are no robust methods for detecting these biases in meta-syntheses of qualitative research similar to ours (*62*). This inability to detect possible publication bias has been a recurring criticism in meta-syntheses of qualitative research (*62*) and should be taken into consideration when generalizing our results.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at https://science.org/doi/10.1126/sciadv.abn8042

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