Penn et al.
CABI One Health (2024) 3:1
https://doi.org/10.1079/cabionehealth.2024.0006

CABI One Health

REVIEW

OPEN ACCESS

General ecosystem health indicators – A scoping review

Gillian Penn[1], Luís Pedro Carmo[2,3], Elena Boriani[4,3], Michelle Gallagher[1], Christi Piper[5], John Berezowski[6,3], Barry J. McMahon[7,3], Thomas Jaenisch[1,3]*

Abstract

Background: Assessing the health status of a natural ecosystem is important across all natural fields of study. Ecologists have discussed and used a variety of terms to describe the health of ecosystems, yet consistent use or adoption of a set of terms has not been established. A common vernacular is necessary to convey the status of an ecosystem to any audience, particularly to influence policy. The purpose of this review is to explore the terms associated with general ecosystem health metrics. *Methods:* A scoping literature review was performed within three databases, using a search string informed by place, interest, and outcome, a modified PICO (Place, Interest, Comparison, Outcome) structure. A three-stage review process was conducted, at title only, abstract, and full text, respectively. The second and third stages were conducted by two independent reviewers. Key ecosystem health indicator terms were extracted from the final article list and categorized into composite terms or individual indicators for the assessment of general ecosystem health. *Results:* The initial search yielded 4733 articles, of which 701 were included for screening at the abstract level. A subsequent full-text review of 118 peer-reviewed articles found 95 distinct indicators and 109 multi-metric index systems that qualify under the study search criteria from a total of 64 scientific journals over 20 years. *Conclusions:* We found a substantial diversity of ecological health terminologies and concepts, reflecting various scientific traditions and disciplines, which highlight not only the necessity to standardize the language for communication but also the opportunity for cross-fertilization. Single distinct indicators were as frequently used as multi-metric index systems. For academic purposes, this raises the question of how underlying value statements and ethical dimensions differ between integrated health terminologies and concepts. For advocacy, we emphasize the need of a consistent core terminology to improve the effectiveness of our messaging.

One Health impact statement

The impact of this work is focused on the systematic investigation of the terminology used for integrated health assessment. We carried out a scoping review of integrated ecosystem health terminology across disciplines, including 64 different journals from 2002 to 2022. This work has the potential to improve actionable policies in favor of environmental and ecosystem protection and remediation. This landscape analysis is a step toward the creation of a meaningful vocabulary of ecosystem health indicators, including how terminology descriptors and their use can be understood by different stakeholders across disciplines, with implications on the dimensions of implicit intrinsic and extrinsic value statements. By having a dedicated terminology associated with the health or disease of ecosystems in general, systems can be compared, and a simplified message can be conveyed, thereby enhancing not only the understanding of the importance of the health of ecosystems but also improving the ways in which we promote ecological health.

Keywords: ecological system, environmental health, ecological indices, eco-health, One Health, indicator, environmental policy

Affiliations: [1]Center for Global Health, School of Public Health, University of Colorado Anschutz Medical Campus, 13001 East 17th Pl, Aurora, CO 80045; [2]Norwegian Veterinary Institute, Elizabeth Stephansens Vei 1, 1433 Ås, Norway; [3]Network for Ecohealth and One Health (NEOH, European Chapter of Ecohealth International); [4]EB Consult, Bøssemagergade 80, 3150 Denmark; [5]Strauss Health Sciences Library, University of Colorado Anschutz Medical Campus, Aurora, CO; [6]Scotland's Rural College, 10 Inverness Campus, IV2 5NA Inverness, UK; [7]UCD School of Agriculture and Food Science, University College Dublin, Ireland

*Corresponding Author: Thomas Jaenisch. Email: thomas.jaenisch@cuanschutz.edu

Submitted: 04 November 2023. Accepted: 16 January 2024. Published: 12 February 2024

Introduction

RATIONALE

Across various disciplines, there is little argument on the importance of dynamic ecosystems, both connected to and separate from humanity. Greater than the sum of its parts, effects can ripple and cascade affecting downstream health of the environment itself, human health, and services available in that system (Fowler *et al*., 2013). Thus, the health of natural ecosystems is important to public and individual health by affecting all aspects of quality of life, including contribution to a positive sense of wellbeing or spiritual wellness (Orradottir and Aegisdottir, 2015; IPBES, 2019). The importance of healthy ecosystems for human health is exemplified through fertile soil for agriculture, robust forests for carbon cycling, clean water for sanitation, drinking and irrigation, and safe air quality (Orradottir and Aegisdottir, 2015; Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [IPBES], 2019), but what are the indicators of health that can be used generally across these systems? Researchers have attempted to gather indicators that can assess ecosystem health *across* scale (i.e., large forest or smaller riverbed) (Jorgensen *et al*., 2010; Rapport and Hilden, 2013; Bradshaw *et al*., 2020), but there continues to be little agreement in the literature as to what constitutes human or environmental "health."

Despite decades of research and use, the definition of health continues to be mercurial, often changing with the authors' worldview and geographical location (i.e., Global North vs South), research goals, scope of application, and cultural perspectives (Ereshefsky, 2009; Leonardi, 2018). While definitions continue to be debated, medicine has generally agreed to the helpful use of vital signs to provide some information on the physiological state of the human (and animal). Ecologists have followed with Rapport asking in 1990s (and the question remains largely unanswered) if we extend that familiar framework of vital signs in medicine as indicators of overall health status to ecosystem health assessments (Rapport, 1994). Further, the authors recognize that these frameworks are Eurocentric in foundation and often fail to recognize the extensive knowledge (contribution) originally developed and refined by Indigenous peoples, cultures, and traditions.

Here we explored the terminological landscape of integrated ecosystem health indicators or indices of health (across systems, beyond human health). We defined an indicator as a term or phrase representing a gauge, measurement, or signal that describes certain existing environmental conditions (Collins Dictionary, 2022); an index refers to a list or collection of related indicators. Andres *et al*. (2021) noted that indicators should be meaningful and standardized to ensure comparability and measurability while Logan *et al*. (2020) applied the SMART (Simple, Measurable, Achievable, Realistic, Time) principle to assess the utility of an indicator or index system. While these rules provide goals to strive toward, we question whether these benchmarks are achievable for useful ecological or environmental indicators.

To improve the health of the ecosystems we are dependent upon, we need to measure their health status and monitor our environmental impacts (Niemi and McDonald, 2004). This requires useful measurement tools and a common vocabulary of indicator terms. Niemi and McDonald (2004) discuss the use of ecological indicators as a method to evaluate the condition of or define the cause of, environmental change. Ecosystem health indicators that are generalizable across ecosystem types are of unique importance, as they allow us to conceptualize the same health to evaluate similar and dissimilar systems. Currently, utilized terms have been in the literature since the 1990s and include: vigor, organization, productivity, and resilience (Rapport, 1992; Rapport, 1994; Costanza and Mageau, 1999; Rapport, 2007; Rapport and Hilden 2013). There is considerable literature on general ecosystem health indicators that are appropriate for use across a range of systems exploring terms and indices such as biodiversity, including The Living Planet Index (underpinned by the ecosystem health indicator biodiversity) (World Wildlife Fund [WWF], 2020), ecosystem services, productivity, and integrity, although the definitions can vary and underlying values are complex (Parrott, 2010; Kandziora *et al*., 2013; Roche and Campagne, 2017; Equihua *et al*., 2020). Figure 1 provides a visual example of the conceivable complexity through an exploration of "ecosystem services" (Kandziora *et al*., 2013). With the variety of indicator definitions, many of these terms are often considered umbrella terms, operating as a class rather than as an individual indicator. Sometimes there are precise sublevel descriptor metrics included, although they may be omitted or tend toward being exclusively system-specific. A cursory literature search for ecosystem health indicators results in system-specific indicators or index matrices, often validated for only one type of environment or ecosystem (Rapport, 1992; Parrott, 2010; Environmental Protection Agency [EPA], 2021). For example, soil chemical content at a specific site and water turbidity are useful in only some applications, and other composite indices such as the Air Quality Index, explicitly focus on one part of a system (EPA, 2021).

Here we provide the rationale behind the obligation to encourage those in the field (biologists, ecologists, conservationists, researchers) to utilize a certain vocabulary when relaying information to those outside of the field, i.e., policy makers, public health practitioners, members of the government, legislatures, environmental and conservation non-governmental organizations, etc. Rapport and Hilden (2013) argue the necessity to expand

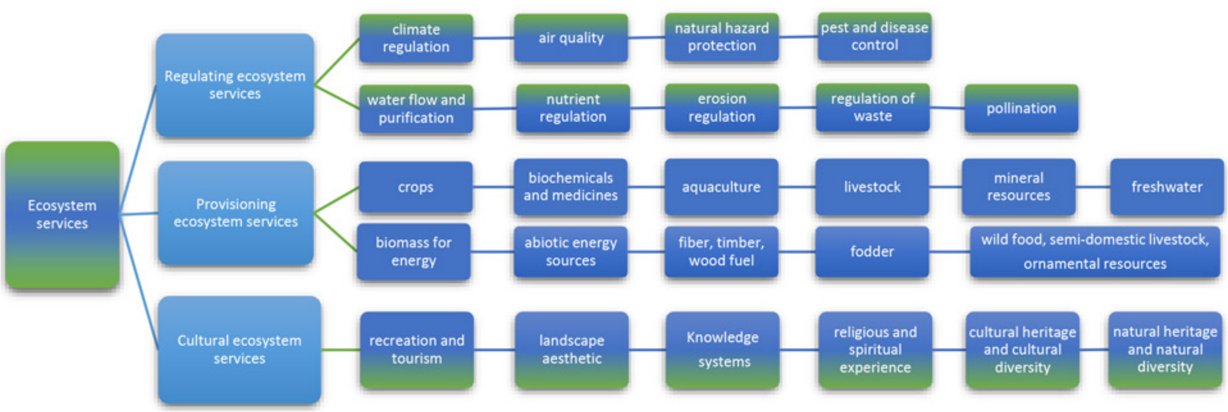

Fig. 1. Original figure, adapted from Kandziora *et al*. (2013) as an example of complex components and underlying values/ assumptions of proponent ecosystem health indicator terms. Ecosystem service is a commonly used umbrella term or high-level indicator of ecosystem health. Kandziora *et al*. (2013) extracted and explored this function and subsequent terms in relation to human-environmental system indicators, describing three subcategories and providing examples of each as shown in the diagram.

the functionality of ecosystem health indicators beyond only the “theory” category: the use of the indicators needs to be fleshed out and made “instrumental” to policy drivers in a way that makes them less abstract and more actionable. This future investigation could provide a vocabulary of indicator terms to be used for difficult-to-measure metrics of general ecosystem health. These researched indicators can then be used throughout policy discourse and used in predictive studies for potential ecosystem clean-up or evaluative studies. Ultimately, we aim that this research will be a base for effective advances to be made that are actionable and for the benefit of environmental health and sustainability.

OBJECTIVE OF THE REVIEW

The objective of this scoping literature review is to explore the landscape of general ecosystem health indicators.

We ask: What are the commonly used ecosystem health indicator terms in the literature over the last 20 years? Are there identifiable knowledge gaps or patterns that prevent interdisciplinary collaboration?

Methods

We used the PRISMA-ScR for the reporting of this manuscript (Page *et al*., 2021).

STAKEHOLDER ENGAGEMENT

In researching and writing the current article, we elicited input from subject matter experts, drawing on the Network for EcoHealth and One Health the European Chapter of Ecohealth International (Network for EcoHealth and One Health [NEOH], 2020). This group had initially formed as the Network for Evaluation of One Health, COST Action TD1404, funded by the European Commission, and then transitioned to become the Network for EcoHealth and One Health (NEOH, 2020). Members of this group were involved in the inception of this question and collaborated throughout the development of this submission.

PROTOCOL AND REGISTRATION

The search protocol is an original unregistered protocol available in the “Supplementary Materials: Additional File 1”.

ELIGIBILITY CRITERIA

A comprehensive review of the literature was conducted to create a catalog of indicator terms for an integrated approach to ecosystem health that are generalizable and appropriate for a variety of ecosystems. The concepts were defined using a modified PICO structure, utilizing Place, Interest, Outcome, (PIO) framed around the primary objective of the research: compile a collection of words or terms that are in the literature that can be used to assess the general health of an ecological system. Search terms and the PIO headings used are included in Table 1 including the potential outcome descriptor that may be positive or negative, recognizing that health assessment may encompass negative aspects such as the burden of disease or sickness.

Scoping exercises of iterative search strings with varying strategies, revealed that the majority of articles retrieved were system-specific, meaning the indicator terms used in the article were not generalizable across systems, for example, water-specific terms such as turbidity and oxygen content cannot be used to measure the health of a forest. Because of this, only articles with clearly generalizable descriptors for the “Outcome” terms were included (see Table 1), while those articles retrieved that included system-specific indicator terms were excluded. Additionally, peer-reviewed journal articles were included if they were published from January 1, 2002 to June 8, 2022.

A list of benchmark articles used to test the reliability of the search within the Web of Science is included in the supplementary material at the end of this manuscript (see Supplementary Materials: Additional File 2).

Papers were excluded if they were strictly review articles or if the indicator terms were clearly system-specific and could not be drafted onto other types of ecosystems. Articles that used multi-metric index (MMI) systems with many individual indicators within a system were excluded if more than half could not be potentially transferred to other ecosystems. To explain this further, ecosystem-specific studies were included if the indicator terms were broad enough despite being utilized to assess a specific ecosystem. For example, a study assessing the health of a watershed would be included if it incorporated terms such as integrity, biodiversity, and biomass or excluded if the focus was instead on salinity of the water, planktonic detritus in the soil, or based on numbers of benthic organisms. Further, an MMI system utilizing individual indicators was included if at least half of the indicators were general indicators of health. If instead, most were system-specific (turbidity, salinity, erosion, etc.) and fewer (less than half) were general, the index system was not included in the review.

INFORMATION SOURCES

Relevant publications were identified by searching the following databases with a combination of controlled vocabulary and keywords: CAB Direct (includes CAB Abstracts and CAB Global Health; Last updated June 8, 2022), Web of Science Core Collection (via Clarivate Analytics, including Science Citation Index Expanded and Social Sciences Citation Index, 1974 to present), and Environment Complete (via EBSCO). All searches were run on June 8, 2022.

We limited the search date range from 2002 to 2022. We developed the search initially for Ovid MEDLINE Web of Science and translated it to the other databases. All search strategies can be found in “Supplementary Materials: Additional File 1”. We exported all results to EndNote 20 to remove duplicates.

Table 1. Search terms utilizing PIO [Place, Interest/Indicator, Outcome] process (Modified PICO systematic search process).

System term (Place)	Indicator term (Interest)	Descriptor term for health/ integrity (Outcome)		
Environment*	Indicator*	Biodiversity	Antifragility	Distress
Ecosystem	Indices	Health	“Report Card”	Organization
Biologic*	Marker*	Integrity	Resources	Sickness
Eco-system	Index	Sustainability	“Disease burden”	Productivity
Habitat	Framework	“System Services”	“Burden of disease”	Resilience
Ecologic*		Vitality	“Health status”	“Nutrient Flow”

indicates the base search term for each database, for example, “Biologic” will incorporate all terms that start with “biologic-” such as biological. The use of quotations around the search term asks for the terms to only be used together; the database will not search them independently or in a different order.

SEARCH STRATEGY

An example of the search string is provided below performed in CAB Direct with the other two from Web of Science and Environment Complete databases provided in "Supplementary Materials: Additional File 1". An experienced medical information specialist (CP) designed the comprehensive search strategy for the concepts of ecosystem, health, and indicators. The search was performed at the title and keyword levels (Table 2).

SELECTION OF SOURCES OF EVIDENCE

To increase consistency among reviewers, the two reviewers met to discuss inclusion and exclusion criteria in preparation for the review screening process with several example articles to evaluate together. The two reviewers worked independently to analyze titles, abstracts and then the full text of all publications identified by the search as above for potentially relevant publications (see Figure 2). Disagreements were resolved via consensus and with a third party, where needed.

This search protocol yielded 4733 results, all of which were screened at the title level by the primary author for broad inclusion based on concept definitions. If titles were unclear, the articles were included for further review. In a second step, the selected abstracts were reviewed independently by two screeners (GP, MG) for consistency with the aims of this study. If the abstract did not provide substantial information to determine if the article was consistent with inclusion criteria of the study, it was accepted for full-text review; disagreements were decided by consensus. Those abstracts deemed consistent by the two screeners were moved onto the full-text review stage, where the same two screeners independently reviewed the full text of

Table 2. Search string from one database, CABDirect.

CAB Direct (includes CAB Abstracts and CAB Global Health; Last updated June 8, 2022)		
Search Date: June 8, 2022		
Search No	**Search Strategy**	**Results**
#1	title:(habitat* OR environment* OR ecosystem* OR eco-system* OR biologic* OR ecologic*)	10,0716
#2	((habitat* OR environment* OR ecosystem OR eco-system OR biologic* OR ecologic*) NEAR/3 (health OR integrity OR sustainability OR "system services" OR vitality OR resilience OR productivity OR organization OR sickness OR distress OR "nutrient flow" OR resources OR "disease burden" OR "burden of disease" OR "health status" OR antifragility))	115,989
#3	((habitat* OR environment* OR ecosystem OR eco-system OR biologic* OR ecologic*) NEAR/3 (indicator* OR marker* OR index OR indices OR "report card*"))	51,965
#4	#1 AND #2 AND #3	1315
#5	yr:(2002 TO 2030)	3,641,428
#6	#4 AND #5	1,261

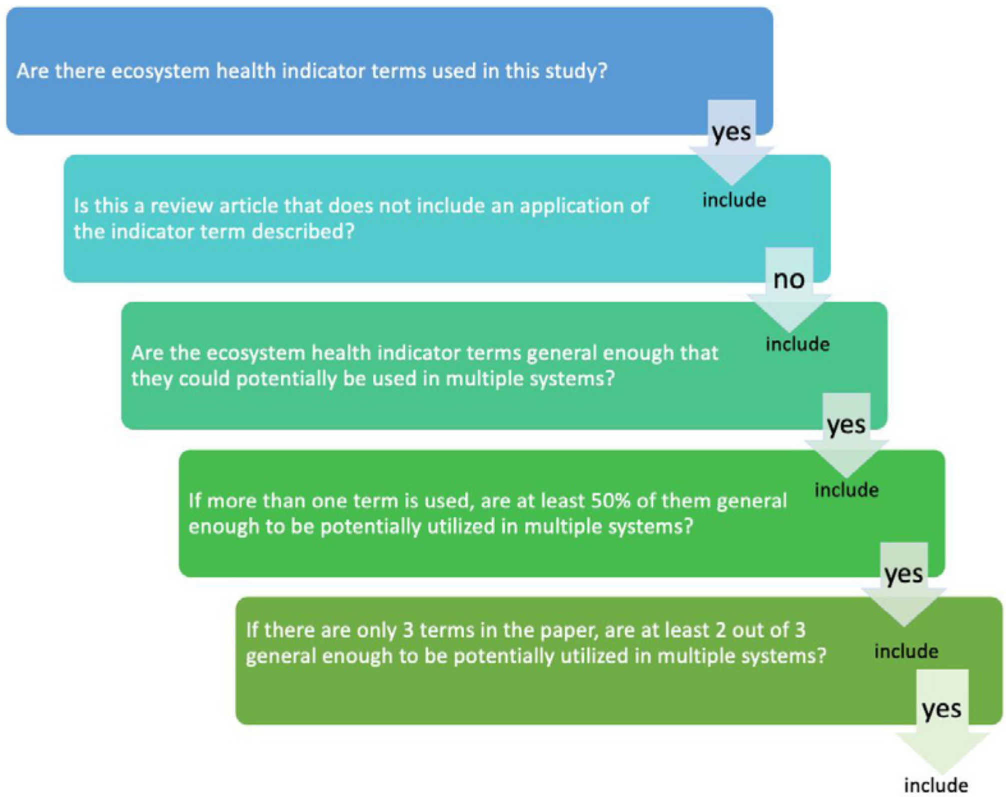

Fig. 2. Inclusion/exclusion criteria questions considered in the review process to determine if the article was to be included or excluded.

retrieved articles against the eligibility criteria. Disagreements were resolved by consensus between the two screeners.

DATA CHARTING

Citations and abstracts were uploaded in Covidence systematic review software (Veritas Health Innovation, Melbourne, Australia. Available at: www.covidence.org).

A data-charting form was developed by the primary author within Covidence for data extraction. The two reviewers independently charted the data and inconsistencies were discussed and resolved between the two reviewers. Once the data chart was established, changes to the information collected were not altered. An example of the data chart can be found in the "Supplementary Materials: Additional File 3".

DATA ITEMS

From the final full-text screening of 304 articles, 118 articles were eligible for data extraction. The articles gathered discussed ecosystem health in broad terms or used generalized terms to describe specific ecosystems. From this list, candidate indicator terms and MMI systems were extracted independently by both reviewers through the Covidence Platform. Discrepancies in terms/indices were few and consensus was reached with discussion between both reviewers (GP & MG).

Data collected from each full-text article at the extraction stage included the following: title, year published, publishing journal, the country where the study was conducted, whether it included individual indicator terms or was an MMI or both, the individual indicator terms used in the study, and the specific MMI used. Additionally, at this stage, we collected whether the study utilized an Index of Biotic or Biologic Integrity (IBI), more information regarding reasoning is provided in the discussion section.

SYNTHESIS OF RESULTS

The studies were individually analyzed and reviewed to extract the indicator terms and MMI's which were then tallied and grouped. The indicator terms were grouped by their base term, for instance, ecosystem integrity and ecological integrity were grouped under "integrity", as shown in Table 3. The data gathered is diagrammatically displayed in the results section of this manuscript visually in diagram (see Fig. 5) showing the 35 most common indicator terms used and with a map depicting the frequency of countries where the studies were performed.

A table with all identified indicator terms and MMIs is provided in the "Supplementary Materials: Additional File 4".

Results

SELECTION OF SOURCE OF EVIDENCE

A total of 6905 papers were gathered from 3 databases: Web of Science (n = 3615), CABDirect (n = 1261), Environment Complete (n = 2029), as shown in Fig. 3. Duplicates were removed resulting in 4733 papers to screen at title level. The remaining 701 papers were screened at abstract level by both reviewers, and 304 articles screened for eligibility at full text. There were 131 studies included in the review with 13 of them removed as they were papers that would be otherwise excluded because they used only the Index of Biologic Integrity or Index of Biotic Integrity (IBI) which are too system-specific. There were 118 studies remaining for data extraction.

CHARACTERISTICS OF SOURCES OF EVIDENCE

The 118 articles that met inclusion criteria for indicator or index extraction were published in 64 different journals and discussed studies from 35 countries. More studies were published in 2021 than any other year (see Fig. 4 for trend line). Most of the studies were performed in China, then the United States, then Brazil, and then Italy (see Fig. 5). The following ranks the articles' frequency per country: China 33, USA 13, Brazil 8, Italy 6, South Korea 5, Russia 4, Spain 3, New Zealand 3, India 3, Global 3, UK 3, The Netherlands 2, Taiwan 2, South Africa 2, Portugal 2, Iran 2, Indonesia 2, Germany 2, France 2, Czech Republic 2, Canada 2, and one each of West Indies, Uruguay, Turkey, Tibet, Switzerland, Mexico, Europe/Eurasia, Cyprus, Colombia, Central Asia, Cameroon, Argentina, and the Arctic.

RESULTS OF INDIVIDUAL SOURCES OF EVIDENCE

See Supplementary Materials: Additional File 3.

SYNTHESIS OF RESULTS

A total of 118 articles were identified for the data extraction portion of this study. Ninety-five individual candidate indicators and 109 MMI systems were extracted, most of which were only used once. The most commonly used indicators were richness, integrity, abundance, biomass, and diversity with varying descriptors (Table 4). For example, of the 23 times that "richness" was used, it was specified as species richness, taxonomic

Table 3. Examples of how indicator terms were tallied and categorized in relation to associated qualifiers.

Example indicator term	Associated qualifier terms found throughout the articles included in data extraction
Richness	species richness, arthropod species richness, taxonomic richness, functional richness
Integrity	ecological integrity, landscape ecological integrity, environmental integrity, ecosystem integrity
Abundance	species abundance, abundance biomass comparison (ABC) curve
Diversity	taxonomic diversity, plant species diversity, functional diversity
Resilience	resilience to disturbance factors, intrinsic resilience, landscape resilience
Ecosystem services	ecosystem service value, ecosystem services demand, ecosystem services supply-demand ratio
Productivity	vegetation productivity, net primary productivity (NPP), ecosystem functioning productivity, total primary production: biomass, total primary production: respiration
Habitat	habitat continuity, habitat diversity, habitat fragmentation, habitat function, habitat heterogeneity, habitat provision, habitat specialists, habitat stress, habitat topographic heterogeneity
Stability	ecological stability, landscape structure stability, vegetation coverage stability, soil food web stability, environmental stability, ecosystem stability
Vulnerability	ecological vulnerability, landscape vulnerability, ecosystem vulnerability

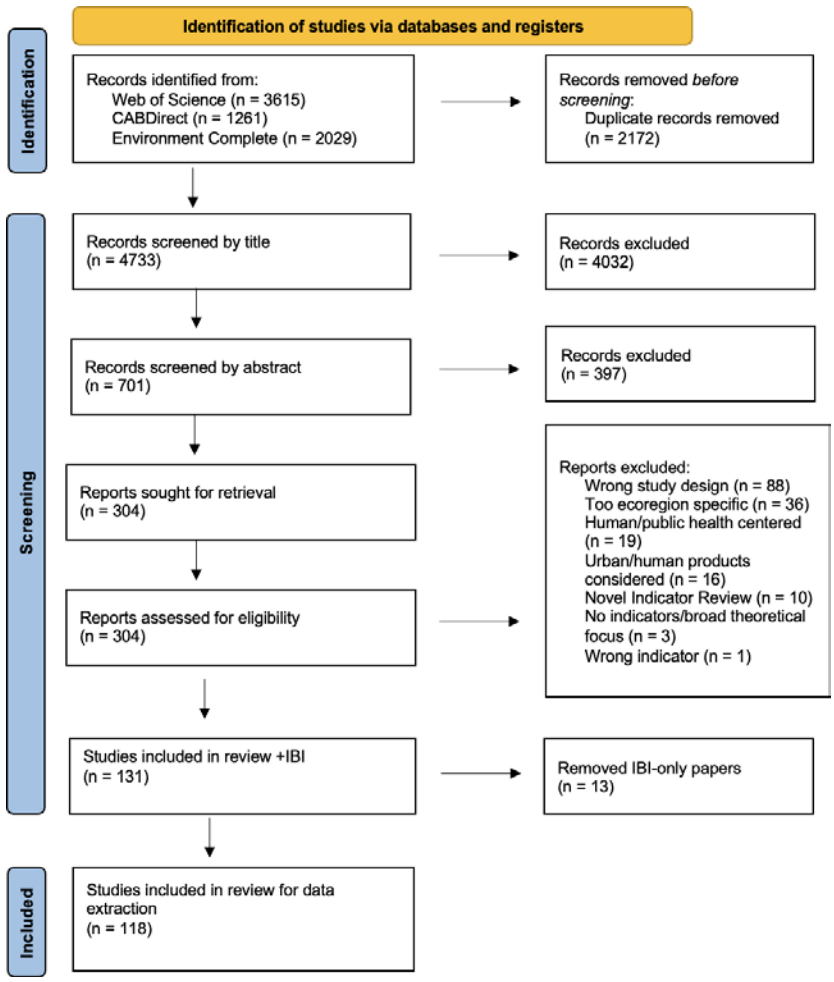

Fig. 3. PRISMA diagram of study identification and screening process. Studies using the index IBI (Index of Biotic or Biologic Integrity) were excluded at the final screening stage and counted separately.

Fig. 4. Dot plot showing the number of studies published per year found in the current research from January 2002 to 8 June 2022.

richness, functional richness, or did not have a qualifier (Table 4). Likewise, the descriptors for “integrity” were as follows: ecological integrity, landscape ecological integrity, environmental integrity, and ecosystem integrity (the latter two occasionally used interchangeably). This pattern is noted across many of the indicators, however, many of the articles did not provide a clear definition of the indicator in use.

A similar convention is found in the evaluation of the MMI systems. Among 81 studies, 109 Index Systems were used for either describing general health across systems or used mechanisms that were non-specific to describe a specific system type. As an example, 14 studies used the Shannon Index, yet it was referred to in several different ways: Shannon Index (1x), Shannon Diversity Index (6x), Shannon Weiner Biodiversity Index (1x), Shannon Weiner Diversity Index (4x), Shannon Weaver Diversity Index (1x), and Shannon-Weiner Index (1x). The most common indices were variations of the Shannon Index, Vulnerability Index, Normalized Differential Vegetation Index, and Qualitative Habitat Evaluation Index.

A proposed future objective of this study is to determine if a set of indicator terms can be created to be used across systems to generally describe their health. If one were to create such a list, these eleven most frequently utilized indicator terms would likely be included: richness, integrity, abundance, biomass, diversity, resilience, biodiversity, ecosystem services value, productivity, habitat, stability, see Fig. 6. Our initial search strategy included some negative indicator outcomes such as the burden of disease, sickness, and distress. While these specific terms were not commonly found in the literature review, others such as (landscape) fragmentation, vulnerability, and disturbance were within the top 35

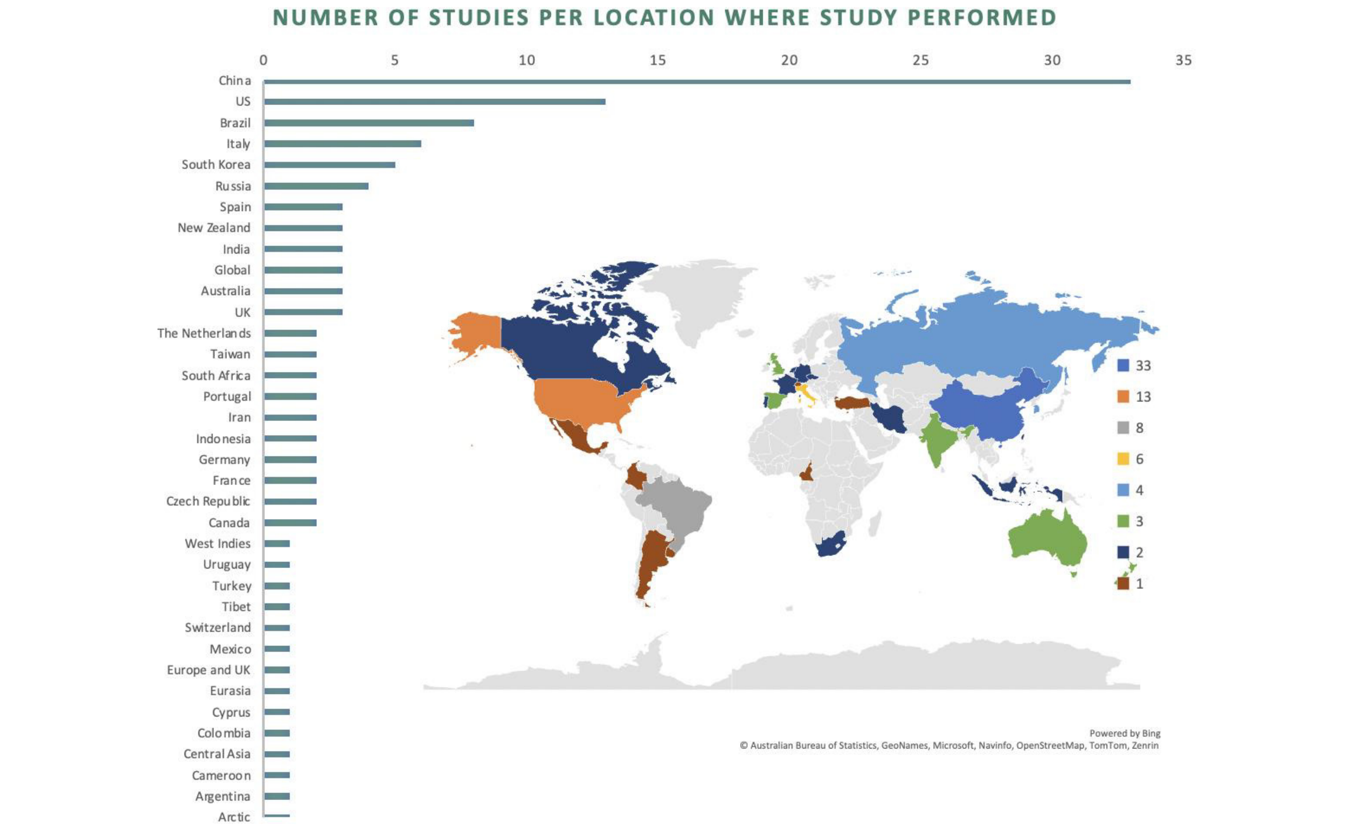

Fig. 5. Plot of country frequency across studies from articles used for data extraction. The 118 articles that were ultimately included for data extraction were from several countries around the world. The numbers on the map indicate the number of studies performed in the country where the research was collected.

Table 4. Results of frequently used indicator terms with their relative associated descriptive qualifiers used in various studies and associated counts tallied throughout the research.

Example indicator term	n	Associated descriptor terms found throughout the articles included in data extraction
Richness	23	11 species richness, 1 arthropod species richness, 9 richness, 1 taxonomic richness, 1 functional richness
Integrity	21	11 ecological integrity, 1 landscape ecological integrity, 3 environmental integrity, 5 ecosystem integrity
Abundance	18	1 species abundance, 1 abundance biomass comparison ABC curve
Biomass	17	
Diversity	16	2 taxonomic diversity, 1 plant species diversity, 1 functional diversity
Resilience	15	1 resilience to disturbance factors, 1 intrinsic resilience, 1 landscape resilience
Biodiversity	14	
Ecosystem services	14	2 ecosystem service value, 1 ecosystem services demand, 1 ecosystem services supply-demand ratio
Productivity	11	1 vegetation productivity, 4 net primary productivity (NPP), 1 ecosystem functioning productivity, 1 total primary production: biomass, 1 total primary production: respiration
Habitat	9	1 habitat continuity, 1 habitat diversity, 1 habitat fragmentation, 1 habitat function, 1 habitat heterogeneity, 1 habitat provision, 1 habitat specialists, 1 habitat stress, 1 habitat topographic heterogeneity
Stability	9	1 ecological stability, 1 landscape structure stability, 1 vegetation coverage stability, 1 soil food web stability, 1 environmental stability, 1 ecosystem stability
Vulnerability	7	5 ecological vulnerability, 1 landscape vulnerability, 1 ecosystem vulnerability

indicators extracted. As noted in Tables 4 and 5, there are a range of descriptors for many of the individual base terms and inconsistent definitions, if any, allowing for only minimally cohesive language in this field. Here we concentrated on only broad (general) indicator terms, acknowledging that a variety of specific and general terms were used in some of the publications screened. Future research would be needed to investigate the reasons why in some instances broad indicator terms were used and in others, specific indicators were preferred. The final 118 papers held little consistency to an explanation on why the research team chose to focus their work with general ecosystem status indicators. Those that did, alluded to previous works by Costanza (vigor, organization, resilience) (Atak and Tonyaloglu, 2020; Pan *et al*., 2021), National or Global environmental health reports or acts such as Intergovernmental Panel on Climate Change (IPCC) or Millennium Ecosystem Assessment (Ausseil *et al*., 2013; Andrés *et al*., 2021), or reference

Fig. 6. Visual depiction of the frequency of the top 35 indicators found in the current study. The more common an indicator, the larger the font on the diagram. Generated using wordclouds.com.

to the importance of regional scale (Ausseil *et al*., 2013; Pan *et al*., 2021). Many papers did not provide an explicit explanation as to why general ecosystem health indicators were chosen for use and therefore was too subjective for consistent extraction. We suggest reasons such as familiarity to proposed/ expected audience (specifically funding), previously accepted terms or metrics, key word-search capture, importance of reference to national or international standards, reports, acts, and importance of scalability.

Discussion

SUMMARY OF EVIDENCE

Ninety-five ecosystem health indicator terms and 109 MMI systems were found by our search strategy. We explicitly tried to capture those studies and indicators that could be used across most ecosystems and tended to err on the side of inclusion. Overall, the variation in the use of the indicators was striking, which often included different qualifiers like environmental integrity, ecological integrity, and ecosystem integrity, again sometimes used interchangeably. Burger (2006) defines an indicator as an "index or measurement endpoint to evaluate the health of a system;" an *environmental* indicator as one that "measures quality in media (water, soil, sediment, air);" and an *ecological* indicator as one that "measures [the] quality of biological component within the broader physical ecosystem," the landscape of the associated definitions was rarely discussed in the articles captured (see Tables 4 and 5). The same phenomenon is seen throughout the use of the index systems with the interchange of environment, ecological, and ecosystem without a precise definition or explanation as to why one was chosen over another. While it is common for researchers and academics to alter and update language with creation of new glossaries every few years, justification of definition or qualifier was rarely provided.

We also found that the majority of indicator terms for integrated health are "positive health indicators" with the exception of vulnerability. As with assessment of human health, the absence of positive health (e.g., disease) is sometimes easier to measure than its presence.

Some of the studies included a loose or general description of the indicators in their studies, specifically excluding a precise definition of the indicator. While evaluating the number of studies that provided a precise definition of the indicator terms was beyond the scope of this review, an example is provided in Table 5 with a comparison of the seven studies that used variations of "vulnerability" as an ecosystem health indicator term. There were several different definitions and descriptions provided for "vulnerability" in these studies (see Table 5).

These substantial heterogeneities suggest that biologists and ecologists have struggled with effectively measuring and defining what ecosystem health means, underpinned by O'Brien *et al*. (2016) and others who stated that it is unrealistic to generate an over-arching definition of environmental health due to the varied environments and scenarios it describes. As early as the 1990s publications have admitted a lack of consensus on how to define ecosystem health (Suter, 1993; Rapport, 1994). Suter (1993) extends this argument and asserts that the use of "ecosystem health" should be avoided due to the inaccuracies in the assumptions around the use of the metaphor. An alternative approach would be to make assessments on a system-by-system basis (Jorgensen *et al*., 2010).

We argue that the format of relying on a system-by-system assessment, when used alone, is insufficient because it does not allow the much-needed generalization to multiple systems and discussion with a varied audience. Therefore, this approach precludes comparison of the health of a system to other dissimilar systems, a requirement across fields, particularly in policy discussions where there is a need to understand the broader context of ecosystem health (Rapport and Hilden, 2013; Bradshaw *et al*., 2020).

The importance of practical, easy to understand indicators of health lies in the way that recommendations are made actionable (Niemi and McDonald, 2004). Stakeholder, in this sense, refers to any ecologist, biologist, researcher, conservationist, etc. that is trying to relay a message about health or disease of a system to someone outside of the field, specifically, for example, to a policy maker or

Table 5. Seven studies that used "vulnerability" as an ecosystem health indicator term and the provided description vulnerability. Provided as an example of the inconsistent and confusing definitions of ecosystem health indicator terms.

Title	Author	Year	"Vulnerability" indicator term	Definition / description provided
Spatial-temporal variations of ecological vulnerability in the Tarim River Basin, Northwest China	Bai, J.; Li, J. L.; Bao, A. M.; Chang, C.	2021	Ecological vulnerability	"… 'vulnerability' refers to the possibilities of an ecosystem suffering from hazards, disturbances, or pressures over time and space (Williams and Kaputska, 2000) or the risks of severe destruction to the ecosystem (Nguyen *et al*., 2016)."
Habitat ecological integrity and environmental impact assessment of anthropic activities: A GIS-based fuzzy logic model for sites of high biodiversity conservation interest	Caniani, D.; Labella, A.; Lioi, D. S.; Mancini, I. M.; Masi, S.	2016	Ecological vulnerability	"…we defined the intrinsic and the integrated habitat vulnerability. The habitat intrinsic vulnerability integrates, with a fuzzy method, different independent landscape metrics, while the latter takes the effects of anthropogenic impacts into account as well. The model for the evaluation of the intrinsic ecological vulnerability … is based on the integration of different spatial metrics…to obtain useful information about the fragmentation, complexity and organization of the habitats."
Ecological vulnerability assessment for ecological conservation and environmental management	He, L.; Shen, J.; Zhang, Y.	2018	Ecological vulnerability	"Ecological vulnerability can be defined as 'the ability of ecosystems to absorb changes of state variables, driving variables, and parameters, and still persist." It is affected by internal and external factors."
Spatiotemporal distribution and influence factors of ecosystem vulnerability of Qunghai-Tibet Plateau	Li; Song	2021	Ecosystem vulnerability	"According to Adger (2006), vulnerability is the sensitivity of ecosystem under the stress of natural and social changes due to the lack of adaptability… At present, the IPCC's definition of vulnerability has been widely accepted and adopted in the field of climate change research. Based on relevant literature, ecosystem vulnerability can be summarized as the sensitivity and resilience of ecosystems in response to external interference including human disturbance, climate change, etc." *Also provides additional definitions of vulnerability in the literature.
Vulnerability assessment of eco-environment in Yimeng mountainous area of Shandong Province based on SRP conceptual model	Liu, Zheng-Jia; Yu, Xing-Xiu; Li, Lei; Huang, Mei	2011	Ecological vulnerability	*Used translator app* The vulnerability of the ecological environment is the ecological system at a specific time-space scale. Its sensitive response and self-recovery ability to external disturbances are the result of the joint action of natural attributes and human economic behavior (Adger, 2006).
A rapid qualitative methodology for ecological integrity assessment across a Mediterranean island's landscapes	Manolaki, P.; Chourabi, S.; Vogiatzakis, I. N.	2021	Landscape vulnerability	No specific definition provided.
Assessing the ecological vulnerability of protected areas by using Big Earth Data	Zheng, Y. M.; Wang, S. D.; Cao, Y.; Shi, J. L.; Qu, Y.; Li, L. P.; Zhao, T. J.; Niu, Z. G.; Yang, R.; Gong, P.	2021	Vulnerability	Given the definition of ecological vulnerability (Turner *et al*., 2003), the conceptual model of vulnerability reflects the degree of sensitivity, exposure, and adaptive capacity involving intrinsic and extrinsic factors (Nillson and Grelsson, 1995). From Turner *et al*. (2003) paper: "Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor."

NGO representative. To be understood, a clear, uncomplicated message must be relayed to policy makers when ecologists and biologists make their case for funding to protect ecosystems (Rapport, 1994). While system-specific terminology is important for researchers and specific indicators might be required to test certain scientific hypotheses, it can be difficult for government representatives and the general public to follow, particularly when each system uses its own complicated vocabulary. An example of this for clarification lies in how limnological health is discussed which holds good consensus in the field and is well-developed compared to other indicators (Whittier *et al*., 2007; Cho *et al*., 2011). However, this multitude of metrics must be reduced in an effort to communicate the condition of our environments more effectively when talking to a broader audience (Jorgensen *et al*., 2010). Thus, more generalized, easily understood indicators can be helpful to raise the profile of messages about environmental needs, regardless of the type of specific system in scope. Our intended audience for this article is specifically directed to our colleagues: those doing the work, performing the studies, and writing the article to express that the sheer volume of words we use to describe (eco)systems is overwhelming. We must understand that those outside of "our" field simply do not have the bandwidth to dive into subtle differences in definitions for the same term nor do they often have the scientific background or capacity to broadly understand the nuances of system-specific research when we leave out broadly generalizable terms that are commonly in use and easily understood. We see this in different circumstances when we (as a scientific community) provide what we feel is irrefutable evidence that action is needed and it simply gets dismissed, is that because the language we are using is too complex? Additionally, how can we discuss comparisons of environments effectively if the assessments rely on completely different ways of assessing health status?

The fact that among seven ecological papers using vulnerability as a health indicator term, there are six different definitions (see Table 5), which provides a convincing example of the variability and heterogenous nature of the landscape of eco-health indicator terms, in general. There are not commonly accepted definitions for many of these indicators in the literature and therefore no coherent way to measure them or compare different systems. Daly *et al*. (2018) further exemplify this in their discussion of ecological diversity that as far back as 1998, biodiversity had more than 85 varying definitions in the literature, additionally, they describe diversity as a higher-level indicator rarified into sub-components including richness, evenness, and disparity with no universal way to measure it. Daly *et al*. (2018) also refer to the use of "diversity" as an index, discussing the Shannon Index[1] as the most commonly used measure of diversity. Our study supported this as it was the most common Index found, although it was described in six different variations, many of which were not then discussed in detail in the associated studies.

Given the challenge of relying on one (or a small few) indicator(s) to broadly represent multiple types of ecosystems, an alternative is combining multiple indicators into an index system or framework to represent different characteristics of a given ecosystem. Utilizing MMI's has clear advantages over a single indicator i.e., ability to synthesize and combine multiple indicators into one assessment (Doren *et al*., 2009; Logan *et al*., 2020). However, it holds the same fundamental challenges as the individual indicators in that it is difficult to assess the health of one system compared to another within one framework. Many of the ecosystems that are being evaluated have already been altered by human intervention therefore obscuring the "ideal," or the counterfactual. Accordingly, Martin and Proulx (2020) questioned "how important is it that we include the current state and not the counterfactual reference point which is likely no longer a possibility?"

At the inception of this research, an initial goal was to categorize the collected indicators into high-level (umbrella terms) vs low-level (sub-component) indicators, however, without consistent definitions this proved to be a challenge. Many scientists argue that using single indicators to describe the health of a system is too narrow (Jorgensen *et al*., 2010; Brown and Williams, 2016). Therefore, the sub-level metrics may be better defined and measured per system and when combined, provide an explanation of the quality of the health status while meeting the ideal standardized requirements. There are common arguments against the use of general ecosystem indicators including: little agreement in the field on definitions of the indicators used, what sub-level indicators are appropriate, and many of the indicators struggle to meet classically accepted metrics including (consistent) measurability, scalability, comparability, etc. (Carignan and Villard, 2002; Kandziora *et al*., 2013; Roche and Campagne, 2017; Ruegg *et al*., 2018; Andrés *et al*., 2021). A problem arises with the convention of categorizing descriptor terms as high-level or low-level terms: as we approach the more granular terms or those with more specific definitions, we become too specific to compare to other systems and too specialized to discuss or transfer knowledge across fields, which is of utmost importance when trying to relay information to those outside of our immediate field (Rapport, 1994; Rapport and Hilden, 2013). As many of the studies do not supply a definition or a reference where one could find a proposed definition in the way the authors of the study intended, too many assumptions would need to be made. Additionally, of those that do define or refer to the indicators in a tiered or hierarchal fashion, there is not always agreement on what indicators are high level vs lower level, meaning those without inherent sub-components within them.

Some indicator terms can inarguably be categorized into higher-level indicators including integrity (ecosystem, environmental, ecological), ecosystem services/ productivity, diversity (biodiversity) (Carignan and Villard, 2002; Burger, 2006; Kandziora *et al*., 2013; Roche and Campagne, 2017), while there are others that are commonly accepted as those without direct sub-components: population density, indicator species, connectance (Siddig *et al*., 2016; Shi *et al*., 2018). There are also many that are correlated to, or proxies of, other indicators and their utility varies on how they are defined (Brown and Williams 2016; Coops *et al*., 2019; Nicholson *et al*. 2021). For example, ecological complexity is often linked to system integrity and resilience, although it can also be an indicator of organization or generally equated to the robustness of a system. Roche and Campagne (2017) describe ecosystem integrity as having five main forms throughout the literature: ecosystem integrity of wilderness, ecosystem function and structural integrity, ecosystem stability and resilience, ecosystem condition and ecosystem quality and value, while Kandziora *et al*. (2013) explore the term ecosystem services as shown in Fig. 1 with a discussion of how it is directly related to integrity but not necessarily defined by it. Côté and Darling (2010) describe resilience as having two components: resistance and recovery, essentially the capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services, which could also be described as tolerance or sensitivity. Very quickly we can see the ideal, neat hierarchy of indicators turning more into a web or network where many are integrated within each other and connected depending on the study or ecosystem of interest.

An unexpected finding of this study was the common use of and confusion associated with the IBI, a multi-metric index system that is the Index of either Biotic or Biologic Integrity, typically used for benthic macroinvertebrates, although it has been adapted to several different fauna by various authors, including birds (Yunchuan *et al*., 2019; Salas-Correa and Néstor-Javier, 2020) and fish (Randall and Minns, 2002; Frimpong *et al*., 2005). The entire collection of IBI's were not included in the final numbers in this study as many were deemed to be too system-specific and therefore were excluded based on the study exclusion criteria. However, the authors felt it important to highlight them separately as they were such a common finding throughout the research portion of this study. We came across 25 studies that used various iterations of the IBI 11 studies calling it the Index of Biologic Integrity, 12 referring to the Index of Biotic Integrity, and 2 used the terms interchangeably, further adding to confusion. The authors

[1] For clarification, the Shannon Index was first referenced in the 1940's and still provides considerable confusion and inconsistencies. Claude Shannon published the first reference to Shannon's Mathematical Theory of Communication co-authored with Warren Weaver in 1949 (Spellerberg and Fedor, 2003). In this paper Shannon credits and cites the mathematician Norbert Wiener (commonly mis-spelled as Weiner) from whom he adopted basic philosophical and theoretical principles. Over the years, much confusion has arisen and mislabeling; Spellberg and Fedor (2003) provided a more detailed description of how some of the confusion may have come about regarding the Shannon Diversity Index. Following its debut into literature in the late 1940's it was adopted into the ecological stream through studies of species diversity and population genetics due to the usefulness to give a more substantial account of an ecosystem's diversity compared to only the number of species (Konopiński, 2020).

of this study could not find a rationale behind choosing one or the other in many of these IBI studies. Classically, the IBI is attributed to James Karr who published and introduced the Index of *Biotic* Integrity in 1981 using fish communities and co-authored a paper where they referred to the *Biologic* Integrity of Aquatic Biota (Karr and Dudley, 1981). Karr describes the Index of Biotic Integrity with the original intent to provide a "broadly based and ecologically sound tool to evaluate biological conditions in streams," and includes metrics "used to assess biological integrity of fish communities based on the Index of Biotic Integrity (IBI)," (Karr, 1991) further confusing the difference between the two indices, if any exists. The specific lack of differentiation supports the almost interchangeable use of biotic and biologic in this context found throughout the research.

Limitations

An important consideration when working in any field is the recognition of inclusivity and (recognizing) inherent exclusions. While we purposefully included all languages in our original search results, the initial search strategy was performed in English. This leads to inherent cultural, implicit, and publication biases, often resultant in (ecology) research as most papers are published in English. English has become the prevailing language across science-related fields, therefore tends to be the most influential (Trisos *et al*., 2021) which effectively confines the researchers' and readers' knowledge by limiting contributions from those in developing or lower-income countries and Indigenous or Tribal cultures.

The search methodology had inherent limitations and inevitably may have excluded relevant articles. Similarly, the terms used for this search were broad and nonspecific, thereby resulting in many extraneous articles with little to no relevance to ecological ecosystem health indicators, as mentioned, was found in the pre-scoping exercises. While the use of adjacency search mechanisms narrowed the search results by excluding many irrelevant articles, it also likely excluded some pertinent articles with titles written in such a way that would not allow capture in the adjacency search. The numbers of articles in preliminary searches were so great, we propose this undertaking could not be performed without limiting as such, knowing that some articles would be missed, with the available resources and investigators.

We had considered limiting the dates of the search further (more recent than the last 20 years) to reduce numbers to a more manageable list, however, there was concern that this may limit significantly important articles because the eco-health field does not advance as rapidly as other fields, such as medicine or technology. The time frame of the last 20 years was chosen intentionally to capture relatively recent additions to the field, while recognizing the important contributions in years prior. We have explored many considerations as to how to reduce the article list without losing important articles, including constraining results to only specific journals based on characteristics such as relevance, popularity, or impact factor as the field is relatively small and the likelihood of missing relevant articles in smaller journals seemed too high, particularly with consideration of resource availability and only a few individuals available to assist in the footwork of this project.

While there are some limitations, this assessment can lay the basis for a transdisciplinary investigation of indicators of ecosystem health, their hierarchy and uses across different (eco)systems. We imagine that underlying value statements for each of the terms – or family of terms – will reveal interesting results in the future. The importance of a coherent dialogue around the general health of the world's ecosystems cannot be understated. A commitment to plain, accessible language will work to limit confusion around the many ways of expressing the health status of a system and allow comparison of different ecosystems in an effort to make legitimate and effective strides toward improvement and evaluation of those strides (Niemi and McDonald, 2004).

Conclusions

This study provides a landscape analysis of terminology used to assess integrated approaches to health. Not surprisingly, the heterogeneity and variability were substantial, while at the same time common patterns became clear, namely most studies were performed in the United States and China and terms that originated in the literature in the 1990s remain some of the more common in use currently. An example of where this work could contribute is in the implementation of the One Health Joint Action Plan (2022–2026) as barriers around communication are commonly referred to throughout the document (FAO, UNEP, WHO, and WOAH, 2022). What is needed is a clear, concise set of commonly used, agreed upon indicators with consistent definitions and mechanisms of measurement which can and will vary somewhat based on the system (IPBES, 2019).

Framing the discussion of ecosystem health indicators (eco-indicators) around the importance of a common terminology is the base for a productive dialogue between scientists, policy makers and stake holders at all levels (researchers, ecologists, biologists, conservationists, academics, members of government/ non-governmental organizations, advocates, legislatures and other policy makers). Clustering and organizing the information about eco-indicators in a systematic way is also helpful to obtain clear communication and avoid misunderstanding, specifically at policy and governmental levels. This review is a step toward the creation of a meaningful vocabulary of eco-indicators, where terminology descriptors and use can be understood by different stakeholders. Working toward this consensus, we can hopefully simplify the verbiage and evaluate if a set of ecosystem health indicator terms can be chosen that will consistently and sufficiently describe the overall health of an ecosystem.

CONFLICT OF INTEREST

No funding declaration or competing interests to declare.

ETHICS STATEMENT

The authors confirm that the research meets any required ethical guidelines, including adherence to the legal requirements of the study country.

ACKNOWLEDGMENTS

We would like to acknowledge members of NEOH Theoretical Working Group for their inception of this project.

AUTHORS' CONTRIBUTIONS

Gillian Penn carried out the formal analysis and investigation; Christi Piper and Gillian Penn performed methodology; Gillian Penn (lead) and Thomas Jaenisch carried out project administration; Gillian Penn, Michelle Gallagher, and Thomas Jaenisch validated the study; Gillian Penn carried out visualization, writing original and subsequent draft preparation, review and editing; Luís Pedro Carmo, Elena Boriani, John Berezowski, J. McMahon, and Thomas Jaenisch conceptualized the study and assisted with review and editing of drafts; Michelle Gallagher assisted in review and editing; Thomas Jaenisch supervised the study. All authors read and approved the final manuscript.

FUNDING STATEMENT

The authors have no funders to declare.

References

Adger, N.W. (2006) Vulnerability. *Global Environmental Change* 16(3), 268–281. DOI: 10.1016/j.gloenvcha.2006.02.006.

Andrés, P., Doblas-Miranda, E., Mattana, S., Molowny-Horas, R., Vayreda, J. *et al*. (2021) A Battery of soil and plant indicators of NBS environmental performance in the context of global change. *Sustainability* 13(4), 1913. DOI: 10.3390/su13041913.

Atak, B.K. and Tonyaloglu, E.E. (2020) Monitoring the spatiotemporal changes in regional ecosystem health: A case study in Izmir, Turkey. *Environmental Monitoring and Assessment* 192(6), 385. DOI: 10.1007/s10661-020-08357-4.

Ausseil, A.-G., Dymond, J., Kirschbaum, M., Andrew, R.M. and Parfitt, R. (2013) Assessment of multiple ecosystem services in New Zealand at the catchment scale. *Environmental Modelling and Software* 43, 37–48. DOI: 10.1016/j.envsoft.2013.01.006.

Bradshaw, C., Ehrlich, P., Beattie, A., Ceballos, G., Crist, E. *et al*. (2020) Underestimating the challenges of avoiding a ghastly future. *Frontiers in Conservation Science* 2, 700869. DOI: 10.3389/fcosc.2020.615419.

Brown, E.D. and Williams, B.K. (2016) Ecological integrity assessment as a metric of biodiversity: Are we measuring what we say we are? *Biodiversity and Conservation* 25(6), 1011–1035. DOI: 10.1007/s10531-016-1111-0.

Burger, J. (2006) Bioindicators: Types, development, and use in ecological assessment and research. *Environmental Bioindicators* 1(1), 22–39. DOI: 10.1080/15555270590966483.

Carignan, V. and Villard, M.A. (2002) Selecting indicator species to monitor ecological integrity: A review. *Environmental Monitoring and Assessment* 78(1), 45–61. DOI: 10.1023/A:1016136723584.

Cho, W.S., Park, Y.S., Park, H.K., Kong, H.Y. and Chong, T.S. (2011) Ecological informatics approach to screening of integrity metrics based on benthic macroinvertebrates in streams. *Annales de Limnologie – International Journal of Limnology* 47, S51–S62. DOI: 10.1051/limn/2011019.

Collins Dictionary (2022) Indicator. CollinsCoBuild. Available from https://www.collinsdictionary.com/us/dictionary/english/indicator (accessed 21 February 2022).

Coops, N.C., Bolton, D.K., Hobi, M.L. and Radeloff, V.C. (2019) Untangling multiple species richness hypothesis globally using remote sensing habitat indices. *Ecological Indicators* 107, 105567. DOI: 10.1016/j.ecolind.2019.105567.

Costanza, R. and Mageau, M. (1999) What is a healthy ecosystem? *Aquatic Ecology* 33, 105–115. DOI: 10.1023/A:1009930313242.

Côté, I.M. and Darling, E.S. (2010) Rethinking ecosystem resilience in the face of climate change. *PLOS Biology* 8(7), e1000438. DOI: 10.1371/journal.pbio.1000438.

Daly, A.J., Baetens, J.M. and De Baets, B. (2018) Ecological diversity: Measuring the unmeasurable. *Mathematics* 6, 119. DOI: 10.3390/math6070119.

Doren, R.F., Trexler, J.C., Gottlieb, A.D. and Harwell, M.C. (2009) Ecological indicators for system-wide assessment of the greater everglades ecosystem restoration program. *Ecological Indicators, Indicators for Everglades Restoration* 9(6), S2–S16. DOI: 10.1016/j.ecolind.2008.08.009.

EPA (2021) Air Data: Air Quality Data Collected at Outdoor Monitors Across the US. Available at: https://www.epa.gov/outdoor-air-quality-data (accessed 1 October 2021).

Equihua, M., Aldama, M.E., Gershenson, C., Lopez-Corona, O., Munguia, M. *et al.* (2020) Ecosystem antifragility: Beyond integrity and resilience. *PeerJ* 8, e8533. DOI: 10.7717/peerj.8533.

Ereshefsky, M. (2009) Defining 'health' and 'disease'. *Studies in History and Philosophy of Biological and Biomedical Sciences* 40, 221–227. DOI: 10.1016/j.shpsc.2009.06.005.

FAO, UNEP, WHO, and WOAH (2022) *One Health Joint Plan of Action (2022–2026). Working Together for the Health of Humans, Animals, Plants and the Environment*. Rome. DOI: 10.4060/cc2289en.

Fowler, S., Rousch, R. and Wise, J. (2013) Concepts in Biology. Pressbooks. Available at: https://opentextbc.ca/conceptsof biologyopenstax/ (accessed 20 March 2021).

Frimpong, E.A., Sutton, T.M. and Engel, B.A. *et al*. (2005) Spatial-scale effects on relative importance of physical habitat predictors of stream health. *Environmental Management* 36(6), 899–917. DOI: 10.1007/s00267-004-0357-6.

IPBES (2019) Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In: Díaz, S., Settele, J., Brondízio, E.S., Ngo, H.T., Guèze, M. *et al*. (eds) IPBES Secretariat, Bonn, Germany. DOI: 10.5281/zenodo.3553579.

Jorgensen, S.E., Xu, F.-L. and Costanza, R (2010) *Handbook of Ecological Indicators for Assessment of Ecosystem Health*, 2nd edn. Boca Raton, FL: CRC Press Taylor & Francis Group, Boca Raton, FL. DOI: 10.1201/EBK1439809365

Kandziora, M., Burkhard, B. and Muller, F. (2013) Interactions of ecosystem properties, ecosystem 16 and ecosystem indicators – A theoretical matrix exercise. *Ecological Indicators* 28, 45–78. DOI: 10.1016/j.ecolind.2012.09.006.

Karr, J.R. (1991) Biological integrity: A long-neglected aspect of water resource management. *Ecological Applications* 1(1), 66–84. DOI: 10.2307/1941848.

Karr, J.R. and Dudley, D.R. (1981) Ecological perspective on water quality goals. *Environmental Management* 5(1), 55–68. DOI: 10.1007/BF01866609.

Konopiński, M.K. (2020) Shannon diversity index: A call to replace the original Shannon's formula with unbiased estimator in the population genetics studies. *PeerJ* 8, e9391. DOI: 10.7717/peerj.9391.

Leonardi, F. (2018) The definition of health: Towards new perspectives. *International Journal of Health Services* 48(4), 735–748. DOI: 10.1177/0020731418782653.

Logan, M., Hu, Z., Brinkman, R., Sun, S., Sun, X. and Schaffelke, B. (2020) Ecosystem health report cards: An overview of frameworks and analytical methodologies. *Ecological Indicators* 113, 105834. DOI: 10.1016/j.ecolind.2019.105834.

Martin, C.A. and Proulx, R. (2020) Level-2 ecological integrity: Assessing ecosystems in a changing world. *Perspectives in Ecology and Conservation* 18(3), 197–202. DOI: 10.1016/j.pecon.2020.08.001.

Network for EcoHealth and One Health [NEOH] (2020) Network for evaluation of One Health; New European Chapter of Ecohealth International. European Cooperation in Science and Technology (COST). Available at: https://neoh.onehealthglobal.net (accessed 1 November 2021).

Nguyen, A.K., Liou, Y.A., Li, M.H. and Tran, T.A. (2016) Zoning eco-environmental vulnerability for environmental management and protection. *Ecological Indicators* 69, 100–117. DOI: 10.1016/j.ecolind.2016.03.026.

Nicholson, E., Watermeyer, K.E., Rowland, J.A., Sato, C.F., Stevenson, S.L. *et al*. (2021) Scientific foundations for an ecosystem goal, milestones and indicators for the post-2020 global biodiversity framework. *Nature Ecology & Evolution* 5(10), 1338–1349. DOI: 10.1038/s41559-021-01538-5.

Niemi, G.J. and McDonald, M.E. (2004) Application of ecological indicators. Annual review of ecology. *Evolution and Systematics* 35, 89–111. DOI: 10.1146/annurev.ecolsys.35.112202.30000005.

Nillson, C.N. and Grelsson, G. (1995) The fragility of ecosystems: A review. *Journal of Applied Ecology* 32(4), 677–692. DOI: 10.2307/2404808.

O'Brien, A., Townsend, K., Hale, R., Sharley, D. and Pettigrove, V. (2016) How is ecosystem health defined and measured? A critical review of freshwater and estuarian studies. *Ecological Indicators* 69, 722–729. DOI: 10.1016/j.ecolind.2016.05.004.

Orradottir, B. and Aegisdottir, H.H. (2015) Healthy Ecosystems, healthy Earth, healthy people. United Nations University. Available at: https://unu.edu/publications/articles/healthy-ecosystems-earth-people.html#info (accessed 22 March 2021).

Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C. *et al*. (2021) The PRISMA 2020 Statement: An updated guideline for reporting systematic reviews. *BMJ* 372, n71. DOI: 10.1136/bmj.n71.

Pan, Z. He, J., Liu, D., Wang, J. and Guo, X. (2021) Ecosystem health assessment based on ecological integrity and ecosystem services demand in the Middle Reaches of the Yangtze River Economic Belt, China. *Science of The Total Environment* 774, 144837. DOI: 10.1016/j.scitotenv.2020.144837.

Parrott, L. (2010) Measuring ecological complexity. *Ecological Indicators* 10, 1069–1076. DOI: 10.1016/j.ecolind.2010.03.014.

Randall, R.G. and Minns, C. (2002) Comparison of a Habitat Productivity Index (HPI) and an Index of Biotic Integrity (IBI) for Measuring the Productive Capacity of Fish Habitat in Nearshore Areas of the Great Lakes. *Journal of Great Lakes Research* 28(2), 240–255. ScienceDirect, DOI: 10.1016/S0380-1330(02)70580-7.

Rapport, D.J. (1992) Evolution of indicators of ecosystem health. In: McKenzie, D.H., Hyatt, D.E. and McDonald, V.J. (eds) *Ecological Indicators*. Springer, New York. DOI: 10.1007/978-1-4615-4659-7_9.

Rapport, D.J. (1994) Ecosystem health: More than a metaphor? *Environmental Values* 4(4), 287–309. DOI: 10.3197/096327195776679439.

Rapport, D.J. (2007) Sustainability science: An ecohealth perspective. *Sustainability Science* 2, 77–84. DOI: 10.1007/s11625-006-0016-3.

Rapport, D.J. and Hilden, M. (2013) An evolving role for ecological indicators: From documenting ecological conditions to monitoring drivers and policy responses. *Ecological Indicators* 28, 10–15. DOI: 10.1016/j.ecolind.2012.05.015.

Roche, K. and Campagne, C.S. (2017) From ecosystem integrity to ecosystem condition: A continuity of concepts supporting different aspects of ecosystem sustainability. *Science Direct Current Opinion in Environmental Science* 29, 63–68. DOI: 10.1016/j.cosust.2017.12.009.

Ruegg, S.R., Hasler, B. and Zinsstag, J. (eds) (2018) *Integrated Approaches to Health: A Handbook for the Evaluation of One Health*. Wageningen Academic Publishers, The Netherlands. DOI: 10.3920/978-90-8686-875-9.

Salas-Correa, A.D. and Néstor-Javier, M.R. (2020) Birds as ecological indicators of successional stages in a secondary forest, Antioquia, Colombia. *Revista de Biología Tropical* 68(1), 23–39. DOI: 10.15517/rbt.v68i1.34913.

Shi, Y., Wang, N., Li, T., Wang, H., Kang, H. and Shi, X. (2018) Evaluation of landscape ecological integrity in the Yulin Region, China. *Sustainability* 10(11), 4300. DOI: 10.3390/su10114300.

Siddig, A.A.H., Ellison, A.M., Ochs, A., Villar-Leeman, C. and Lau, M.K. (2016) How do ecologists select and use indicator species to monitor ecological change? Insights from 14 years of publication in ecological indicators. *Ecological Indicators* 60, 223–230. DOI: 10.1016/j.ecolind.2015.06.036.

Spellerberg, I.F. and Fedor, P.J. (2003) A Tribute to Claude Shannon (1916–2001) and a Plea for More Rigorous Use of Species Richness, Species Diversity and the 'Shan-Non-Wiener' Index. *Global Ecology and Biogeography* 12, 177–179. DOI: 10.1046/j.1466-822X.2003.00015.x.

Suter II, G.W. (1993) A critique of ecosystem health concepts and indexes. *Environmental Toxicology and Chemistry* 12(9), 1533–1539. DOI: 10.1002/etc.5620120903.

Trisos, C.H., Auerbach, J. and Katti, M. (2021) Decoloniality and anti-oppressive practices for a more ethical ecology. *Nature Ecology & Evolution* 5, 1205–1212. DOI: 10.1038/s41559-021-01460-w.

Turner, B.L., Kasperson, R.E., Matson, P.A., McCarthy, J.J., Corell, R.W. *et al.* (2003) A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America* 100(14), 8074–8079. DOI: 10.1073/pnas.1231335100.

Whittier, T.R., Hughes, R.M., Stoddard, J.L., Lomnicky, G.A., Peck, D.V. and Herlihy, A.T. (2007) A structured approach for developing indices of biotic integrity: Three examples from streams and rivers in the Western USA. *Transactions of the American Fisheries Society* 136(3), 718–735. DOI: 10.1577/T06-128.1.

Williams, L.R.R. and Kapustka, L.A. (2000) Ecosystem vulnerability: A complex interface with technical components. *Environmental Toxicology and Chemistry* 19(4),1055–1058. DOI: 10.1002/etc.5620190435.

WWF (2020) Living Planet Report 2020 – Bending the curve of biodiversity loss. In: Almond, R.E.A., Grooten, M. and Petersen, T. (eds) WWF, Gland, Switzerland. ISBN 978-2-940529-99-5. Available at: https://f.hubspotusercontent20.net/hubfs/4783129/LPR/PDFs/ENGLISH-FULL.pdf.

Yunchuan, D., Yadong, X., Yunyi, Z. and Diqiang, L. (2019) Summary comments on assessment methods of ecosystem integrity for national parks. *Biodiversity Science* 27(1), 104. DOI: 10.17520/biods.2018142.