CAWTHRON

REPORT NO. 3818

COMPILATION OF POTENTIAL ATTRIBUTES OF ECOLOGICAL INTEGRITY FOR AOTEAROA NEW ZEALAND

COMPILATION OF POTENTIAL ATTRIBUTES OF ECOLOGICAL INTEGRITY FOR AOTEAROA NEW ZEALAND

ANNA BERTHELSEN[1], JO CAVANAGH[2], JOANNE CLAPCOTT[1], CARLOS CAMPOS[1], ADRIAN MCDONALD[3], ROLAND EVELEENS[1], KATE ORWIN[2], DUANE PELTZER[2]

[1.] CAWTHRON INSTITUTE

[2.] MANAAKI WHENUA – LANDCARE RESEARCH

[3.] UNIVERSITY OF CANTERBURY

Prepared for Ministry for the Environment

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

REVIEWED BY:
Jim Sinner

APPROVED FOR RELEASE BY:
Grant Hopkins

ISSUE DATE: 30 September 2022

RECOMMENDED CITATION: Berthelsen A, Cavanagh J, Clapcott J, Campos C, McDonald A, Eveleens R, Orwin K, Peltzer D 2022. Compilation of potential attributes of ecological integrity for Aotearoa New Zealand. Prepared for Ministry for the Environment. Cawthron Report No. 3818. 77 p. plus appendices.

EXECUTIVE SUMMARY

The New Zealand Government plans to repeal the Resource Management Act 1991 (RMA) and replace it with three new pieces of legislation. One of these is the Natural and Built Environments Act (NBA, in draft[1]), which specifies that environmental limits are to be prescribed in the National Planning Framework (NPF). To inform the NPF, the Ministry for the Environment (MfE) is seeking to identify indicators (or 'attributes') of ecological integrity (EI) that are suitable for setting environmental limits.

Attributes need to cover various environmental domains (Land [including Soil], Freshwater, Coastal and Seabed, Estuaries and Air), to consider indigenous biodiversity as a cross-domain theme and to relate to significant environmental issues. This requires compilation of potential attributes of EI in priority topic areas, as well as their assessment against key criteria in relation to management (including policy) and in a limit-setting context. MfE are also interested to know whether there are any gaps in their proposed definition of EI, which includes five components: ecological representation, composition, structure, function and resilience.

MfE contracted Cawthron Institute, Manaaki Whenua Landcare Research and University of Canterbury to carry out this work in two phases. Phase 1 (this report) focuses on compilation and synthesis of potential attributes (with no policy or management lens applied) as well as on identifying any gaps in the MfE-proposed definition of EI, while Phase 2 is to provide an assessment of the potential attributes against key criteria in relation to management (including policy) and in a limit-setting context.

We conducted a literature search of thousands of published and unpublished articles across the five domains to identify potential attributes of EI. Our primary focus was on literature pertaining to Aotearoa New Zealand, but we also supplemented our findings using international monitoring frameworks and literature.

The literature yielded an overall abundance of potential attributes of EI across the domains: Land (subdomains: > 150 for Terrestrial and 245 for Soil), Freshwater (251), Coastal and Seabed, and Estuaries (> 580 combined), and Air (37), with indigenous biodiversity included as a cross-domain theme for all. Our approach developed a documented and repeatable search of the literature and provides a crucial summary of knowledge from published and unpublished sources. Key points from our across-domain synthesis for the EI components are as follows:

- Across all domains the attributes associated with composition and structure dominated; for Air, all attributes related to structure.
- Functional attributes were also quite common in all domains except for Air.

[1] https://environment.govt.nz/assets/publications/Natural-and-Built-Environments-Bill-Exposure-Draft.pdf

- Attributes for ecological representation and resilience were relatively few across the domains. Attributes for ecological representation were dominated by variations on broader environment or habitat extent with a greater number captured for the marine-related (Coastal and Seabed, and Estuaries) domains and terrestrial subdomain.
- Attributes specifically relating to indigenous species or indigenous biodiversity were identified for all domains except Air and the Soil subdomain. However, a number of biotic attributes did not distinguish between indigenous or non-indigenous species (e.g., coastal macroinvertebrate community abundance and diversity), and in this regard they technically do not meet the requirements under the EI definition provided. Some other attributes were specifically related to non-indigenous species (e.g., non-native species diversity).
- EI components are interrelated. Biotic structural components can be based on composition information, some composition attributes relate to function, and attributes relating to resilience are often measured by attributes associated with other EI components such as composition and function.
- The MfE definition of EI aligns in many respects with definitions used in the literature for the domains. However, the Freshwater and marine-related domain descriptions also include consideration of reference or baseline condition. For the Soil subdomain, EI is not used in the literature, but rather 'soil health' or 'soil quality', which can have a similar intent to the MfE EI definition, with the exception of the specification of 'indigenous biodiversity' in the MfE definition. For the Air domain, it was noted that the MfE EI definition could be strengthened to explicitly include climatic factors (rather than just abiotic physical factors) in the definition of structure.

Additional key points across domains were:

- A number of attributes were found to be connected across domains e.g., erosion or leaching, which traverse the land and water domains. Across-domain attributes also relate to domain boundaries e.g., riparian vegetation and tidal wetlands.
- Across domains, the development and/or use of attributes among different systems is uneven. For example, many of the Soil subdomain attributes are developed and applied in agroecosystems, whereas many Terrestrial subdomain metrics have been developed in indigenous forests and shrublands. Additionally, Freshwater attributes have been relatively well-developed into national scale monitoring frameworks. There was also unevenness across domains in relation to the type of attributes or threats they respond to. For example, there was a higher proportion of activities-based attributes (e.g., fishing-related) for the marine-related domains and a dominance of climate change-related attributes for the Air domain, while attributes relating to chemical contamination were common for most domains.

- Gaps in potential attributes for different EI components for Aotearoa New Zealand were identified through the international literature for all domains.
- A common theme for emergent attributes across the Terrestrial and Soil subdomains and Freshwater and marine-related domains is the use of eDNA or rRNA approaches to provide further detail on species presence and composition.

The next step is to provide assessment of potential attributes identified in this report against key criteria in relation to the policy, management, and limit setting context. This work is planned for Phase 2 of the project.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF APPENDICES

GLOSSARY

Potential attribute	A 'measurable characteristic (numeric, narrative, or both)'.
Coastal and Seabed	For the purposes of our report, Coastal and Seabed includes coastal waters and the underlying seabed. Coastal waters are defined in the NBA Exposure Draft as: '…seawater within the outer limits of the territorial sea and includes – (a) seawater with substantial freshwater component; and (b) seawater in estuaries, fiords, inlets, harbours, or embayments'. The landward boundary of coastal wasters was identified as Mean High Water Springs.
Domain	The five domains are Land (including Soil), Freshwater, Coastal and Seabed, Estuaries and Air. Indigenous biodiversity is considered as a cross-domain theme' rather than a domain. Additionally, for the purposes of our report, Land (including Soil) was often considered as two separate subdomains: 'Terrestrial', which is the aboveground component, and 'Soils'.
Ecological integrity (MfE definition)	The ability of the natural environment to support and maintain the full range of indigenous biodiversity and ecosystem functioning, both within and across ecosystems. It requires supporting and maintaining: • ecological representation: the occurrence and extent of ecosystems and indigenous species and their habitats across the full range of environments • its composition: the natural diversity and abundance of indigenous species, habitats, and communities within and across ecosystems; and • its structure: the biotic and abiotic physical features and characteristics of ecosystems; and • its functions: the ecological and physical functions and processes of an ecosystem; and • its resilience: any other properties that contribute to the ecosystem's ability to recover from the adverse impacts of natural or human disturbances.
Ecosystem	As defined in the NBA: '… a system of organisms interacting with their physical environment and with each other'.

Estuaries	Partially enclosed water bodies where freshwater meets and mixes with saltwater from the sea. Additional notes on how estuaries were further defined for the purposes of our report: • the landward boundary was considered to be Mean High Water Springs and the seaward boundary was across the estuary entrance (e.g., prominent headlands) • overall, estuaries were included within the Coastal and Seabed domain boundary • our literature search terms for estuaries also included harbours, inlets, sounds and fiords.
Freshwater	As defined in the NBA exposure draft: 'all water except coastal water and geothermal water'.
Indigenous biodiversity	The variety of living organisms indigenous to New Zealand, the ecological complexes of which they are a part, including diversity within species, between species, and of ecosystems.
Land (including Soil)	For the purposes of our report, Land (including Soil) is the soil and underlying rock as well as the life (animals and vegetation) above and below ground. It includes ecosystems and life, but riverbeds and lakebeds are excluded. Land to the mean high water spring mark (e.g., sand dunes) is included.
NPF	National Planning Framework
NPSFM	National Policy Statement for Freshwater Management
NBA	Natural and Built Environments Act (still in draft as of the date of this report).
Natural environment	As defined in the NBA exposure draft: '(a) the resources of land, water, air, soil, minerals, energy, and all forms of plants, animals, and other living organisms (whether native to New Zealand or introduced) and their habitats; and (b) ecosystems and their constituent parts'.
River	As defined in the NBA exposure draft: '…a continually or intermittently flowing body of freshwater; and (b) includes a stream and modified watercourse; but (c) does not include an irrigation canal, a water supply race, a canal for the supply of water for electric power generation, a farm drainage canal, or any other artificial watercourse'.

1. INTRODUCTION

1.1. Background and report objectives

The New Zealand Government plans to repeal the Resource Management Act 1991 (RMA) and replace it with three new pieces of legislation. One of these is the Natural and Built Environments Act (NBA, in draft[2]), which aims to 'promote the protection and enhancement of the natural and built environment, while providing for housing and preparing for the effects of climate change'. This Act requires environmental limits to be prescribed in a new National Planning Framework (NPF), with the purpose of environmental limits being to protect either or both of the following: (a) the ecological integrity of the natural environment and (b) human health.

To inform the NPF, the Ministry for the Environment (MfE) is seeking to identify indicators (or 'attributes', as referred to in the National Policy Statement for Freshwater Management [NPSFM] 2020), of ecological integrity (EI) suitable for setting environmental limits. Attributes need to cover various environmental domains (Land [including Soil], Freshwater, Coastal and Seabed, Estuaries and Air), to consider indigenous biodiversity as across-domain theme and to relate to significant environmental issues. This work initially requires compilation of potential attributes of EI in priority topic areas, and, following this, their assessment against key criteria for use in management (including policy) and limit setting. MfE are also interested to know whether there are any gaps in their definition of EI.

MfE contracted Cawthron Institute, Manaaki Whenua Landcare Research and University of Canterbury to carry out this work in two phases. Phase 1 focuses on compilation of potential attributes and on identifying differences in the MfE definition of EI compared to how EI is defined in the literature. Phase 2 will provide an assessment of potential attributes against key criteria in relation to management (including policy) and the limit setting context. This report encompasses Phase 1, with specific objectives being to:

- search the literature to compile a list of potential attributes of EI for each domain (considering indigenous biodiversity as a cross-domain theme) with respect to significant environmental issues. The intention here was to 'cast a wide net' to help ensure that all potentially relevant attributes were identified. Management (including policy) considerations are outside the scope of Phase 1. Therefore, even though all attributes identified in our report are relevant for EI, some attributes may not be appropriate for setting limits under the NBA.
- identify any key differences between the MfE definition of EI and how EI is defined in the literature for each of the domains.

[2] https://environment.govt.nz/assets/publications/Natural-and-Built-Environments-Bill-Exposure-Draft.pdf.

Note that consideration of any mātauranga Māori informed frameworks or cultural indicators is outside of the scope of our work. Considering attributes specifically related to human health was also outside the scope.

2. METHODS

We surveyed the literature to identify attributes relevant to EI (as defined by MfE) for Aotearoa New Zealand in four steps. First, we identified published literature within Aotearoa New Zealand relevant to EI for the five domains. Second, we used a combination of approaches to refine and filter this literature to those publications considered relevant to the domains and the development of attributes of EI applicable to the most significant environmental issues. Third, we used heuristic ad hoc searching of databases and obtained expert input across domains to determine if there are new, emerging or unpublished work within Aotearoa New Zealand relevant to this synthesis. Finally, we conducted a non-systematic 'rapid review' of the international literature on EI to supplement attributes that have not been adopted or applied within Aotearoa New Zealand (Booth et al. 2016). These four steps are described in more detail below. This is followed by details on how we recorded the literature review outputs and analysed the results.

2.1. Systematic literature review including refining and filtering (Steps 1 and 2)

2.1.1. Initial search

Our systematic review approach (Step 1) was based on aspects of the PRISMA[3] framework, i.e., it involved a detailed plan and search strategy, but it did not include a meta-analysis component (O'Dea et al. 2021). Our search strategy considered a series of search strings in title, abstract, key words and author address fields, as follows:

> ('ecological integrity' OR 'ecosystem integrity' OR 'ecosystem condition' OR 'ecosystem health' OR 'community composition' OR ' community representativeness' OR 'community structure' OR 'ecological resilience' OR 'ecological function*') AND ('new zealand' OR 'aotearoa' or 'NZ').

Our search terms were designed to represent EI broadly, as well as to encompass the specific EI components as defined by MfE (i.e., composition, structure, function, resilience and representation). The strings reduced bias by helping us identify all relevant studies on a particular subject matter. Our searches were conducted on the Web of Science (WoS) core collection. A preliminary systematic search yielded 9,986 results (20 June 2022).

[3] Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology.

2.1.2. Search for relevance

Using one search engine across all domains (WoS core collection), we then evaluated these results for relevance using the following criteria:

- domain-specific contributions (refer search terms in Table 1) AND
- responses to significant environmental issues (refer search terms in Table 2) AND
- relevance by including the search terms ('attribute*' OR 'indicator*' OR 'monitor* OR 'management' OR 'application') AND
- exclusion terms (if used, these differed among domains as detailed in the results, refer Section 3).

Thus, to qualify for further assessment for a given domain, an item of literature had to meet each of the first three criteria and not be excluded by specific considerations (if any) for that domain. All fields (title, abstract, keywords and author address) were searched for text matching the above criteria.

After this process was completed, it became clear that attributes related to the Air domain are always secondary drivers of EI. None of the identified abstracts related purely to the Air domain. Thus, to identify attributes associated with the Air domain, an extra identification of the range of secondary domains was included for completeness. It should also be noted that the original search and the subsequent searches by domain missed a large amount of literature; hence, we also did ad hoc searching (detailed further below), which was particularly important for the Air domain.

The raw outputs of the literature search for each domain were saved in Excel file format and can be provided to MfE on request.

We then conducted further assessment of article relevance (Step 2), depending on the number of search results and additional considerations. This was based on expert evaluation of returned literature to identify studies relevant for attribute and metadata extraction based on title and abstract of studies. In some cases, the PDF was also obtained during this process so that further details in the article text could be examined to determined relevance. Factors for exclusion during this process included studies not relevant for Aotearoa New Zealand e.g., search identified Aotearoa New Zealand authors but article concerned another location. Exclusion factors also related to 'incorrect' domain (e.g., many freshwater studies were identified in the final returned literature search results for Land (including Soil)) or a focus on something other than a potential attribute (e.g., management, policy, governance, engineering, or conservation).

Following this, we obtained all article pdfs and any missing dois for all articles and extracted metadata from each article (i.e., populated our 'attribute list and metadata' data file); refer Section 2.4 'Recording literature search outputs' below.

Table 1. Terms used to define each of the domains for the systematic literature search. Note that indigenous biodiversity search terms (last row) were included in each domain-specific search.

Domain	**Search Terms**
Freshwater	Fresh Water, Freshwater, Groundwater, River, Stream, Lake, Wetland, Waterway, Glacier, Glacial
Coastal and Seabed	Coastal Waters, Coastal, Coast, Marine, Ocean, Seabed, Sea Floor
Estuaries	Estuar*, Harbour, Inlet, Sound, Fiord
Land (including Soil)	Soil, Soil Health, Land, Forest, Alpine, Agriculture, Urban, Vegetation, Terrestrial
Air	Air quality, Air pollution, Atmosphere, Climate, Climate Change, Weather, Meteorology
Indigenous biodiversity	Indigenous Biodiversity, Biodiversity, Biological diversity

Table 2. The significant environmental issues (SEI) for each domain. These were determined by the report authors to represent a range of environmental issues. Note that SEIs relating to indigenous biodiversity were considered for each of the domains.

Domain	**Significant environmental issues**
Land (including Soil)	Agriculture Biodiversity decline Biological invasion Climate change Contaminants (metals, organic contaminants) Contaminated land Diseases Disturbance Erosion Habitat loss Habitat modification Land fragmentation Land use change Land use intensity, compaction, leaching Mining Pests Soil acidification Salinisation Urban expansion/urbanisation including sealing Weeds
Freshwater	Climate change, flow regime, water temperature, water allocation, water abstraction Eutrophication, nutrient enrichment, nutrient loading Exploitation of resources Habitat modification, Habitat loss, Biodiversity loss Litter Non-indigenous species, invasive species Pollution, sedimentation, heavy metals Pathogens, toxins, emerging contaminants
Coastal and Seabed, and Estuaries	Climate change, acidification, water temperature, air temperature, sea level rise, increasing storm intensity, increasing flood intensity, increasing storm frequency, increasing flood frequency, shoreline erosion Eutrophication, nutrient enrichment, nutrient loading Exploitation of resources Habitat modification, Habitat loss, Biodiversity loss Human presence, human activity Hydrologic disruption, hydrodynamic disruption Litter Non-indigenous species, invasive species Pathogens, toxins, emerging contaminants Pollution, sedimentation, heavy metals
Air	Air Pollution/Air Quality: particulate matter, nitrogen dioxide, sulphur dioxide, carbon monoxide, surface ozone, airborne microplastics Attribution Climate change: temperature, precipitation. Wind, humidity, greenhouse gases (CO_2, CH_4, NO_2) Climate variability: Southern Annular Mode, ENSO, natural variability Cold extremes: frost

Domain	Significant environmental issues
	Drought: precipitation, evaporation, wind, temperature Extreme events: could include drought, storms, heatwaves, cold spells and floods Floods Heat waves: temperature Storms: precipitation/rainfall, wind Weather patterns

2.2. Additional literature for Aotearoa New Zealand (Step 3)

Further ad hoc, heuristic searching was used to identify additional relevant publications, including unpublished 'grey literature' sources. Our ad hoc searches included several approaches:

i) publications that cited or were cited by articles identified in the systematic literature searches in steps 1 and 2 above
ii) expert knowledge of the authors
iii) additional experts acting as 'critical friends' particularly to identify unpublished literature or additional attributes to consider
iv) Google and Google Scholar searches were used to identify additional publications for assessment.

For the Air domain, it was clear that a large portion of the literature focusing on atmospheric science, air quality or climate change was missing from the initial search results. To mitigate this, additional targeted searches (using the Scopus search engine) were completed using attributes identified by the original literature search as further search terms to identify extra attributes and subsets of attributes. Expert knowledge was then used to add extra search terms. To ensure transparency, Table 3 identifies all the Air domain specific search terms used in targeted searching. In each case, the search was of the form ('Air [targeted search term]' and 'ecosystems') and then a subset was created to save only records which included 'Aotearoa' or 'New Zealand'. Each list of results was then examined to find relevant studies. The total of individual records collected was over 7500 and this resulted in the identification of just under 196 relevant Aotearoa New Zealand-based studies, though the number of unique records was smaller than this number as some records were found in multiple searches.

Table 3. Targeted Air domain search terms used in literature searches.

Targeted search term (explanatory note in brackets)	Number of studies identified	Number of relevant Aotearoa New Zealand studies found using search term	Total number of Aotearoa New Zealand studies found that were relevant to this search term from any source (only filled when different from previous number)	Comment
Ammonia	448	6	7	
Arsenic	347	4	8 (Heavy metals)	
Atmospheric nitrogen deposition	393	7	11	
Atmospheric particulate matter	55	1	4	
Atmospheric humidity	52	1		
Biomass burning	129	5		
Black carbon	96	1	0	Only reference really more relevant to particulate matter
Carbon Monoxide	30	1	2	
Climate indices	682	16		
Climate change	46	5		
CO (chemical symbol)	2000	24	2	Many references actually only related to CO_2
Daily Temperature range (ETCCDI climate indices)	64	3		None specific to search term
Eddy covariance	22	11		
ENSO (teleconnection pattern)	9	3	5	
Fire	1376	27	23	Some only indirectly relevant to search term
Frost days	12	1		
Gaseous pollutants	140	2		
Greenhous gases	54	17		
Heavy metals	15	1		
Herbicide and pesticide atmospheric transport	11	0		
Light pollutions	49	2		
Microplastics	144	3	5	All occurring in 2021

Targeted search term (explanatory note in brackets)	Number of studies identified	Number of relevant Aotearoa New Zealand studies found using search term	Total number of Aotearoa New Zealand studies found that were relevant to this search term from any source (only filled when different from previous number)	Comment
Number of summer days (ETCCDI climate indices)	50	1		
Noise pollution	72	2	1	Marine settings so questionable whether should be classified in AIR domain
Nox (chemical symbol)	43	2	11	
Ocean acidification	316	11		
Ozone	152	7	Tropospheric ozone depletion (3)- Stratospheric ozone depletion (6)	Number of found references refer to changes in atmospheric state variables (temperature, winds) indirectly related to ozone depletion
PAH (polynuclear aromatic hydrocarbons)	7	4	2	
Particulate matter	41	2	4	
PM2.5	23	2	4	
POPs (Persistent Organic Pollutants)	88	0	2	
PRCPTOT (ETCCDI climate indices for Precipitation total)	1	0		
Precipitation change	176	4	29	
Rainfall change	117	9	29	
SAM (teleconnection indices)	5	4	4	
Sensible heat flux	3	0	2	All connected to agriculture
Snowfall	36	1	6	
SO_2 (chemical symbol)	39	2		

Targeted search term (explanatory note in brackets)	Number of studies identified	Number of relevant Aotearoa New Zealand studies found using search term	Total number of Aotearoa New Zealand studies found that were relevant to this search term from any source (only filled when different from previous number)	Comment
Sox (chemical symbol)	7	0		
Sulphur dioxide	39	0		
Temperature change	544	20	37	
Tropospheric ozone	10	2	3	
Wind or wind extremes	19	0	6	
Total	**7517**	**196**	**216**	

During our literature searches and refinement of articles for relevance, care was taken to ensure that there were no gaps in relation to sub-domains spanning domain borders (for example, wetlands, dune systems, riparian vegetation, air temperature).

In all cases, there were diminishing returns of investment in time or effort to discover additional attributes or records, but the systematic and ad hoc searches provided confidence that no major potential attributes developed or used in Aotearoa New Zealand were excluded.

2.3. International literature to supplement our findings (Step 4)

Steps 1–3 were focused on knowledge from Aotearoa New Zealand. For Step 4, we completed targeted searches of the international literature to identify additional potential attributes. Priority was given to identifying major reviews, syntheses or monitoring frameworks focused on regions where these approaches are most advanced including Australia, the United Kingdom, the United States and the European Union. A secondary goal of our international literature search was to identify attributes from additional sources to those listed above that could be used in Aotearoa New Zealand. These targeted searches were conducted based on expert knowledge of the authors, e.g., by searching for relevant key words in the literature and/or publications by authors or organisations active in particular domains. A systematic search of the international literature would have been an enormous task (> 1 million records), beyond the scope of the current work, and unlikely to yield major attributes not already considered in Aotearoa New Zealand or by international frameworks.

2.4. Recording literature search outputs

We recorded the number of search results across domains. For each record retained for further assessment (from systematic and ad hoc searches), we compiled potential attributes and associated metadata. When compiling the attributes, we aimed to be as granular as possible. However, in some cases (especially for the Coastal and Seabed, and Estuaries domains, and the Terrestrial subdomain) it was more practical to combine multiple attributes into one 'attribute topic' or focus on an attribute 'leader' given the volume of attributes or development of these in existing monitoring frameworks or research. The attribute and metadata information was compiled in 'potential attribute and metadata' files for the domains (see supplementary files, Appendix 1). The metadata recorded for each attribute (or attribute topic) included two types, described below.

2.4.1. Attribute-related metadata

Attribute-related metadata recorded are as follows:

- component of EI addressed (ecological representation, composition, structure, function, resilience) as per the MfE definition (refer Glossary). Assignment of a component/s to each attribute was based on an author's expert opinion and discussed amongst the project team for alignment purposes.
- potential attribute (or attribute topic) (i.e., name or high-level description).
- attribute 'method' (high level comments, not for all attributes).
- potential attribute 'group' (or 'class for Air) to provide a logical grouping for a set of related attributes e.g., 'fish' could be the group for fish-related attributes—this was done subjectively for individual domains based on expert judgement.
- domain (Land [including Soil] - also broken down into the subdomains Terrestrial and Soil, Freshwater, Coastal and Seabed, Estuaries, Air).
- subdomain i.e., key habitat, ecosystem or community within the domain that the attribute relates to (if relevant, not for all attributes). No additional information was provided in this respect for the Soil and Terrestrial subdomains (listed above).
- commonly used attributes (i.e. that were high in prevalence). These were found in more than ten publications (in the systematic search) or considered to be commonly used in Aotearoa New Zealand based on authors' professional judgement (in the ad hoc search). Additional information (i.e., regarding moderate and low prevalence) was also provided.
- source of attribute: 'NZ' if attribute was encountered in the systematic or ad hoc review of NZ literature, or 'international' if acquired from ad hoc overseas literature search.
- attribute scale and units of measurement; details of the study system and methods used; and threats, drivers or environmental issue addressed by the study (for

some domains or subdomains only, as an illustration of information that may be useful during Phase 2).

We also noted any definitions of EI used in the literature returned by the searches.

2.4.2. Reference metadata

Reference-related metadata recorded are as follows:

- key reference/s for each potential attribute (including year of publication).
- literature search type for each record (Aotearoa New Zealand (NZ) systematic, NZ ad hoc, or international).

2.5. Summarising compiled attributes

We summarised our compiled potential attributes in two ways. First, we provided a summary of commonly used potential attributes for each domain (in text and tables) for each of the EI components defined by MfE. It is important to note that while it was helpful for summarising our findings, ‘common usage’ of attributes doesn’t necessarily indicate usefulness in a management, policy or limit setting context and vice versa—attributes not commonly used could potentially be useful. Thus, to provide additional information, we separately provided summaries of emerging attributes identified from the Aotearoa New Zealand literature and of additional international attributes in the text. Second, we discussed differences in the MfE definition of EI in comparison to how EI has been defined in the literature for the domains. This was based on definitions of EI noted during compilation of attributes from the literature. However, we also supplemented this with other seminal reports on this topic for Aotearoa New Zealand (and also in some cases for overseas).

While we aimed to standardise across domains, slightly different approaches (including levels of detail) for reporting and summarising the results were taken in some cases for the domains. For example, for the Air domain, all attributes identified were included in the attribute summary in the report (rather than just the commonly used ones), given the relatively small number of attributes identified for this domain overall. Reasons for this include how well developed the monitoring frameworks (and thus associated attributes) are across domains and the volume of attributes identified, and that different domains sometimes approach the same things slightly differently.

3. LITERATURE SEARCH AND ATTRIBUTE COMPILATION SUMMARY

3.1. Search items

The number of search results for each domain (considering Terrestrial and Soil as subdomains) are detailed in Table 4. Key international monitoring frameworks retrieved during ad hoc searching are listed in Table 5. For ad hoc searching in particular, the intent was to fill gaps in potential attributes obtained from the systematic results rather than to identify all relevant publication records. The following sections provide a summary of attribute results for each domain.

Table 4. The number of individual articles (published or unpublished depending on the search type) relating to literature search results and refining for relevance for each domain. NZ = Aotearoa New Zealand.

<table>
<tr><th>Domain or subdomain</th><th>Overall number of systematic search results</th><th>Number of NZ systematic search results refined for relevance from which attributes were compiled</th><th>Number of NZ ad hoc articles from which attributes were compiled (to supplement attributes from systematic search)</th><th>Number of international ad hoc articles (including international monitoring frameworks) from which attributes were compiled (to supplement attributes from the systematic and NZ ad hoc searches)</th></tr>
<tr><td>Terrestrial</td><td>1516</td><td>266</td><td>46</td><td>8</td></tr>
<tr><td>Soil</td><td>1516</td><td>144</td><td>28</td><td>26</td></tr>
<tr><td>Freshwater</td><td>708</td><td>100</td><td>22</td><td>7</td></tr>
<tr><td>Coastal and Seabed</td><td>561</td><td>41[a]</td><td rowspan="2">> 80</td><td rowspan="2">> 20</td></tr>
<tr><td>Estuaries</td><td>209</td><td>75</td></tr>
<tr><td>Air</td><td>930 (+7517 ad hoc results)</td><td>67</td><td>196</td><td></td></tr>
</table>

[a] Coastal attributes were also compiled from the 'Estuaries' records list.

Table 5. Key international monitoring frameworks retrieved during ad hoc searches.

Framework	Domain or subdomain	Location	Description
Essential Biodiversity Variables (EBVs)	Terrestrial	International	A suite of measures deemed essential for measuring state and change in biodiversity (Pereira et al. 2013; see also Bellingham et al. 2020) for links to Aotearoa New Zealand implementation of EBVs).
The Group on Earth Observations Biodiversity Observation Network (GEOBON)	Terrestrial	International	Global networks of monitoring biodiversity and ecosystem state and change have been developed to support national and regional commitments to global obligations such as the Convention on Biological Diversity and Ramsar. Frameworks for data collection and interoperability that are scalable are well developed and published. EBVs have emerged as part of this network https://geobon.org/. There are marine, freshwater and soil Biodiversity Observation Networks ('BONs').
Ecological Integrity of National Parks	Terrestrial	Canada	The Canada Parks system is one of the most well-cited uses of ecological integrity (EI) indicators for assessing the condition of parks where historical baselines are uncertain because of a deep history of human uses (Fraser et al. 2009; Parks Canada Agency 2011; see also discussion in McGlone et al. 2020). https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/ecological-integrity-national-parks.html.
National Park Service's (NPS) Vital Signs Monitoring Programme	Terrestrial	USA	Identified metrics of status and trend in structure, composition, and function of forests impacted by multiple agents of change. Developed for temperature forest systems (Tierney et al. 2009).
Intergovernmental Panel for Biodiversity and Ecosystem Services (IPBES)	Terrestrial	International	Many of the global and regional data associated with IPBES are relevant for EI, particularly monitoring of regional biodiversity change, and ecosystem functions. Two areas of specific strengths for NZ are the role of local and indigenous peoples in conservation, and the impact of biological invaders (https://ipbes.net/global-assessment).
Terrestrial Ecosystem Research Network (TERN)	Terrestrial	Australia	TERN is a land observatory that includes landscape observation, ecosystem observation, and ecosystem processes. Nationally structured data collection for vegetation, soils, remote sensing information and biodiversity across Australia across land uses. Well documented and open access methods and protocols are well developed. https://www.tern.org.au/.
Forest Structural Condition Index Ecoregional Potential	Terrestrial	International	Emerging metric of forest EI combining GEOBON approaches of remote sensing with ground-based monitoring data. More general treatment and links with Convention on Biological Diversity (CBD) targets for reducing biodiversity loss through the Global Biodiversity Framework (GBF) are provided in Hansen et al. (2019, 2021).

Framework	Domain or subdomain	Location	Description
Comprehensive assessment of soil health (CASH)	Soil	USA	Cornell Soil Health Assessment Manual (Mobius-Clune et al. 2016).
Tier 1 Soil Health Indicators	Soil	USA	Soil Health Institute (National Soil Health Measurements to Accelerate Agricultural Transformation – Soil Health Institute).
Sustainable management assessment framework (SMAF)	Soil	USA	United States Department of Agriculture (USDA) (Andrews et al. 2004).
Soil Health Indicators	Soil	USA	USDA- Natural Resources Conservation Service (NCRS) (Stott et al. 2019).
Soil function assessment	Soil	EU	LANDMARK programme (https://landmark2020.eu/project-details/
Land Use/Land Cover Area Frame Survey (LUCAS)	Soil	EU	Jones et al. (2021).
United States Environmental Protection Agency (EPA) Recovery Potential Screening framework	Freshwater	United States of America (USA)	Countrywide framework for comparing watershed condition and the potential for ecosystem recovery following restoration.
Australian Integrated Ecosystem Condition Assessment Framework	Freshwater	Australia	Condition assessment framework designed for the integrated monitoring of aquatic ecosystems.
United Nations (UN) Sustainable Development Goal (SDG)	Freshwater	International	SDG seeking to ensure availability and sustainable management of water and sanitation for all. Includes targets and indicators for improving ambient water quality (Target 6.3) and protecting and restoring ecosystems (Target 6.6).
United States National Aquatic Resource Survey	Freshwater, Coastal and Seabed, Estuaries	USA	National collaborative program between EPA, states, and tribes to assess the quality of the nation's coastal waters, lakes and reservoirs, rivers and streams, and wetlands using statistically-based survey design.
European Union Water Framework Directive 2000 (WFD)	Freshwater, Coastal and Seabed, Estuaries	Europe	Cross-border framework to protect and enhance the health of aquatic ecosystems while maintaining socioeconomic systems.
Essential Ocean Variables (EOVs)	Coastal and Seabed, Estuaries	Global	Specific priority variables for monitoring life in the sea through the Global Ocean Observing System.
Integrated estuary assessment framework	Estuaries	Australia	Framework that can be used to assess the biophysical health of estuarine and coastal systems but which also links into the social and economic

Framework	Domain or subdomain	Location	Description
			values of such systems. An important part of this is to identify appropriate indicators of both ecosystem and economic and social values.
International Cooperative Programme on Assessment and Monitoring of the Effects of Air Pollution on Rivers and Lakes	Air	International	Assesses the degree and geographical extent of acidification of surface waters.
Essential Climate Variables	Air	Global	Specific priority variables for monitoring climate within the Global Climate Observing System.
Network for Detection of Atmospheric Composition Change	Air	Global	This network was established to collect long-term databases for detecting changes and trends in atmospheric composition and to understand their impacts on the atmosphere and to establish scientific links and feedbacks between changes in atmospheric composition, climate, and air quality.

3.2. Land (including Soil)

We have divided Land (including Soil) into two subdomains (Terrestrial and Soil) and, after the first section, discussed them separately below for clarity due to the different fields of expertise needed to evaluate the literature for each subdomain.

3.2.1. Summary of search results for Terrestrial

Our systematic search of the WoS core collection (see Section 2.1, Tables 1 and 2) yielded 1853 records. We next excluded disciplines not relevant to the Land (including Soil) domain (i.e., disciplines or publications that are clearly for other domains, i.e., marine, aquatic and meteorological journals) and retained 1516 records.

Additional domain-specific exclusion criteria were then applied to this long list to remove records not relevant for assessing attributes of EI; this required expert evaluation of individual records, particularly to exclude non-New Zealand studies (i.e., many records contained a contributor from this country, but the study itself was done elsewhere). Records were excluded for:

- studies based solely on in-lab or ex situ variables (i.e., of limited value as attributes of ecosystems)
- studies considering only pairwise interactions or within species effects (e.g., biocontrol agent selectivity on a host organisms)
- studies within agricultural systems that considered only the effects of one or few management treatments on productivity but included no wider evaluation of responses within the agroecosystem
- purely conceptual or policy-directed studies.

After these exclusions, 326 records were retained for more detailed evaluation. We then evaluated individual records to generate metadata for each record (supplementary file, Appendix 1). Records were next split into 'Terrestrial' and 'Soil' subdomains; results are summarised separately below.

3.2.2. Summary of potential attributes for Terrestrial

Our systematic search yielded 266 records for assessment of potential attributes for aboveground terrestrial systems. An additional 46 records were included through ad hoc searching as outlined in the methods above. Also included were selected international records (*n* = 8) that outline frameworks for collation and structuring of attributes. Leading attributes derived from this analysis are summarised in Table 6.

More than 150 potential attributes of EI for aboveground terrestrial systems were identified (see Appendix 1). Many additional attributes were discovered during the systematic and ad hoc searches, but their relevance as EI attributes together with the feasibility of summarising vast numbers of potential metrics here meant attributes were grouped under a leading attribute. For example, there are dozens of diversity metrics, but only few commonly reported metrics are listed in Table 6. Similarly, plant functional traits are widely used to assess both functional diversity and ecosystem functioning, but > 100 plant functional traits could contribute to potential attributes (see www.try-db.org/).

Many attributes of EI are well advanced through other frameworks, such as the global and Aotearoa New Zealand-specific implementation of several attributes known as essential biodiversity variables (EBVs; see Pereira et al. 2013; Bellingham et al. 2020). Finally, for many attributes, there are distinct taxon- or system-specific attributes used throughout the literature, and these are not exhaustively listed. As an example, 'dominance' of species can be determined from biomass, population density, cover, size, or frequency; so although identical metrics or data may not be collected across different taxa or systems, appropriate measures of dominance can be quantified. Overall, the majority of complied attributes provide commonly used potential attributes for three components of EI (i.e., composition, structure, and function). There are few commonly used attributes for ecological representation and resilience.

Table 6. Commonly used Terrestrial potential attributes used in Aotearoa New Zealand, along with less commonly reported but potentially useful attributes (labelled 'other potential attributes'). Attributes were collated from a systematic search of peer-reviewed publications and an ad hoc review of Aotearoa New Zealand-based literature. 'Group' is based on logical grouping for a set of related attributes. A complete list of potential attributes and accompanying metadata are in Appendix 1 (supplementary file). Note that many attributes are used to answer study-specific questions; only a subset are used specifically for monitoring purposes. Attributes either represent individual attributes or attribute topics. EBV = Essential Biodiversity Variable.

Ecological integrity component	**Group**	**Commonly used potential attributes**	**Other potential attributes**	**Further attribute details**
Ecological Representation	Ecosystem Representativeness	Land Environmental Class (Land Environments of NZ (LENZ)) Land Environment (NZ Environmental Data Stack (NZEnvDS))	Threatened Environments Classification (TEC) BioFRAG (habitat fragmentation) Restored Significance (Vital Sites and Actions)	Attributes are derived directly from spatial data layers, in this case multivariate maps of soil, climate and landform related to biological properties. Some metrics for fragmentation and edge effects on composition are available.
Composition	Species diversity	Native species diversity (EBV). Numerous metrics of diversity are available (richness, evenness, chao estimators, etc.)	Beta- and gamma diversity Slope of richness-area relationship Number of threatened species	Numerous methods and indicators are used to quantify species diversity. An EBV; See Bellingham et al. (2020), and https://geobon.org/ebvs/what-are-ebvs/).
		Non-native species diversity	Numerous metrics of diversity are available (richness, evenness, chao estimators, etc.). Number of invasive species	Directly related to invasions as a threat and management activities. For many groups, invasion by non-native species is increasing through time and contributing to changes in diversity.
	Phylogenetic diversity	Phylogenetic diversity (EBV)	Net relatedness index	An EBV less commonly considered than taxonomic diversity. Rapid improvements in molecular and analytical tools are emerging.
	Species dominance	Native species dominance (EBV)	Native species density, biomass, cover, height or size	Dominance measures vary among taxa and systems but are commonly measured. An Essential Biodiversity Variable (EBV).
		Non-native species dominance	Non-native species density, biomass, cover, height or size Pest capture rates	Directly related to invasions as a threat and management activities.
	Species occupancy	Native species presence (EBV)	Native species distributions	An EBV. Requires spatial structure for sampling.

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Composition, cont.		Non-native species presence	Non-native species distributions Pest capture rates (TCI)	Directly related to invasions as a threat. Requires spatial structure for sampling.
		Indicator species presence	Rare species presence Keystone species presence Presence of non-production species in agroecosystems	Widely used for rare/threatened species across different taxa and systems. Some work done on species combinations as indicators. Usually considered habitat quality.
	Community composition	Compositional dissimilarity (EBV) Biotic homogenisation Species co-occurrence	Multivariate axes of composition Quantitative vegetation classification Compositional nestedness	Essential well-established attribute internationally. Many similarity indices or multivariate methods are used (e.g., Jaccard, Bray-Curtis) to quantify compositional change. An EBV. Requires spatial structure across scales for sampling.
	Genetic diversity	Genetic diversity of species population (richness and heterozygosity)(EBV)	Genetic differentiation (number of genetic units and genetic distance) (EBV) Effective population size Holobiont composition	An EBV. Rapidly developing field. Focused on few species targeted for population recovery.
	Composition of regenerating species	Species composition of early life stages	Fledging success of birds Seedling species composition Sapling species composition	Composition of recruitment is often a more sensitive or early indicator of restoration or threat than indicators for established populations.
	Trait diversity	Trait diversity (EBV) Trait richness	Feeding groups	Trait diversity has emerged as complimentary to taxonomic and phylogenetic diversity. An EBV.
	Interaction diversity	Interaction diversity (EBV)	Food web structure Network properties	Range of metrics are developed and published for food webs or networks. Analytically challenging. An EBV.
	Population abundance	Population size	Pest trap catch index Nesting density Invertebrate abundance	Often set as a target or limit for species. Most often applied to vertebrate pests or bird species in NZ.
Structure	Biomass	Carbon Species abundance (EBV)	Coarse Woody Debris (CWD) Exclosure effects on mass	Fundamental indicator for multiple purposes. Change in biomass indicates productivity or disturbance.
	Vertical structure	Ecosystem vertical profile (EBV)	Height frequency Tree height	Fundamental ecosystem property related to habitat provision, light capture and physical structure.

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure, cont.	Vegetation cover	Live cover fraction (EBV)	Foliar Browse Index (FBI) Foliar Cover Index (FCI) Leaf Area Index (LAI)	Very widely collected information across vegetation-types.
	Population structure	Population size class distribution	Presence of large trees Juvenile survivorship Stand structure	Distributions of size, age and sex indicative of population processes. Applied across animals and plants.
	Landscape structure	Connectivity Fragmentation	Habitat equivalence Structural connectivity	Diverse set of attributes available describing ecosystem spatial structure, but few are deployed in NZ. This is a current gap for understanding biodiversity changes in modified landscapes.
	Ecosystem distribution	Ecosystem distribution (EBV)	LENZ Rare ecosystem cover Wetland extent Wetland condition	Fundamental information on the spatial distribution of ecosystems.
Function	Functional traits	Plant functional traits Feeding groups Functional diversity	Specific root length fine root dry matter content (DMC) Specific Leaf Area (SLA) Foliar N, P Body size Trophic position	Large body of knowledge and databases on functional traits are developed across taxa including plant functional traits, feeding groups of invertebrates. Collectively, these traits underpin the 'plant economics spectrum' used to predict nutrient use, growth, and other functions within species and at the community-scale.
	Primary Productivity	Aboveground Net Primary Production (ANPP) Ecosystem phenology	Tree growth Tree mortality Net gas exchange Pasture accumulation Net Ecosystem Exchange (NEE)	Fundamental measure of ecosystem energy capture. Underpins all functions. Essential, well-established attribute in NZ. All approaches used: plot-based, eco-physiological, models, remote sensing.
	Species functioning	Species phenology (EBV) Species morphology (EBV) Species physiology (EBV)	Species movement (EBV)	Multiple EBVs relate directly to species-population processes and functioning. This information varies widely among species and systems.
	Consumption	Diet selection Species palatability Invertebrate consumption	Selection consumption Pest irruption Stocking density	Includes herbivory and pathogens. A focus in NZ has been on the selective damage by pests, resource selection by native species, and pasture production.
	Species regeneration	Recruitment of juveniles	Tree recruitment Seedling recruitment Nesting success	Broad set of attributes often linked to population health, habitat quality or management activities.

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Function, cont.	Native dominance	Dominance of ecological functioning	Per unit impacts on ecological process	Lee et al. (2005) and others; dominance of ecological process and function, not biomass per se.
	Toxicity	Contaminant presence in organism	Toxicity to individual (LD50)	Almost no records from systematic survey or associated with community or ecosystem-level responses. There is a large literature on toxicity screening and secondary poisoning of individual taxa within New Zealand (e.g., see Eason et al. 2013).
	Floral resources	Pollen production Nectar production	Flowering phenology Flower visitation rate Pollen limitation	Some work on seasonality and spatial available for bees. Fundamental data for native species largely unavailable.
	Fruit availability	Fruit produced	Species specific fruit production	Widely captured as a response variable to possum control.
	Propagule pressure	Seedfall Dispersal	Mast seeding	Generation of movement of seeds or juveniles. Variability through time crucial to consider.
	Ecosystem configuration	Matrix contrast Fragmentation impacts	Functional connectivity Rare ecosystem status Landscape resource diversity Edge effects	Diverse group of landscape metrics often linked to ecological process (e.g., habitat quality, species' movement)
	Soil fertility	Litterfall Litter decomposition	Litter carbon (C), nitrogen (N), phosphorus (P) content Soil C, N, P content Soil organic matter	Covered primarily in soil attribute summary (see Table 7).
	Interactions	Functional originality Dissimilarity of interactions	Parasitism rate Rate of attack Root mycorrhizal colonisation	Numerous food web and network metrics are available but require both intensive data collection and specialist expertise to analyse and interpret. Mutualisms included here.
	Ecosystem disturbance	Cultural disturbance Pathogen presence	Canopy cover Fire risk (flammability index) Stocking density Soil disturbance	Pests, pathogens attributes above are also potential drivers of disturbance.
	Regulating Ecosystem services	Water regulation Soil formation	Soil erosion control Climate regulation	More details in Dymond (2013) review.

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Resilience	Resilience	Change in composition or structure attributes over time or in response to disturbance	Food web stability Stability of network properties	Resilience with respect to EI was nearly absent from the systematic search of NZ literature but could be derived from changes over time in other indicators.

3.2.3. Attribute results summary for Terrestrial

Brief comments for components of EI for the Terrestrial subdomain follow.

Ecological representation

Literature on ecological representation is complex and varied. Representation is a major underpinning measure for NHMS and biodiversity monitoring schemes (e.g., Lee et al. 2005; Bellingham et al. 2020; McGlone et al 2020; Walker et al. 2021). Some of the most widely adopted approaches are large-scale mapping of representative environments derived from multiple environmental, climatic and landscape features, but not diversity (e.g., LENZ, TEC, NZ data stack). Other approaches to ecosystem representation in Aotearoa New Zealand, such as the Ecosystem Classification system developed by Singers and Rogers (2014), rely primarily on botanical surveys and expert knowledge rather than quantitative multivariate estimates of representation. Hybrid approaches, such as the Vital Sites and Actions model (VSA, Overton et al. 2015), combine mapping with estimates of ecological uniqueness but have not been widely adopted to date. Overall, there are several complementary attributes for ecological representation available from regional to national scales. Greater inclusion of biodiversity into ecological representation is likely in the future, given this is an Essential Biodiversity Variable (EBV) (see also Schmeller et al. 2018).

Composition

Excellent compositional data have been collected nationally as a consequence of multiple long-term monitoring efforts for biodiversity, vegetation assessment, soil characterisation and carbon estimates. Attributes of composition typically involve assessing community composition, changes in composition or grouping using multivariate statistical methods. Reflecting the various ways in which composition data are collected, and differences among both taxa and ecosystems, there are no consistent analytical methods used across systems. Terrestrial vegetation is relatively well-characterised and quantitatively-derived community attributes are available (e.g., Wiser et al. 2011). Similarly, for bird communities, there is a nationally representative atlas and there are long-established monitoring protocols (e.g., 5-minute bird counts) that are frequently used to quantify species' occupancy and community composition alike. A particular requirement within Aotearoa New Zealand is characterisation of the presence and abundance of non-native species: this is crucial for many attributes including estimates of diversity, responses to management, or interactions with other drivers of change (e.g., see Vitousek et al. 1997; Simberloff 2019; Hulme 2020). However, there is a systematic underrepresentation of some taxa (e.g., invertebrates) or systems (e.g., urban environments, agroecosystems). Similarly, some EBVs such as phylogenetic and genetic diversity are rarely estimated.

Structure

Many structural attributes are collected at the same time as compositional data. Structure is driven across scales by abundance and dominance of plant species within sites, reflected by numerous measures of biomass, vertical structure, and cover (including in height tiers). For other taxa, structure is reflected primarily as abundance-occupancy relationships (birds). Across these groups, population abundance and structure provide additional insights into population processes at site or larger spatial scales. For example, changes in tree size class distributions determine forest physical structure, habitat quality, effects of disturbance. Moreover, when size class distributions are considered together other data such as functional traits or additional attributes such as disturbance or pest species abundance, this provides greater insights in changes into many components of EI, and ability to assign responses to particularly drivers. Similarly, population size or structure is often used as a target or limit for species, both recovery of native species (e.g., minimum viable population size for bird species) and management of biological invaders (e.g., population density of pest mammals). Landscape-scale structure has been relatively well characterised for forests and wetlands, but not for many other systems including naturally rare or threatened ecosystems (Williams et al. 2007; Holdaway et al. 2017).

Function and process

Attributes for function and process are many and varied, including those related to belowground functions and soils processes (see Soil subdomain summary below). Species' functional traits are commonly used as indicators of ecological processes or ecosystem functions. This is part of a global move to better understand the role, function and importance of species and diversity in systems, or put another way, the consequences of species additions or removals from systems. For example, plant functional traits are widely collected to estimate functional diversity in communities. This diversity is related to resource use and thus energy flows and nutrient cycling in ecosystems and can be used to predict specific processes such as palatability to invasive herbivores or litter decomposability. Many traits also relate to EBVs including species phenology, morphology, and physiology.

Processes or functions can also be directly quantified or estimated. For example, Aboveground Net Primary Production (ANPP) is estimated from repeated measures of plots, models, or gas exchange measurements, or using remote sensing techniques. These approaches have different qualities and strengths as attributes that are not covered in further detail here but could form a good example of how multiple approaches could be deployed for some attributes. Regeneration of species and contributions to community structure are captured by a suite of attributes including timing, success and recruitment of propagules or offspring. For plants, some information is available for floral resources, mostly for understanding resource availability to honeybees or birds. Similarly, seed or fruit production is highly variable among species and sites but is linked to both regeneration processes and knock-on trophic consequences, such as mast seeding events driving pest mammal irruptions.

Processes at the ecosystem-level include landscape configuration and its effects on function, such as movement of species across boundaries, species-area relationships, and provision of resources and habitat quality. Some international concepts, such as ‘extinction debt’ (i.e., the future declines in diversity driven by current changes to ecosystem area or condition) have not yet been considered in Aotearoa New Zealand. Many interactions or functions are captured by studies of food webs or networks. Although this approach provides numerous metrics of function such as interactions among species, plant-pollinator relationships, cascading effects of feeding groups, and functional niche of species or guilds, the intensive nature of data collection, analyses and interpretation likely limit the use of these metrics as attributes. Finally, the importance given to understanding ecosystem disturbance in Aotearoa New Zealand terrestrial environments is reflected by the large number of potential attributes spanning stocking density, fire risk, soil erosion, geological processes, pathogens, and cultural disturbance. Disturbance is also considered through changes in other attributes, for example, changes in tree size class distributions and foliar cover over time.

Resilience

Resilience rarely featured in the systematic literature review, and not as an attribute of EI. Most records related to resilience were on pasture production within agroecosystems, used manipulative experiments at small scales (e.g., to test ideas of biodiversity and stability), or used purely modelling approaches. Resilience as an attribute requires determining changes over time in other in other attributes spanning composition, structure and function. However, the relatively long history of monitoring, repeated measures of sites and plots, and interest in large-scale disturbances including climatic, geological and from fire mean that recovery of species populations, structure, composition and function could be assessed from an EI perspective despite a dearth of publications on this topic. Resilience has been explicitly considered for specific systems, including trajectories of wetland restoration, recovery of forest fragments, and major meta-analyses of plant, bird and invertebrate community responses to pest mammal management (e.g., Binny et al. [2021]; see also review by Gladstone-Gallagher et al. [2022] on linking NZ social-ecological resilience across domains).

Attribute gaps for Aotearoa New Zealand (supplemented by international literature)

International studies help to reveal gaps or underutilisation of some potentially excellent attributes of EI in Aotearoa New Zealand. For example, global efforts to develop a core suite of attributes for monitoring biodiversity (GEOBON) and Essential Biodiversity Variables (EBVs) reveal that genetic and phylogenetic diversity are rarely reported in Aotearoa New Zealand. Recent syntheses highlight the crucial importance of monitoring and reporting on genetic diversity within species (O’Brien et al. 2022), which is nearly absent from biodiversity monitoring and reporting in Aotearoa New Zealand (e.g., see Table 1 in Bellingham et al. 2020).

The effects of contaminants on integrity do not feature for terrestrial systems at least with respect to integrity. However, many studies were revealed in our search but were typically based solely on in-lab or ex situ variables, considered only within species effects, and most were within agricultural systems and were thus considered of limited value as attributes of EI. As an example, the toxicity of several rodenticides and herbicides used in Aotearoa New Zealand were tested under lab conditions on the western fence lizard (*Sceloporus occidentalis*), a surrogate organism for native lizards. How such screening procedures might inform (Weir 2016). The relevance of such toxicity screening approaches for risk to populations, and potentially attributes of EI, is unresolved. Secondary contamination or toxicity to terrestrial organisms is possible, for example through trophic transfer of sodium monofluoroacetate (1080) to non-target species (Eason et al. 2013; Morriss et al. 2016). There is a large literature on non-target effects of these and other chemicals used in the environment that was not covered here. However, if species-specific effects of contaminants is considered within scopes, additional work is warranted linking studies of in situ impacts with population-level indicators such as population structure or juvenile survivorship.

Some international concepts that are reasonably well-established, such as 'extinction debt' (i.e., the future declines in diversity driven by current changes to ecosystem area or condition) have not yet been considered in Aotearoa New Zealand. Similarly, research into characterising and understanding changes in landscape structure are well advanced overseas and could be applied to help to overcome gaps in our knowledge and attributes of EI in, for example, biodiversity changes in modified landscapes.

Emerging attributes

The rapid development of new technologies and approaches to quantifying the state and trend of terrestrial environments provides opportunities for new attributes of EI. For example, eDNA and other molecular approaches complement current approaches to monitoring diversity and function (e.g., Holdaway et al. 2017; Dickie et al. 2018). Advances in and increasing use of LiDAR and remote sensing technologies are rapidly producing high quality and quantities of data that could be used to quantify structure, and in some cases, aspects of composition and function (e.g., Cavender-Bares et al. 2022). Similarly, major efforts internationally to better link remote sensing or earth observation data with plot or ground-based monitoring have generated several emerging indicators: these include the Forest Structure Condition Index, Lost Forest Configuration, and several community-scale indices like the Bioclimatic Ecosystem Resilience Index and Species Habitat Index (see summary of Hansen et al. 2021). In many cases the underpinning data needed to develop these attributes is available in Aotearoa New Zealand, it is a current gap in research effort and publication. The information produced by these technologies holds great promise for future monitoring including development or refinement of attributes of EI.

Similarly, major efforts internationally to better link remote sensing or earth observation data with plot or ground-based monitoring have generated several emerging attributes of EI (Hansen et al. 2021; see also TERN network protocols).

However, additional developments in data management, analytical approaches and interpretation are required to implement many of these emerging attributes. Genetic variation within and among species is both a gap in current attributes and an area with multiple emerging attributes. Genetic diversity is one of three levels of diversity recognised in the Convention on Biological Diversity (along with among species and ecosystems) and underpins species' adaptation and resilience to environmental changes. Both genetic approaches and non-genetic proxies (e.g., effective population size) could be deployed as attributes of genetic diversity. Moreover, these attributes can be summarised using consolidated scoring systems and can be scaled from local to national reporting (O'Brien et al. 2022; see also Hoban et al. 2022).

3.2.4. Summary of search results and potential attributes for Soil

The systematic literature search on WoS resulted in 1561 articles for Land (including Soil) with 144 initially identified as specifically relevant for the Soil subdomain in Aotearoa New Zealand, noting that some of these papers include above and below-ground attributes. Review of these papers and ad hoc searches provided over 300 Soil subdomain attributes—this included attributes relevant to air, such as ammonia deposition, ammonia volatilisation and greenhouse-gas (CO_2, CH_4, N_2O) emissions; and water attributes, such as infiltration rate and surface run-off. We observed that the use of some attributes (particularly soil fauna) was strongly linked to individual researchers, and partially reflects the relatively small number of researchers working on these issues in this country. The search terms used were not particularly effective at finding literature related to erosion, compaction and leaching; this gap was filled by ad hoc searches. Review of Aotearoa New Zealand unpublished literature provided a useful cross-check on attributes identified through the systematic search of published literature; few additional attributes were identified in this way. A summary of Soil subdomain attributes used in Aotearoa New Zealand are provided in Table 7.

The targeted search of international literature (unpublished and published) demonstrated the extent to which soil indicators and measures of soil health are an active area of research in Europe and the USA, primarily in relation to agroecosystems. While a significant number of additional attributes could be added as a result of review of the international literature (e.g., Zwetsloot et al. [2022] includes a list of 289 measures used to assess soil biology and biological processes in soil, and an earlier European assessment of soil indicators identified 290 potential indicators related to 188 key issues for 9 soil threats [Huber et al. 2008]) we included only those that that addressed material gaps in the compiled attributes.

The national and international literature on soil quality/health measures is dominated by studies on agroecosystems, although some studies focused on soil quality in other systems (e.g., O'Neil et al. 2005). From a contaminant perspective, there is a wealth of literature on the assessment and management of soil contaminants. This literature includes remediation or rehabilitation of soils impacted by contamination, both within and outside of agricultural environments. However, these studies tend to have a more limited range of soil attributes outside of contaminant concentrations or toxicity assessments and hence were not targeted in ad hoc searching.

Table 7. Commonly used Soil attributes used in Aotearoa New Zealand (NZ), along with less commonly used but potentially useful attributes (labelled 'other potential attributes'). Attributes were collated from a systematic and ad hoc review of Aotearoa New Zealand-based literature. 'Group' is based on logical grouping for a set of related attributes. Almost all attributes are used at a single time-point at a small spatial scale. For the full list of potential attributes and accompanying metadata, see Appendix 1 (supplementary file). Note that many attributes are used to answer study-specific questions; only a subset are used specifically for monitoring purposes. Attributes either represent individual attributes or attribute topics.

Ecological integrity component	**Group**	**Commonly used potential attributes**	**Other potential attributes**	**Further attribute details**
Ecological Representation		*No attributes found*		Note text commentary on representation.
Composition	Microbial	Bacterial community composition	Targeted functional groups (e.g., ammonia-oxidising bacteria and archaea)	
		Fungal community composition		
		Microbial biomass carbon	Archaeal community composition	
	Mesofauna	Nematode abundance	Mites, Collembola, enchytraeids	Many different groups, individual expertise.
		Nematode community composition		
		Nematode functional groups		
	Macrofauna	Earthworms	Gastropods, Araneae, Arthropods, etc.	The macrofauna groups targeted within NZ are variable and partly driven by individual expertise.
	Microbial diversity	Richness		
	Mesofauna diversity	Nematode richness	Other mesofauna richness	
	Macrofauna diversity	Richness		
Structure (biotic)	Microbial structure metrics	Fungal: bacterial ratio		Indicative of nutrient cycling rates.
		Gram positive: gram negative ratio		Indicative of changes in nutrient cycling or carbon and water availability.

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure (biotic), cont.	Mesofauna structure metrics		Plant parasite index	Nematode-based metrics give an indication of the relative abundance of different energy pathways within soil which relates to nutrient cycling pathways; other indices are indicative of community stability and resource enrichment.
		Nematode channel ratio Nematode maturity index	Enrichment index	
			Nematode Structure index	
Structure (chemical)	Carbon-related variables	% Carbon	Carbon stocks Labile carbon pools (e.g., hot and cold-water extractable carbon)	
			Particulate organic matter, mineral-associated organic matter	
	Nitrogen-related variables	% Nitrogen	Dissolved organic nitrogen	
		Ammonium and nitrate (mineral nitrogen)	Aerobic mineralisable nitrogen	
		Anaerobic mineralisable nitrogen	Hot-water extractable nitrogen	
			Nitrogen stocks	
	Phosphorus-related variables	Total phosphorus	Phosphorus fractions	
		Olsen phosphorus	Bray phosphorus	
		Phosphorus-retention (Anion-storage capacity)	Phosphorus stocks	
	Chemical Ratios	Carbon:Nitrogen ratio	Nitrogen:Phosphorus	
			Carbon:Phosphorus	
	Base cations	Cation Exchange Capacity	Base saturation	
		Individual cation concentrations		
	Sulphur	Concentration (Total, organic)		
	pH	pH		
	Electrical conductivity	Electrical conductivity		Measures soil salinity.

Ecological integrity component	**Group**	**Commonly used potential attributes**	**Other potential attributes**	**Further attribute details**
Structure (chemical), cont.	Sodium adsorption ratio	Sodium adsorption ratio		Primarily used in context of application of wastewater to land.
	Trace elements (TE)	Basic trace element contaminant suite	Extended TE suite, Selected TE e.g., iron, silica, aluminium, extractable TE e.g., $Ca(Cl)_2$, Mehlich-3	Specific studies can target specific TE or broader range of TE, primarily from a contaminant assessment but can also be for micronutrients and/or soil acidity/aluminium toxicity.
	Organic contaminants	Concentration		Study specific for a range of contaminants e.g., PAH, pesticides.
Structure (physical)	Macroporosity	Macroporosity @ -10kPa	Macroporosity @ other pressures	Used to assess compaction and also relevant for the assessment of soil hydraulic properties.
		Macroporosity @ -1500kPa (wilting point)	Total porosity	
	Bulk density	Bulk density[1]		Related to soil compaction.
	Soil texture	Particle size		Relates to sand, silt and clay contents.
	Water-related metrics	Water holding capacity	Near-saturated/Unsaturated hydraulic conductivity	Relevant attributes will be dependent on purpose for use.
		Gravimetric moisture content	Hydrophobicity	
		Other	Water table level	
			Mottling, Soil colour (Maunsell colour chart)	Colour and mottling relevant for hydric (wetland) soils.
			Continuous measurement via sensors	
			Critical source area (broader spatial scale)	
	Aggregates	Aggregate stability	Aggregate size distribution	Aggregate stability refers to the ability of aggregates to maintain structure when subjected to outside forces (typically water).
	Soil penetration resistance	Resistance		Relates to compaction
	Pedology	Soil classification	Stage of development	
			Parent material	
			Soil depth	

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure (physical), cont.	Slope, altitude			Most relevant in context or erosion and / or conservation / indigenous environments.
	Soil temperature	Temperature		
	Litter layer	Depth		
	Sealing	% sealed		
Function	Measured carbon cycling rates	Basal respiration	qCO2 (metabolic quotient)	
		Decomposition rates in situ	Chamber-based respiration	
		Eddy covariance	Methane	Eddy covariance often not replicated across sites as it expensive. It is also used to estimate net primary productivity.
	Modelled carbon cycling	CenW		Models used are expertise related, CenW includes N and P cycling.
	Modelled GHG emissions, modelled N-leaching	Overseer		
	Measured nitrogen cycling rates	N mineralisation rates	Net or potential nitrification rate	
			Nitrous oxide emissions	
			Ammonia deposition and volatilisation	
			N isotopes	
			Denitrification rates	
			Nitrate and ammonium utilisation	
	Enzyme activity	Carbon, nitrogen and phosphorus enzymes	Sulphur enzymes	Various enzymes targeted depending on the study.
	Functional gene abundance	qPCR of specific genes	GeoChip	Variable genes targeted from carbon, nitrogen, phosphorus cycling to disease suppression, stress tolerance, plant growth regulatory genes.
	Catabolic activity	MicroResp	Biolog	
	Water-related rates	Infiltration	Water retention curve	
		Leaching		

Ecological integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Function, cont.	Water-related rates, cont.	Surface run-off	Evapotranspiration	
	Toxicity testing		e.g., Pollution induced community tolerance, Collembolan reproduction test	Study-driven methods, multiple standardised testing available.
	Erosion	Sediment yield, erosion rate		SedNetNZ (modelled estimates, includes erosion via different sources).
Function (ecosystem services)	Provisioning services e.g., primary production	'bundles' of soil processes considered relevant for the different functions/services		Broader soil functions considered in the context of the delivery of ecosystem services.
	Regulating services e.g., flood mitigation, filtering of nutrients and contaminants			
Resilience	Resilience to drought	Lab-based resistance/resilience assay (drought)		

3.2.5. Attribute results summary for Soil

For the Soil subdomain, the EI components of composition, structure, and function dominated the literature. Ecological representation needs to be considered on a broader spatial scale than the Soil attributes are typically used for, and resilience is most often derived from the composition, structure, and/or function attributes and/or how data are collected (e.g., over time after researcher-initiated disturbance).

Attributes include those currently used for state-of-the-environment reporting by regional councils; these focus on soil chemistry (% carbon, % nitrogen, anaerobic mineralisable N, Olsen P, C:N ratios, pH, basic contaminants suite) and some physical variables (macroporosity, bulk density and aggregate stability) but no biological variables or direct measures of biological functions.

Ecological representation

With regards to ecological representation, the distribution of different soils across the landscape will differ due to natural variation in soil-forming factors and this will influence above-ground ecosystems and ecosystem functioning. Ecosystem representation (primarily of vegetation and associated fauna) is typically assumed to be captured through LENZ (which needs updating), while programmes such as S-Map or the Fundamental Soils layer provide coverage of the distribution of soil types across Aotearoa New Zealand. Other attributes such as Land Use Capability may also be useful to inform management activities. Soil type may influence the values measured by some attributes, although land use and associated land management activities will be the dominant influence.

Composition

Within Aotearoa New Zealand, studies on biotic composition are dominated by studies on microbial communities, with the use of other biota (e.g., meso- and macrofauna) largely researcher-driven. Studies on microbial community composition have mainly used phospholipid fatty acids (PLFA) in the past, but molecular approaches are now more commonly used as they provide more detailed information. Molecular approaches, and how best to interpret the resulting data, are currently very active areas of research. Visual identification and counting is primarily used for faunal species, although molecular approaches are also being evaluated.

Structure

There is overlap between biotic attributes of structure and composition where these attributes are based on biota e.g., bacteria, fungi, invertebrates, as structure attributes are often derived from composition data. Similarly, there are a number of biological indicators strongly linked to soil function, for example, various indices of nematode trophic structure and feeding groups. Some attributes that can be assigned as biotic attributes are perhaps more accurately considered as abiotic attributes e.g., soil organic carbon and anaerobic mineralisable nitrogen. Regardless, abiotic attributes dominate the attributes widely used for soil quality monitoring both nationally and internationally and are often relevant for informing assessment of soil function and processes.

Function and processes

There is a wide range of attributes related to specific soil functions or processes with carbon and nitrogen mineralisation most commonly used. There is some variation in the methods used to assess the various functions or processes. Soil function can also be specified at a higher level to indicate ecosystem 'service' delivery (Dominati 2013); this approach is adopted to a greater extent in recent international literature (e.g., Buneman et al. 2018; Creamer et al. 2022).

Resilience

As noted for land, resilience rarely featured in the systematic literature review. Resilience is often calculated based on changes in composition, structure and function attributes through time after disturbance, including after human-induced disturbances. One laboratory-based assay for assessing resilience to drought was identified (Table 7).

Attribute gaps for Aotearoa New Zealand (supplemented by international literature)

There are multiple recent international studies that will be immensely valuable in the further assessment of attributes for use in Aotearoa New Zealand. For example, recent publications include the release of a recommended suite of indicators by the Soil Health Institute in the United States, which draws on an evaluation of soil indicators used across North America (Norris et al. 2022), and multiple papers and reports arising from the EU H2020-funded programme *Landmark* for which the overall scientific aim was to 'Comprehensively quantify the current and potential supply of soil functions across the EU, as determined by soil properties (soil diagnostic criteria), land use (arable, grassland, forestry) and soil management practices with relevance for farmers and farm advisors, legislators and policy-makers https://landmark2020.eu/project-details/.

The European Environment Agency has also released a draft report on indicators and thresholds for soil quality assessments in Europe with a specific focus on soil indicators relevant for assessing threats to soil, including soil erosion and soil sealing and includes a soil loss rate threshold of $2t{\cdot}ha^{-1}{\cdot}y^{-1}$ (Bartiz et al. 2021). Bagnall et al. (2022) provide an evaluation of soil hydraulic properties for the assessment of soil health; Lipztin et al. (2022) provides an evaluation of soil organic carbon indicators; Griffiths et al. (2018) and Zwetsloot et al. (2022) provide evaluation and approaches to the use of soil biological indicators. The Soil Health Institute has recently recommended that soil organic carbon concentration, carbon mineralisation potential, and aggregate stability provide the minimal suite of measurements be widely applied across North America (and likely beyond) for the assessment of soil health.

Wood et al. (2022) asked whether there is sufficient knowledge in the 'right' areas to effectively use soil health indicators, for example, is an increase in a soil health property good or bad? How much do desirable outcomes change when a soil property changes, and is the relationship between the two linear?

Emerging attributes

Methods used to quantify some variables are changing, with the use of molecular methods to measure soil biology and ecosystem functions increasing significantly, and the use of attributes such as hot water extractable carbon, and particulate organic matter:mineral-associated organic matter ratios are also increasing in popularity.

3.3. Freshwater

3.3.1. Summary of search results and potential attributes

The systematic literature search of the WoS core collection returned 708 results for Freshwater articles (Table 4). Screening of titles and abstracts for relevance to EI in Aotearoa New Zealand led to 145 relevant articles for Freshwater from which to compile attributes and metadata; this was further reduced to 100 articles on inspection of full texts. From these, 252 potential attributes with accompanying metadata were compiled, primarily related to biotic structure and composition (see Table 8).

The results from the systematic search were supplemented with further ad hoc searches of both Aotearoa New Zealand and international literature, which spanned published literature, grey literature and monitoring frameworks (Table 5), as well as expert knowledge from the authors. The ad hoc searches added 89 additional potential attributes including those related to wetlands, groundwater, and abiotic structure. These searches also identified different subdomains for 25 attributes already recorded from the systematic search, including attributes already used as limit-setting attributes within Aotearoa New Zealand. For example, while bacterial, dissolved organic carbon and nutrient concentrations were recorded for monitoring lakes and rivers multiple times in the published literature, the use of these attributes for monitoring groundwater was only recorded in the unpublished literature. Additionally, most attributes related to wetland condition, such as wetland extent or vegetation condition, were only found through the ad hoc searches. There was also a potential mismatch between the prevalence of some attributes in the published literature (vs the unpublished literature) and their relevance for defining limits or targets i.e., chlorophyll-*a* (chl-*a*) concentration and periphyton biomass are attributes that are already widely used for monitoring in Aotearoa New Zealand but did not feature frequently in the published literature.

Table 8. Commonly used <u>Freshwater</u> potential attributes in Aotearoa New Zealand, along with less commonly used but potentially useful attributes (labelled 'other potential attributes'). Attributes were collated from a systematic and ad hoc review of Aotearoa New Zealand-based literature. 'Group' is based on logical grouping for a set of related attributes. Almost all attributes are used at a single time-point at a small spatial scale. For the full list of potential attributes and accompanying metadata, see Appendix 1 (supplementary file). Note that many attributes are used to answer study-specific questions; only a subset are used specifically for monitoring purposes.

Ecological Integrity component	**Group**	**Commonly used potential attributes**	**Other potential attributes**	**Further attribute details**
Ecological representation		*No attributes found*		
Composition	Fish	Fish biomass		
		Fish Index of Biotic Integrity (Fish IBI)	Fish abundance, fish density	
	Invertebrates	% Ephemeroptera, Plecoptera, Trichoptera (EPT) density		
		% EPT richness		
		Average score per metric		
		Delta-15N of primary consumers		Metric calculated from food web isotope values.
		EPT density		
		EPT richness		
		Macroinvertebrate biomass		
		Macroinvertebrate community assemblage change		Differences in communities over space or time (beta diversity).
		Macroinvertebrate community composition		
		Macroinvertebrate Community Index (MCI)		
		Macroinvertebrate density		
		Macroinvertebrate diversity		Shannon or Simpson diversity calculated from species presence and abundance.
		Macroinvertebrate functional diversity		Diversity of functional groups e.g., functional feeding groups.
		Macroinvertebrate taxonomic richness		

Ecological Integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Composition		Macroinvertebrate trait composition		
		Quantitative Macroinvertebrate Community Index (QMCI)		
		Zooplankton community composition		
	Microbes	Bacterial community composition	Fungal community composition	Emerging attribute–- rRNA extraction used for taxa identification.
		Escherichia coli (*E. coli*) concentration		
		Faecal coliform concentration		
		Microbial community composition		Emerging attribute–- rRNA extraction used for taxa identification.
		Microbial diversity		Emerging attribute–- taxonomic richness and diversity assessed using eDNA or rRNA.
	Primary producers	Periphyton biomass	Periphyton accumulation	Assessed as either chlorophyll-*a* or total biomass.
		Periphyton taxonomic richness		
		Planktonic cyanobacterial biovolume		
Structure (abiotic)	Ecosystem intactness	Alteration of drainage		
		Connectivity barriers		Assessment of barriers preventing movement of water, resources, and animals between water bodies and with adjacent land ecosystems.
		Wetland extent		Component of the Wetland Condition Index, potentially falls under the land domain.
	Environmental tracers	Chlorofluorocarbons– 11, 12 & 13, Deuterium, Oxygen-18, Radon, Sulphur hexafluoride, Tritium		Generally considered descriptive attributes for ageing groundwater, but included as water quality measurements within the NEMS for Discrete Groundwater Quality.
	Habitat	Catchment erosion susceptibility		Potentially falls under the land domain.
		Degree of sedimentation/ erosion		Qualitative component of Wetland Condition Index.
		Fine sediment cover		

Ecological Integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure (abiotic), cont	Habitat, cont	Fish spawning habitat extent		
		Habitat Quality Index		Qualitative rapid habitat assessment combining sedimentation, instream habitat and riparian vegetation
.		Streambank erosion susceptibility		
		Substrate composition	Particle size, Substrate embeddedness	
	Hydraulic integrity	1 in 5-year low flow		
		7-day mean annual low flow (MALF)		
		Artificial impervious land cover		Potentially falls under the Land (including Soil) domain, component of wetland Index of Ecological Integrity.
		Bed movement	Instability Index	
		Discharge		
		Drainage alteration		Component of wetland Index of Ecological Integrity.
		Flow velocity		
		Frequency of events exceeding three times the median flow (FRE3)		
		Groundwater depletion		
		Groundwater discharge rate		
		River disturbance index		
		Groundwater level	Water table height	Also assessed within the Soil subdomain.
		Groundwater level variability		
		Groundwater recharge rate		
		Groundwater volume/flow		
		Mean flow		
		Mean flow in the naturally driest calendar month	Proportion of flow in February	

Ecological Integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure (abiotic), cont.		Stream depth		
		Wetted width		
	Physico-chemical conditions	Ammonium nitrogen (NH4-N)		
		Chlorophyll-*a*		
		Dissolved metals & trace ions (aluminium, arsenic, bicarbonate, bromide, cadmium, carbon dioxide, carbonate, chloride, chromium, copper, fluoride, iron, lead, magnesium, manganese, potassium, silica (reactive), sodium, sulphate, zinc)		
		Dissolved organic carbon		
		Dissolved oxygen		
		Dissolved Reactive Phosphorus (DRP)		
		Euphotic depth	Water clarity	Also referred to as Secchi depth.
		Nitrate (NO_3-N)		Key measure of nitrogen toxicity
		Nitrate leaching risk		Qualitative component of wetland Index of Ecological Integrity determined using catchment mapping.
		Nitrate-nitrite N (nOx-N)	Nitrite nitrogen (NO2-N)	Key driver of periphyton biomass.
		pH		
		Soluble reactive phosphorus (SRP)		
		Specific conductivity		
		Total Nitrogen (TN)		Can be measured or modelled with catchment data (e.g., Freshwater Environments of New Zealand (FENZ) or Catchment Land Use for Environmental Sustainability (CLUES)).
		Total (dissolved) alkalinity		
		Total (dissolved) hardness		
		Total dissolved salts		
		Total dissolved solids		

Ecological Integrity component	Group	Commonly used potential attributes	Other potential attributes	Further attribute details
Structure (abiotic), cont.	Physico-chemical conditions	Total Oxidised Nitrogen (TON)		
		Total Phosphorus (TP)		Can be measured or modelled with catchment data (e.g., FENZ or CLUES).
		Total suspended solids		
		Trophic Lake index (TLI)		Calculated from Chlorophyll-*a*, euphotic depth, TN & TP.
		Turbidity		
		Water clarity		
		Water temperature		
	Sediment	Suspendable sediment		
Structure (biotic)	Browsing & predation	Damage by domestic or feral animals		Wetland specific, component of Wetland Condition Index.
		Introduced predator impacts on wildlife		Wetland specific, component of Wetland Condition Index.
	Ecosystem intactness	Fire damage		Wetland specific, component of Wetland Condition Index.
		Introduced fish presence		Component of the Wetland Condition Index.
		Wetland extent		Component of the Wetland Condition Index.
	Food webs	Carbon range, Food chain length, Nearest neighbour distance, Trophic area		Metric calculated from food web isotope values–- likely impractical for regular monitoring.
	Primary producers	Algal traits		Life history, physiological and morphological traits of algal taxa present.
		Introduced plant canopy cover		Wetland specific, component of Wetland Condition Index.
		Introduced plant understorey cover		Wetland specific, component of Wetland Condition Index.
		Lake Submerged Plant Index–- Native Condition Index		
		Lake Submerged Plant Index–- Invasive Impact Index		
		Macrophyte cover		
		Natural vegetation cover		Specifically addressing wetlands.
		Riparian vegetation cover		

Ecological Integrity component	**Group**	**Commonly used potential attributes**	**Other potential attributes**	**Further attribute details**
Function		Ecosystem metabolism		Determined using open channel measurements of dissolved oxygen.
		Humification		Component of Wetland Condition Index indicating soil decomposition in wetlands–- Potentially falls under the Land (including Soil) domain.
		Organic matter decomposition		
		Periphyton accumulation	Periphyton biomass	Assessed as either chlorophyll-*a* or total biomass accrued over time.
Resilience		*Change in composition/structure attributes over time or in response to disturbance*	*Food web stability*	*Uncommon*

3.3.2. Attribute results summary

Within the Freshwater domain, the systematic search returned an abundance of results relating to attributes of EI. From the initially high number of results, many papers were rejected based on having been done overseas (despite having Aotearoa New Zealand-based contributors or references), addressing other domains or not assessing ecological responses. Of the 252 potential attributes identified, most attributes related to the EI components of structure and composition, with some measures of function, few measures of resilience and no attributes relating to ecological representation. The majority of studies used fine-scale, single point measurements of EI attributes to assess ecosystem responses relative to reference conditions or between treatment groups, with minimal consideration given to defining EI.

Ecological representation

As with the Soil subdomain, ecological representation needs to be considered on a broader spatial scale than was directly assessed by Freshwater attributes we identified. No attributes of ecological representativeness were identified through either the systematic or the subsequent ad hoc searches. However, resources do exist for assessing representation. The Freshwater Environments of New Zealand data base (FENZ; Leathwick et al. 2010) and NZ Rivers Map interactive mapping tool (Whitehead & Booker 2019) provide information that classifies ecologically similar rivers and streams, lakes and wetlands, and predicts hydrology, habitat and biotic indices for all river reaches in Aotearoa New Zealand. In addition, the New Zealand Freshwater Fish Database offers a national scale public record of fish observations and distribution patterns.

Composition

Attributes related to composition employ measures of abundance and diversity, as well as multivariate analyses to assess differences in the diversity and abundance of algal, macroinvertebrate, macrophyte and microbial communities. Measures of composition incorporate all fish-, macroinvertebrate- and microbe-related attributes, including attributes used in existing regional and national monitoring programs. The complexity of attributes related to composition ranged from simple counts through to calculated indices employing species abundance and known tolerances (e.g., Fish IBI and MCI) and multivariate analyses. As a result, the specific attributes employed in a given study were selected to address the specific aims of that study. Measures of composition were employed across rivers, lakes, and wetlands to measure either how composition shifted over time or space in response to environmental variation or compare attribute results to pre-defined condition bands. Many measures of composition employed either visual or genetic identification of taxa, although some measures went beyond taxonomic identity to consider species function (i.e., trait composition).

Structure

Structural measures of habitat, hydraulic and physico-chemical conditions were very common. Further measures of introduced species impacts, food webs and primary producer characteristics were also found. This is very likely a reflection of the widespread use of abiotic structural measures (see Table 8) in existing regional and national monitoring programs, as these measures are a practical way to assess environmental conditions. Measures of biotic structure were focused around riparian and submerged vegetation cover, but also included food web characteristics and assessments of the impact of introduced species and fire. Alongside these specific attributes, aggregate indices that combine multiple variables into a single ecosystem condition value were also recorded (e.g., Trophic Lake Index, Wetland Condition Index).

In addition, many attributes related to hydraulic integrity were retrieved through the ad hoc search – due to attributes specifically addressing hydrology rather than ecology. The separation between ecological and hydraulic integrity attributes arose from the different time frames and approaches required to evaluate hydrological and ecological variables. While hydraulic integrity was identified as a relevant environmental issue in the ecological studies returned by the systematic search, these studies were mostly short-term assessments of ecological responses to artificially manipulated reductions in water flow or increases in water temperature studies. In contrast, the development of hydraulic attributes considered multi-year time series information on water quantity to characterise river flow regimes.

Function and processes

Functional attributes were focused on primary production and decomposition, with ecosystem metabolism, gross primary production and organic matter decomposition being most prevalent. As these attributes directly assess the supply and cycling of food resources and nutrients within ecosystems, they are highly relevant measures of ecosystem function. Other less prevalent measures of function were the retention of coarse particulate organic matter and sediment, the accumulation of periphyton, microbial activity and the dispersal of macroinvertebrates. Given that ecological functions are inherently processes, functional attributes tended to be measured over short time periods, with the resultant rates then extrapolated to longer time scales.

Resilience

Attributes relating to resilience were identified but not common. The resilience-related attributes were derived from assessing how structure or composition changed over time in response to disturbance e.g., changes in species richness or in the prevalence of specific traits. The attributes were identified from experimental studies of ecosystem responses to artificially manipulated environmental stressors.

Attribute gaps for Aotearoa New Zealand (supplemented by international literature)

Comparison of literature from Aotearoa New Zealand with overseas literature and monitoring frameworks identified gaps relating to wetlands, groundwater and hydrological attributes. While international frameworks largely employed similar attributes—because attributes of EI (and ecological health) are relatively well developed in the Freshwater domain (e.g., Clapcott et al. 2018), many attributes related to the wetland and groundwater subdomains were only found within the grey literature. In addition, a key suite of attributes relating to chemical contaminants (e.g., pesticides) was only found within international monitoring frameworks. Hydrological attributes were already assessed within the published literature from Aotearoa New Zealand, but articles seldom contained ecological components and hydrological indices were generally poorly utilised relative to other countries. For example, attributes of habitat and hydrological connectivity were only found in international literature. Additionally, attributes spanning the overlap between domains (e.g., the riparian zone) were rare and specific attributes relating to temporary waters (e.g., ephemeral stream or spring habitats) were not found. There was also little consideration of larger scale processes such as habitat connectivity or the persistence of cyclical patterns over time (e.g., fish spawning).

Emerging attributes

Molecular indicators for biotic structure and composition were identified as the main field of development for new EI attributes for freshwater. Specifically, eDNA or rRNA approaches were identified as potentially allowing a more complete assessment of taxonomic groups, or assessment of bacterial or fungal communities (Jackson et al. 2016; Wood et al. 2021).

3.4. Coastal and Seabed, and Estuaries

3.4.1. Summary of search results and potential attributes

The systematic literature search of the WoS core collection returned 561 results for Coastal and Seabed and 209 results for Estuaries (Table 4). An exclusion used in our search was for Atmosphere/Meteorological sciences in relation to discipline. Screening of titles and abstracts (and full texts in some cases) for relevance to EI in Aotearoa New Zealand led to 41 and 75 relevant articles for Coastal and Seabed, and Estuaries, respectively, from which to compile potential attributes and metadata. The results from the systematic search were supplemented with further ad hoc searches of both Aotearoa New Zealand and international literature, which spanned published and unpublished literature and monitoring frameworks (Table 5), as well as expert knowledge from the authors and additional experts (see Acknowledgements). The attributes compiled through ad hoc searches represented a high proportion of the potential attributes (more than half of those compiled, Aotearoa New Zealand and international combined). Information from attributes gained through ad hoc searching was also used to supplement metadata for attributes already compiled through the systematic search (e.g., additional domains, subdomains, or methods) although this was not exhaustive. Additional information on subdomains may need to be obtained during Phase 2 of the project, which could be done for a refined set of attributes. For example, additional subdomain information could be in relation to estuary 'type' (e.g., as in Hume et al. 2016) or whether the attribute is applicable to a subtidal or intertidal environment (if relevant).

Overall, > 580 potential attributes and/or attribute topics (Coastal and Seabed, and Estuaries combined) with accompanying metadata were compiled from search results (see Table 9 for commonly used attributes). For practicality, many of the potential attributes were grouped as 'attribute topics' for which multiple attributes were represented under one 'attribute topic'. If attributes were presented individually, the compiled list of these would been extremely large. Many of the compiled attributes related to both 'Coastal and Seabed' and 'Estuaries', given the environmental similarities between these domains. In some cases, the exact domain the attribute related to was not specified. To cater for this, we assigned these attributes under the 'Coastal' domain but only after we had judged that they didn't only apply to areas outside the seaward boundary of the coastal domain (if they did then they were not compiled in our attribute list). The 'Coastal' domain was also assigned if the attribute related to both coastal areas and estuaries; however, only the Estuaries domain was assigned if the attribute only related to estuaries and not also to Coastal. Other domains (Air, Land [including Soil]) were also noted (in Appendix 1) where the attributes were also applied in these domains.

Table 9. Commonly used Coastal and Seabed and Estuaries potential attributes used in Aotearoa New Zealand. Attributes were collated from a systematic and ad hoc review of New Zealand-based literature. 'Group' is based on logical grouping for a set of related attributes. For the full list of potential attributes and accompanying metadata, see Appendix 1 (supplementary file). Note that many attributes are used to answer study-specific questions; only a subset are used specifically for monitoring purposes. Attributes either represent individual attributes or attribute topics.

Ecological Integrity Component	**Group**	**Commonly used potential attributes**	**Further attribute details**	**Domain** (note the use of 'Coastal' here can include estuaries but 'Estuaries' means estuaries only)
Ecological Representation	Habitats or substrates	Habitat or substrate area or extent (broad-scale) *For example, in relation to intertidal and subtidal habitats, subtidal biotopes, biogenic habitats (including increasing or declining), dominant substrates, coastal wetland (seagrass, saltmarsh, mangrove), macroalgae including blooms, changes in spatial coverage of Submerged Aquatic Vegetation and Gross Nuisance Areas.*	Various attributes used across subdomains, but all use broad-scale methods to measure broad-scale area/extent	Coastal
	Human activities	Human activities area or extent (broad-scale) *For example, in relation to commercial coastal seabed trawling and dredging, activities and impacts (e.g., coastal hardening, coastal dredging, commercial fishing, recreational fishing and harvesting, aquaculture, shipping) and marine protected areas including compliance.*		Coastal
	Oceanographic	Oceanographic features area or extent (broad-scale) *For example, sea surface temperature, water column primary productivity (measured using remote sensing).*		Coastal
Composition	Algae	Microalgae (phytoplankton, microalgae, cyanobacteria) species: abundance of individuals *For example, cell counts and chlorophyll-*a *or fluorescence used as a proxy.*		Coastal
		Opportunistic Macroalgal Blooming Tool score	Index calculated from various parameters, including those relating to	Estuaries

Ecological Integrity Component	Group	Commonly used potential attributes	Further attribute details	Domain (note the use of 'Coastal' here can include estuaries but 'Estuaries' means estuaries only)
Composition, cont**.**			composition, structure and representation	
	Birds	Bird-related population measures *For example, indigenous shorebird numbers, assemblage metrics of sea and shore birds such as counts and assessment of species viability.*		Coastal
	Epibiota and epifauna (soft sediment)	Epibiotic and epifauna soft sediment communities; abundance and diversity		Coastal
	Fish	Fish abundance and diversity metrics *For example, abundance, diversity, and demographic attributes, community indices, changes in distribution, assemblage metrics of large predatory fish such as counts and assessment of species viability, fish functional richness, evenness, indices and modelling.*	Relate to various types of fish (e.g., reef, demersal) depending on the attribute	Coastal
	Fisheries stocks and bycatch	Fisheries-related measures of stocks and bycatch *For example, fish state of stocks and bycatch, scallop population indices, commercial catch, bycatch of protected seabird, sea lion and fur seal species.*		Coastal
	Habitat	Habitat types number and diversity		Coastal
	Marine mammals	Assemblage metrics of marine mammals e.g., based on counts and assessment of species viability.		Coastal
	Macroinvertebrates	Macroinvertebrate indices (multivariate and univariate) *For example, abundance, richness, evenness, NZ-AMBI, key taxa population structure, functional group metrics, Traits Based Index, National Benthic Health Models for mud and metals, community composition (multivariate analysis)*		Coastal
	Rocky reef	Intertidal and subtidal community abundance and diversity		Coastal

Ecological Integrity Component	**Group**	**Commonly used potential attributes**	**Further attribute details**	**Domain** (note the use of 'Coastal' here can include estuaries but 'Estuaries' means estuaries only)
Composition, cont**.**	Rocky reef, cont.	*For example, community indices for invertebrates and macroalgae*.		
	Species	Indigenous or non-indigenous (including high risk), key pest species. *For example, number of threatened/at risk/extinction status, outbreaks, richness, abundance, movement, Invasive species (presence or spread, outbreaks, number recognised as major threats)*		Coastal
	Microbial	Microbial (e.g., Faecal coliforms, Enterococci, *Escherichia coli*) concentrations in water		Coastal
Structure	Birds	Bird-related 'non-population' measures *For example, indigenous shorebird status, range and description of important breeding and non-breeding sites.*		Coastal
	Contamination or toxins in organisms	Contaminants or toxins in organisms *For example, organism (resident) contaminant levels, Faecal indicator bacteria, trace metals in mussel tissues, contamination in fish tissues, cyanobacteria toxin concentrations*		Coastal
	Eutrophication	Eutrophication and/or enrichment-related indices or assessment *For example, Enrichment Stage, Eutrophication indices or assessment*		Estuaries
	Litter	Litter-related (e.g., plastic, rubbish) measures *For example, beach litter density and percentage item count and weight per type*		Coastal
	Seagrass	Physical measures of seagrass		Coastal

Ecological Integrity Component	Group	Commonly used potential attributes	Further attribute details	Domain (note the use of 'Coastal' here can include estuaries but 'Estuaries' means estuaries only)
Structure, cont.	Seagrass, cont.	*For example, shoot and leaf density, leaf length, above ground biomass (leaves) and below ground biomass (rhizomes).*		
		Indirect indicators of seagrass health *For example, amount or presence of fungal wasting disease, fine-scale epiphyte/sediment/macroalgal cover.*		Coastal
	Sediment	Metals concentrations		Coastal
		Sediment characteristics (multivariate analysis)		Coastal
		Grain size composition, including percent mud		Coastal
		Nutrient concentrations		Coastal
		Organic content		Coastal
		Redox, including depth of/to redox discontinuity layer [RPD]		Coastal
		Sulphide concentrations		Estuaries
	Substrates and organisms (fine-scale area)	Substrates and organisms, area of (fine-scale) *For example, percent cover of sessile rocky reef organisms and substrates, or seagrass or soft sediment benthic macroalgae*		Coastal
	Water	Metals concentrations		Coastal
		Absorbance, colour, clarity		Coastal
		Oxygen-related measures *For example, dissolved or saturated oxygen, biological or biochemical oxygen demand*		Coastal
		Organic carbon or particulate carbon		Coastal
		Water level, e.g., sea level		Coastal

Ecological Integrity Component	**Group**	**Commonly used potential attributes**	**Further attribute details**	**Domain** (note the use of 'Coastal' here can include estuaries but 'Estuaries' means estuaries only)
Structure, cont.	Water, cont.	Light, including photosynthetically active radiation, irradiance		Coastal
		Nutrient concentrations, e.g., nitrogen and phosphorus and related species		Coastal
		Oxidation-reduction potential		Coastal
		pH		Coastal
		Salinity, conductivity		Coastal
		Temperature *For example, sea surface temperature and marine heatwave forecasting.*		Coastal
		Turbidity, also suspended particulate matter and suspended solids/sediments		Coastal
	Wave events	Extreme wave events		Coastal
Function	Benthic fluxes	Benthic fluxes *For example, nutrient- and oxygen-related*		Estuaries
	Nutrient, sediment and *E. coli loads*	Nutrient, sediment and *E. coli* loads *For example, modelled using Catchment Land Use for Environmental Sustainability (CLUES)*		Estuaries
	Sediment accumulation	Sediment accumulation rate		Estuaries
Resilience	Eutrophication	Eutrophic Susceptibility of estuaries *For example, various individual measures such as flushing potential, dilution potential, physical susceptibility or export potential, nutrient load threshold, nutrient load and closure period (for intermittently closed/open lakes and lagoons / estuaries)*		Estuaries

3.4.2. Attribute results summary

Our literature searches for the Coastal and Seabed, and Estuaries (i.e., marine-related) domains led to the compilation of a high number (> 580) of potential attributes of EI (including attribute topics). Most of these were from Aotearoa New Zealand, which aligns with the fact that marine environmental monitoring is regularly carried out at local and regional scales here (e.g., for state of the environment and resource consent-related purposes) (e.g., Hewitt et al. 2014; Zaiko et al. 2018). However, attributes of EI are generally not well developed (e.g., standardised) at the national level for Aotearoa New Zealand's coastal waters and estuaries (PCE 2020). Fisheries-related attributes, that are relevant to EI, for coastal waters and estuaries are also commonly used in Aotearoa New Zealand (e.g., as reported in Our Marine Environment 2019). Our compiled attributes primarily relate to the EI components composition and structure, followed by ecological representation and function and with very few relating directly to resilience. These results are discussed in more detail below in the context of each EI component, as well as in relation to potential attribute gaps for Aotearoa New Zealand and emerging developments.

Ecological representation

As with the Soil subdomain and Freshwater domain, ecological representation within the marine-related domains needs to be considered on a broader spatial scale than was directly assessed by most of the attributes. However, there is no definition for broad- vs fine-scale in this context. Furthermore, fine-scale data can often be aggregated and/or extrapolated into broad-scale data.

Nevertheless, a considerable number of commonly used attributes for these two domains were assigned to the 'ecological representation' component of EI. These were related to broad-scale area of habitat or substrates (subtidal or intertidal), and oceanographic features. They also related to the area of human activities such as commercial coastal seabed trawling and dredging, coastal hardening and dredging, commercial and recreational fishing, aquaculture and shipping (Our Marine Environment 2019). Note that ecological classifications, such as those previously summarised by MfE[4], may also prove useful for developing and measuring attributes for ecological representation. Examples of classifications include the Land Cover Database (e.g., in relation to coastal wetlands), DOC's portal containing seagrass and mangrove area cover[5], Coastal and Marine Habitat and Ecosystem Classification System (CMHEC) and the New Zealand Seafloor Community Classification (Stephenson et al. 2021).

[4] https://environment.govt.nz/publications/environment-new-zealand-2007/chapter-1-environmental-reporting/ecological-classifications/

[5] https://www.doc.govt.nz/nature/habitats/estuaries/our-estuaries/seagrass-and-mangrove-extent/

Composition

A high proportion of commonly used attributes relate to composition, which likely reflects the widespread use of many of these attributes in regional monitoring programmes (e.g., Robertson et al. 2002; Hewitt et al. 2014) and research. The attributes fitted within various biological groupings including algae, birds, epi-fauna or biota, fish, fisheries stocks and bycatch, habitats, marine mammals, soft sediment macroinvertebrates, rocky reef, indigenous and non-indigenous species and microbiology. Commonly used attributes identified in relation to 'fisheries stocks and bycatch' likely reflects the large impacts that fisheries-based activities can have on marine ecosystems and species in Aotearoa New Zealand (e.g., Our Marine Environment 2019, Durante et al. 2020, Edgar et al. 2017, Fisheries New Zealand 2022).

The 'composition' component is specifically defined by MfE as relating to species, habitats and communities that are indigenous only. Therefore, it was not obvious how to assign attributes for non-indigenous (e.g., invasive) species that related to composition (e.g., abundance and diversity). Furthermore, many commonly used composition attributes did not specifically relate to indigenous elements. For example, abundance and diversity indices for benthic macroinvertebrate communities encompass all taxa regardless of whether they are indigenous or not. In this regard, they therefore technically do not meet the composition requirements under the MfE EI definition. In terms of spatial scale, attributes relating to fine scales (e.g., percent cover of organisms or substrates in quadrats) were included under composition. However, as mentioned for ecological representation above, there was no cut-off for defining fine vs broad scales in this context.

Structure

Many of our compiled potential attributes of EI for the marine-related domains were assigned under the 'structure' component. As for composition, this likely reflects the widespread use of many attributes in regional monitoring programmes (e.g., Robertson et al. 2002; Hewitt et al. 2014) and research. Commonly used structural attributes related to the water column, sediment quality, contamination or toxins in organisms, litter (e.g., plastic or rubbish) and wave events. Other groupings, largely biotic, were seagrass, birds, substrates and organisms (fine-scale cover or area), as well as eutrophication.

Function and processes

Very few commonly used potential attributes were assigned under the 'function' component of EI. Those that were, related to sediment accumulation rate, benthic fluxes (e.g., in regards to oxygen and nutrients) and nutrient, *E. coli* and sediment loads in estuaries (e.g., based on catchment modelling). Primary productivity of phytoplankton (often measured by cell counts or using chl-*a* as a proxy) could also be considered under function; however, this was often measured 'point in time' (rather than as a rate over time) and therefore was considered to relate more directly to composition or structure than function. The small number of commonly used function-related attributes may be due to the difficulty of study (they are often technically more complex or more time consuming to determine) relative to the attributes under ecological representation, composition and structure. Note that indices (e.g., the macroinvertebrate Traits Based Index [TBI]) that measure abundance and/or diversity of functional traits, species and groups were assigned under composition rather than under function.

Resilience

The only attribute for resilience considered to be commonly used in Aotearoa New Zealand was 'Eutrophication susceptibility of estuaries'. Some attributes assigned under other EI components can also be used to assess resilience. For example, the TBI indicates functional redundancy (a measure of resilience) but is constructed from the richness of macrofaunal taxa in seven functional groups (Rodil et al. 2013), and therefore was assigned under 'composition' (but, as mentioned above, it also relates to function). Another example of interrelatedness between resilience and other EI components is demonstrated by an experimental study on macrobenthic recovery processes following catastrophic sedimentation on estuarine sandflats (Thrush et al. 2003). This study measured recovery (which could be considered a measure of resilience) using compositional attributes such as macroinvertebrate abundance and numbers of taxa.

Gaps for Aotearoa New Zealand (supplemented by international literature)

We filled gaps in the list of potential attributes (or attribute topics) for Aotearoa New Zealand by supplementing from the international literature (monitoring frameworks). Examples of attributes used overseas but not used commonly or at all in Aotearoa New Zealand included size of hypoxic zone and soundscape mapping in relation to underwater noise (in relation to ecological representation), fish kills, litter-related (e.g., plastic, rubbish) deaths of marine animals and seagrass root microbiome (in relation to composition) and seagrass ecosystem function (including secondary production) and organic carbon metabolism (in relation to function). Also, functional traits analysis has been widely applied overseas to understand the functional response of biological communities to environmental and pressure gradients (Smit et al. 2021); however, this type of analysis was less common in the domestic literature we searched.

There were also many international multi-metric indices, especially in relation to eutrophication and/or macroinvertebrates but also to habitat quality, including wetland condition (e.g., wetland stress indices). Many of these comprised individual attributes similar to (or the same as) those already used in Aotearoa New Zealand. However, even aligned attribute terms can be represented by various attributes in terms of methods and metrics used. For example, in terms of methods, chl-*a* in the water column can be measured by instrument (i.e., fluorescence), satellite or laboratory analysis. In terms of metrics, for example, dissolved oxygen can be considered as a percentile (e.g., 10th percentile, Ferreira et al. 2011) or as an average (MPI 2019).

Refer to supplementary file for details on all international attributes compiled (Appendix 1).

Emerging attributes

Quite a few of the articles from which we compiled attributes were relatively recent (published in the past five years). These largely represented experimental and research studies not focused on developing monitoring indicators, although some did have this particular purpose. For example, newly developed potential attributes for Aotearoa New Zealand include the multivariate Benthic Health Models (Clark et al. 2020), which were recently included within an 'estuaries' module for Land, Air, Water Aotearoa (LAWA)[6] for the purpose of monitoring the impacts of sediment mud content and trace metals. There has also been recent development of modelling approaches, for example, a Bayesian Network model to inform the management of multiple stressors (suspended sediment, sediment mud and metal content, and nitrogen inputs) on estuarine ecosystems (Bulmer et al. 2022).

Molecular eDNA indices for environmental monitoring are also under development for Aotearoa New Zealand, for example, for use in monitoring salmon farms in the Marlborough Sounds, Pochon et al. (2021) and estuaries (Clark et al. 2020). Furthermore, a recently funded Cawthron-led research project aims transform coastal monitoring by harnessing microbial communities (using eDNA methods) to disentangle multi-stressor impacts[7]. Another example is a non-invasive method to monitor marine pollution from bacterial DNA present in fish skin mucus (Montenegro et al. 2020).

Other emerging attributes applied in the coastal environment relate to 'contaminants of emerging concern' (Stewart et al. 2016), microplastics (Bridson et al. 2020; Clere et al. 2022) and monitoring of coastal suspended sediment using satellite remote sensing techniques over broad spatial and temporal scales (Pinkerton et al. 2022). Some of the emerging attributes (including approaches) relate to function. For example, the Aquatic Eddy Covariance technique can be used to quantify in situ seafloor metabolism over large areas (including across habitats) of benthic communities (e.g., Rodil et al. 2019[8]). Emerging carbon-related functional attributes include sediment carbon sequestration rate and greenhouse gas (GHG) fluxes of intertidal benthic habitats (Perez et al. 2017; Albot et al. in prep[9], Hamilton et al. 2020) as well as Forensic Carbon Accounting to analyse carbon flows between the atmosphere and ocean, and into and out of seaweeds (Hurd et al. 2022).

[6] https://www.lawa.org.nz/learn/glossary/b/benthic-health-model/

[7] https://www.mbie.govt.nz/science-and-technology/science-and-innovation/funding-information-and-opportunities/investment-funds/endeavour-fund/success-stories/

[8] Study conducted overseas but by authors that have ties to Aotearoa New Zealand.

[9] Albot O, Levy R, Ratcliffe J, Naeher S, Ginnane C, Cooper J, Wood C, Dunbar G (in prep). Blue carbon soil stocks, sources and preservation within New Zealand saltmarshes.

3.5. Air

3.5.1. Summary of search results and potential attributes

The systematic literature search resulted in 936 articles related to the Air domain or subset terms already defined. Further screening for relevance reduced this to 67 articles, from which 15 attributes were identified. Further, targeted literature searches based on those 15 attributes and expert selection (see Table 3) helped to identify another 196 articles after a search through over 7500 records, which included additional metadata to bring the total number of attributes to 37. None of these attributes are specific to Air and each attribute currently identified has some relation to another domain (Freshwater, Land [including Soil] etc.); Table 10 identifies the relevant secondary domains in each case. In addition, the definitions of ecological representation, composition, structure and function provided by MfE mean that for the Air domain all attributes relate to ecological structure because they all are based on abiotic physical features. In addition to attributes that would formally be related to the AIR domain, we also identify a secondary set of confounding attributes that would be important to consider.

Table 10. Potential attributes identified for Air for Aotearoa New Zealand. Attributes were collated from a systematic and ad hoc review of Aotearoa New Zealand-based literature. Most attributes are used across a range of spatial scales and benefit from time series. For the full list of potential attributes and accompanying metadata, see Appendix 1 (supplementary file). Note that many attributes are used to answer study-specific questions; only a subset are used specifically for monitoring purposes. All attributes for the Air domain relate to the EI component 'structure'. Prevalence relates to usage of the attribute in the literature – see Section 2 Methods. Note that some attributes represent confounding factors, which would ideally be considered along with the more common Air attributes.

Attribute class	**Potential attribute**	**Prevalence** L=low M=moderate H=high	**Secondary Domain/s**
Surface pollutants	Particulate matter	L	All
	Airborne microplastics and nanoplastics	M	All
	Biogenic aerosol	L	All
	Tropospheric ozone pollution	L	Land (including Soil), and indigenous biodiversity
	Black carbon	L	Land (including Soil), and indigenous biodiversity
	Sulphur oxides (sOx)	M	Freshwater, Coastal and Seabed, Estuaries, and indigenous biodiversity
	Nitrogen oxides (nOx)	M	All
	Carbon monoxide	L	All
	Ammonia	M	Freshwater, Coastal and Seabed, Estuaries and indigenous biodiversity
	Heavy metals	M	All
	Polycyclic aromatic hydrocarbons (PAHs) and other hydrocarbons	M	All
Stratospheric Ozone Depletion	Stratospheric ozone depletion	H	All
	Ozone depleting substances (CFC11,CFC12,CFC13,HFCs, halons, etc.)	H	All
	Enhanced UV irradiance due to stratospheric ozone depletion	H	Estuaries, Land (including Soil), indigenous biodiversity
Confounding factor attributes			
Teleconnection	El Niño Southern Oscillation index	M	All
	Southern Annular Mode index	M	All
	Interdecadal Pacific Oscillation index	L	All
Light	Light Pollution	M	All
	Surface Solar Irradiance	H	All
	Photosynthetically Active Radiation	M	All
Climate change related attributes			
Temperature	Air temperature: change attributable to human-induced climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Air temperature seasonality: change attributable to human-induced climate change	M	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Reduction in cold weather extremes (e.g., frost days) attributable to climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Increase in hot weather extremes intensity and occurrence attributable to climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.

Attribute class	Potential attribute	Prevalence L=low M=moderate H=high	Secondary Domain/s
Temperature, cont.	Frost days (ETCCDI climate indices)	H	Land (including Soil), indigenous biodiversity.
Precipitation	Precipitation occurrence: change attributable to human-induced climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Precipitation Intensity: change attributable to human-induced climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Precipitation seasonality: change attributable to climate change	M	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Snowfall and snow line change	L	Land (including Soil), indigenous biodiversity.
Greenhouse gases	Carbon dioxide concentration: change attributable to human emissions	H	All
	Nitrous oxide concentration: change attributable to human emissions	M	All
	Methane concentration: change attributable to human emissions	M	All
Other confounding attributes			
	Noise pollution	L	Coastal and Seabed, Estuaries
	Fire indices: change attributable to climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Change in wind and wind extremes attributable to climate change	H	Freshwater, Estuaries, Land (including Soil), indigenous biodiversity.
	Latent Heat flux	H	Land (including Soil) and indigenous biodiversity
	Sensible Heat flux	H	Land (including Soil) and indigenous biodiversity

3.5.2. Attribute results summary

As noted above, based on MfE definitions of the EI components, all of the Air domain attributes we identified relate to *structure*. These metrics are all quantitative and have been studied based on existing networks within Aotearoa New Zealand or can be obtained from international data, such as satellite observations. With some additional collation and analysis, these attributes can be used in an EI context, noting that some datasets are already routinely collated by Statistics New Zealand.

The abiotic physical nature of every attribute identified in the Air domain potentially highlights a weakness when considering the Air domain in the context of EI as defined by MfE. In the atmospheric sciences it would be more common to think about composition attributes in terms of concentrations of chemical species, such as CO, CO_2, CH_4, O_3 and/or pollutants such as particulate matter. State attributes would represent the state of the atmosphere or climate, such as temperature, wind, precipitation, and irradiance.

To allow some grouping in the Air domain, attributes were assigned a prevalence level based on usage in the literature and also a class based on common root causes or impacts. The nine resulting attribute classes relate to a range of possible attributes, some of which may be considered confounding factors that would need to be monitored to be comprehensive or to examine interactions between various environmental issues. Additional commentary on each of these nine classes is provided in Appendix 2, Section 1.

Attribute gaps for Aotearoa New Zealand (supplemented by international literature)

Very little Aotearoa New Zealand based literature is available on issues of surface air pollutants, tropospheric ozone, acidification or eutrophication with a specific focus on how these attributes relate to ecosystems and EI. Other gaps include attributes for airborne microplastics, which are now recognised to be nearly ubiquitous globally and a potential threat to the marine-atmosphere environment (Allen et al. 2022), and noise pollution, which affects multiple domains but appears in the sampled Aotearoa New Zealand literature only in a marine context.

Emerging attributes

The most obvious emerging attribute identified in our literature review relates to airborne microplastics. The very small amount of literature found on microplastics for Aotearoa New Zealand that mentioned airborne sources was all post 2021. The most relevant work was De Bhowmick et al. (2021), which looked at current status and future directions for effort.

4. DEFINING ECOLOGICAL INTEGRITY

Below we discuss differences in the MfE definition of EI (as outlined in the Glossary) in comparison to how EI is defined in the literature for each domain.

4.1. Land (including Soils)

4.1.1. Terrestrial

For terrestrial systems, most studies use definitions of EI that are broadly consistent with the MfE definition, and this is crucial for linking national monitoring efforts and development of indicators with various international efforts or commitments such as Ramsar, CDB and IPBES (see also international frameworks in Table 5 above). These definitions are largely derived from Andreasen et al. (2001) and are widely used for ecological assessment and applications of EI internationally (e.g., Wurtzebach & Schultz 2016; Hansen et al. 2021; see also Brown and Williams 2016) and in New Zealand (McGlone et al. 2020). Some minor differences include the following:

- The widely cited Canada National Parks Act defines EI as 'a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes'. This definition thus focuses on discrete areas (parks) and emphasises persistence of function.
- There is some debate on historic range of variation viz natural range of variation for defining EI, and this aspect of EI definition should be made more explicit for indicators. Preference is normally given to historic range of variation as a baseline (e.g., starting with Egan & Howell 2001).
- A somewhat distinct line of work on EI focuses on quantifying the effects of human pressure, or proxies of human-induced impacts. Here, the absence of human effects (i.e., intactness of a system) is considered to represent high EI (e.g., Theobald 2013; Beyer et al. 2020; see also McGlone et al. 2020). This approach continues to be used in some international studies, particularly for mapping or landscape-scale assessments (e.g., Theobald 2013).

Overall, there is a huge international literature on EI for terrestrial systems, most of which is broadly consistent with the definition used here. Crucially, many international commitments or networks (e.g., CDB, IPBES, GEOBON) use this definition of EI for monitoring and reporting at regional and international levels.

4.1.2. Soil

The term ‘ecological integrity’ is rarely used in discussion of soils. Instead, ‘soil health’ or ‘soil quality’ is typically used although there is debate in the literature about when and where these terminologies might apply, and the real difference between these terms—with many authors considering the terms to be synonymous (see Buneman et al. 2018; Lehmann et al. 2020, and Creamer et al. 2022 for outlines of the debate over time). The simple definition of soil health as 'the continued capacity of a soil to function as a vital living ecosystem that sustains plants, animals and humans', originating from the USDA-NCRS[10], has been used in several recent papers (e.g., Creamer et al. 2022; Liptzen et al. 2022). While this definition is conceptually similar to the MfE definition of EI, the specification of *indigenous* biodiversity in EI is a key point of difference. Specifically, no mention was made of indigenous biodiversity in any literature assessed for soils in the current project. This may be in part due to a dominant focus on the soil microbial community in soil health assessments (as compared to soil fauna), both because this community is exceptionally diverse and because truly indigenous species are challenging to identify. It is relevant to note that a recent study identified that protection of aboveground biodiversity may not sufficiently reduce threats to soil biodiversity (Cameron et al. 2019).

Internationally, an ecosystem services (also more recently considered as Nature's contribution to people [Diaz et al. 2018]) framework is increasingly used to assess soil quality and health. In this case, individual soil functions are grouped together to inform the extent to which soils are contributing to ecosystem services (Buneman et al. 2018) with Primary Productivity, Nutrient Cycling, Water Regulation and Purification, Carbon and Climate Regulation, and Habitat for above- and below-ground Biodiversity being considered important in agroecosystems (Shulte et al. 2014). Creamer et al. (2022) further sub-divided soil functions into sub-functions to link to specific processes and noted that some processes are relevant for multiple sub-functions or functions. An alternative approach adopted by the European Environmental Agency (Bartiz et al. 2021) gives greater consideration to the context in which soil indicators are likely to be used—in the management of land or soil to reduce soil degradation arising from soil threats including soil erosion, sealing, and contamination (including excess nutrients). Consideration of the specific contexts, i.e., the problems or threats the NBA and NPF are intended to address, will help to identify relevant attributes for Aotearoa New Zealand for a given domain.

4.2. Freshwater

Previous reviews of ecological assessment frameworks for freshwaters considering EI have identified consistent components of EI including addressing a range of biota and processes (Karr 1991), ecological structure and function (Rapport et al. 1998), physical, chemical, and biological integrity (Barbour et al. 2000) and that ecosystems are resilient to change (Clapcott et al. 2018). The components of EI are interrelated in that composition is usually inherent within structure, and function is not exclusive, i.e.,

[10] https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/soils/health/?cid=stelprdb1048783

biological structure and function, physical structure and function, chemical structure and function are often linked.

Given that some freshwater ecosystems are now irreversibly modified, further definitions of EI have evolved to specifically include human modification. In considering the application of EI to freshwater management in Aotearoa New Zealand, Schallenberg et al. (2011) defined it as 'The degree to which the physical, chemical and biological components (including composition, structure and process) of an ecosystem and their relationships are present, functioning and maintained close to a reference condition reflecting negligible or minimal anthropogenic impacts'. Therefore, integrating the multiple components of EI within an assessment framework and selecting an adequate reference condition were both considered important for adequately characterising EI.

4.3. Marine

During attribute compilation in our study (refer Section 3.4.2), it was apparent that components of EI (as defined by MfE) can be interrelated, as also mentioned for the Freshwater domain above. Drawing on EI definitions from freshwater and terrestrial systems (i.e., Lee et al. 2005; Schallenberg et al. 2011), Thrush et al. (2011) outlined four pillars of EI for marine ecosystems: nativeness, pristineness, diversity and resilience. Contributing to aspects of these pillars, Thrush et al. (2011) also identified six features of EI for Aotearoa New Zealand marine ecosystems to include in marine EI monitoring. Four of these features were 'trophic structure', 'habitat structure and complexity', 'diversity' and 'resilience' (Thrush et al. 2011), all of which are generally encompassed within the MfE EI definition. The two additional features outlined by Thrush et al. (2011) were 'environmental context and history', which relates to knowledge of historical baselines and reference conditions, and 'disturbance regime', described as 'natural, human, intensity, extent, frequency'. Neither historical baselines nor reference conditions are included in the MfE definition of EI. Disturbance regime could potentially relate directly to the MfE component of function, although the inclusion of 'human' under disturbance regime deviates from this. Conversely, in contrast to the MfE EI definition, none of the descriptions of EI features outlined by Thrush et al. (2011) specifically mention indigenous biodiversity, however presumably 'nativeness' as an EI pillar aligns with this concept.

4.4. Air

The MfE definition of EI is comprehensive in many respects, but given that human-induced climate change represents one of the most important threats to ecosystems, the current definition could be adjusted to better reflect the interrelatedness of EI across domains, including the influence of climatic factors on all other domains. At present, without some clarification, many of the attributes identified in the Air domain could be incorrectly interpreted as outside the EI definition. Additionally, research shows climate change will undermine many of the Sustainable Development Goals (SDGs) and that supporting the Paris Agreement commitments will conversely support the SDGs (Fuso Nerini et al. 2019). This reflects the interconnected nature of these two systems and that climate change again poses a major stress for all ecosystems. Griggs et al. (2021) has also identified that weather and climate information is currently underutilised in supporting the SDGs and therefore provides arguments why these attributes must be considered within analyses of EI. We also note that climate change is often identified as a threat multiplier, thus examination of attributes relevant to climate change are likely important to help understand whether other attributes are being impacted by this confounding factor. We also note that there is a considerable set of literature connecting air quality and climate change, which means that to be comprehensive, it may be advisable to include climate change-related confounding factors alongside air quality attributes. For example, work by Bytnerowicz et al. (2007) highlighted that the integrated effects of air pollution and climate change on forest ecosystems may significantly differ from the sum of the separate effects. More recent work by Fiore et al. (2015) has also identified the interplay between air quality and climate. We also note that state attributes of the atmosphere have significant impacts on air pollutants. For example, winds define the airborne transport of pollutants and thus define the regions exposed, while rainfall partially defines deposition. Thus, any changes in these variables due to climate change would significantly impact pollutant attributes.

Climate change represents a risk to ecosystem functioning resulting from the interaction of climate-related hazards, vulnerability and exposure (IPCC 2014). The climate hazard in this context can be defined by a number of attributes connected to abiotic physical features (structure), or more specifically to climatic features. Exposure would be defined by the variation of these features across Aotearoa New Zealand (representation). Quantification of vulnerability relates to the resilience aspect in the MfE EI definition. These three aspects and/or interconnections could be more explicitly identified within the MfE definition to recognise climate-related risks more clearly.

The dynamic adaptative policy pathway approach detailed in Haasnoot et al. (2013) has been highlighted in government documents (MfE 2022) as a useful decision-making tool for climate change policy and adaptation. This framework could be equally well used within the EI space to recognise the climate-ecosystem nexus. A strict application of the EI definition as currently specified to variables that directly represent ecosystem health would exclude several of the confounding attributes, limiting the application of many of the attributes within the pre-defined scope. Simply put, many of the other attributes considered are likely to interact or respond to the confounding attributes in a complex bi-direction way.

5. SYNTHESIS ACROSS DOMAINS

Overall, there was a large number of potential attributes for all domains identified in the literature, except for Air where direct connection to ecosystems was not as common within the relevant Aotearoa New Zealand literature. A synthesis across domains in respect to the EI components is as follows:

- Across all domains, attributes associated with composition and structure dominated; for Air, all attributes related to structure.
- Functional attributes were also quite common in all domains except for Air.
- Attributes for ecological representation and resilience were relatively few across the domains. Attributes for ecological representation were dominated by variations on broader environment or habitat extent (e.g., LENZ classes, threatened environments classification, FENZ classification of river reaches, coastal wetlands and substrates, human activities in coastal areas, and oceanographic features), with the marine-related (Coastal and Seabed, and Estuaries) domains and Terrestrial subdomain having the greatest number of such attributes. The presence or distribution of fine-scale features (e.g., keystone or indicator species) could also be used to provide a measure of representation especially if data were extrapolated across an area. Attributes relating to resilience were often measured by monitoring changes in an attribute associated with other EI components (e.g., composition or function) over time.
- Attributes specifically relating to indigenous species or indigenous biodiversity were identified for all domains except Air and the Soil subdomain. However, a number of biotic attributes, did not distinguish between indigenous or non-indigenous species (e.g., coastal macroinvertebrate community abundance and diversity), and in this regard, do not technically meet the requirements under the EI definition provided. Some other attributes were specifically related to non-indigenous species (e.g., non-native species diversity).
- EI components are interrelated. Biotic structural components can be based on composition information, some composition attributes relate to function, and attributes relating to resilience are often measured by attributes associated with other EI components such as composition and function.
- Similarities as well as some differences were identified between the MfE definition of EI and how EI is defined in the literature:
    - The MfE definition of EI aligned in many respects with EI definitions used in the literature for the Terrestrial subdomain and the Freshwater and marine-related domains. However, the Freshwater domain description also include consideration of reference condition, while ‘knowledge of historical baselines’ is included in the definition used for marine-related domains. For the Soil subdomain, EI is not used in the literature, but rather ‘soil health’ or ‘soil quality’, which can have a similar intent to the MfE EI definition, with the exception of the specification of ‘indigenous biodiversity’ in the MfE definition.

For the Air domain, it was also noted that the MfE EI definition could be strengthened to explicitly include climatic factors (rather than just abiotic physical factors) in the definition of structure.

Additional key points across domains are:

- A number of attributes are connected across domains. For example, erosion, compaction and leaching impact some form of water (ground, surface, coastal), vegetation cover can influence the extent to which erosion may occur; emissions of ammonia and greenhouse gases (CO_2, CH_4, N_2O) from soil affect air quality; and deposition of nitrogen-, sulphur- and contaminant-aerosols including dust can impact on all other domains. Across-domain attributes also relate to domain boundaries e.g., freshwater inputs are integrally linked with estuarine environments; coastal wetlands and dune environments can span below and above mean high water springs, and inland wetlands can span Freshwater and Land (including Soil) domains.
- Across domains, there was an unevenness in the development and use of attributes. For example, many of the Soil subdomain attributes are developed and applied in agroecosystems, whereas many Terrestrial subdomain metrics have been developed in indigenous forests and shrublands. Monitoring frameworks (and hence associated attributes) for Aotearoa New Zealand are well-developed at the national scale for the Freshwater domain in comparison to other domains generally. The marine-related (Coastal and Seabed, and Estuaries) domains include more activity-related metrics than the other domains, with many of these associated with fishing. For the Air domain, there was a dominance of climate-related attributes, which were also present in the literature for all other domains. Attributes relating to chemical contamination were common for most domains. Further, many systems are knowledge- or data-deficient, such as alpine areas, successional habitats, and naturally uncommon ecosystems. No attempt was made during our systematic search to quantify potential biases in the development and use of attributes.
- Gaps in potential attributes for different EI components for Aotearoa New Zealand were identified through the international literature for all domains.
- A common theme for emergent attributes across the Terrestrial and Soil subdomains and Freshwater and marine-related domains is the use eDNA or rRNA approaches, which potentially allow a more complete assessment of taxonomic groups or assessment of bacterial or fungal communities and in turn provide greater detail on composition and structure of those communities.

6. CONCLUSIONS

Our review of the literature yielded an abundance of potential attributes of EI. Our approach developed a documented and repeatable search of the literature and provides a crucial summary of knowledge from published and unpublished sources. Overall, there were a relatively high number of potential attributes identified for all domains except for Air. The number of attributes identified for each domain was Land (including Soil) (subdomains: > 150 for Terrestrial and 245 for Soil), Freshwater (251), Coastal and Seabed, and Estuaries (> 580 combined), and Air (37), with indigenous biodiversity considered as a cross-domain theme. Key points from our across-domain synthesis for the EI components are as follows:

- Across all domains, attributes associated with composition and structure dominated; for Air, all attributes related to structure.
- Functional attributes were also quite common in all domains except for Air.
- Attributes for ecological representation and resilience were relatively few across the domains. Attributes for ecological representation were dominated by variations on broader environment or habitat extent with a greater number captured for the marine-related (Coastal and Seabed, and Estuaries) domains and Terrestrial subdomain.
- Attributes specifically relating to indigenous species or indigenous biodiversity were identified for all domains except Air and the Soil subdomain. However, a number of biotic attributes did not distinguish between indigenous or non-indigenous species (e.g., coastal macroinvertebrate community abundance and diversity), and in this regard technically do not meet the requirements under the EI definition provided. Some other attributes were specifically related to non-indigenous species (e.g., non-native species diversity).
- EI components are interrelated. Biotic structural components can be based on composition information, some composition attributes relate to function, and attributes relating to resilience are often measured by attributes associated with other EI components such as composition and function.
- The MfE definition of EI aligned in many respects with definitions used in the literature for the domains. However, the Freshwater and marine-related domain descriptions also include consideration of reference or baseline condition. For the Soil subdomain, EI is not used in the literature, but rather ‘soil health’ or ‘soil quality’, which can have a similar intent to the MfE EI definition, with the exception of the specification of ‘indigenous biodiversity’ in the MfE definition. For the Air domain, it was also noted that the MfE EI definition could be strengthened to explicitly include climatic factors (rather than just abiotic physical factors) in the definition of structure.

Additional key points across domains were:

- A number of attributes were found to be connected across domains e.g., erosion or leaching, which traverse the land and water domains. Across-domain attributes also relate to domain boundaries e.g., riparian vegetation and tidal wetlands.
- Across domains, the development and/or use of attributes among different systems was uneven. For example, many of the Soil subdomain attributes are developed and applied in agroecosystems, whereas many Terrestrial subdomain metrics have been developed in indigenous forests and shrublands. Additionally, Freshwater attributes have been relatively well-developed into national scale monitoring frameworks. There was also unevenness across domains in relation to the type of attributes or threats they respond to. For example, there was a higher proportion of activities-based attributes (e.g., fishing-related) for the marine-related domains and a dominance of climate change related attributes for the Air domain, while attributes relating to chemical contamination were common for most domains.
- Gaps in potential attributes for different EI components for Aotearoa New Zealand were identified through the international literature for all domains.
- A common theme for emergent attributes across the Terrestrial and Soil subdomains and Freshwater and marine-related domains is the use eDNA or rRNA approaches to provide further detail on species presence and composition.

The next step is to provide assessment of potential attributes identified in this report against key criteria in relation to the policy, management, and limit setting context. This work is planned for Phase 2 of the project.

7. ACKNOWLEDGEMENTS

Additional experts outside the core project team include Drs Dana Clark, Don Morrisey and Anastasija Zaiko (Cawthron Institute); Angela Bownes and Robyn Simcock (Manaaki Whenua Landcare Research). The Ministry for the Environment contributed to conversations and provided relevant information and feedback throughout the project.

8. REFERENCES

Allen RB, Forsyth DM, MacKenzie DI, Peltzer DA 2022. Robustness of field studies evaluating biodiversity responses to invasive species management in New Zealand. New Zealand Journal of Ecology (in press).

Andreasen JK, O'Neill RV, Noss R, Slosse NC 2001. Considerations for the development of a terrestrial index of ecological integrity. Ecological Indicators 1: 21–35.

Andrews SS, Karlen DL, Cambardella CA 2004. The soil management assessment framework: a quantitative soil quality evaluation method. Soil Science Society of America Journal 68, 1945–1962.

Bagnall DK, Morgan CKL et al. 2022. Selecting soil hydraulic properties as indicators of soil health: Measurement response to management and site characteristics.

Barbour MT, Swietlik WF, Jackson SK, Courtemanch DL, Davies SP, Yoder CO 2000. Measuring the attainment of biological integrity in the USA: a critical element of ecological integrity. Hydrobiologia 422: 453–464.

Bartiz et al. 2021. EEA – Soil monitoring in Europe. Indicators and thresholds for soil quality assessments. Draft report for review. EEA ETC/ULS Report 2021.

Bellingham PJ, Richardson SJ, Gormley AM, Allen RB, Cook A, Crisp PN, Forsyth DM, McGlone MS, McKay M, MacLeod CJ, van Dam-Bates P 2020. Implementing integrated measurements of essential biodiversity variables at a national scale. Ecological Solutions and Evidence 1(2): 12025.

Binny RN, Innes J, Fitzgerald N, Pech R, James A, Price R, Gillies C, Byrom AE 2021. Long-term biodiversity trajectories for pest-managed ecological restorations: eradication vs. suppression. Ecological Monographs 91(2): e01439.

Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, Bustamante M, Cinderby S, Davidson E, Dentener F, Emmett B, Erisman JW, Fenn M, Gilliam F, Nordin A, Pardo L, De Vires W 2010. Global assessment of nitrogen deposition effects on terrestrial plant diversity: A synthesis. Ecological Applications 20(1): 30–59.

Booth A, Sutton A, Papaioannou D 2016. Systematic approaches to a successful literature review. London: SAGE. 424 p.

Brown ED, Williams BK 2016. Ecological integrity assessment as a metric of biodiversity: are we measuring what we say we are? Biodiversity and Conservation 25: 1011–1035.

Bulmer RH, Stephenson F, Lohrer AM, Lundquist CJ, Madarasz-Smith A, Pilditch CA, Thrush SF, Hewitt JE 2022. Informing the management of multiple stressors on estuarine ecosystems using an expert-based Bayesian Network model. Journal of Environmental Management 301: 113576.

Bridson JH, Patel M, Lewis A, Gaw S, Parker K 2020. Microplastic contamination in Auckland (New Zealand) beach sediments. Marine Pollution Bulletin 151: 110867.

Bünemann EK, Bongiorno G, Bai Z, Creamer RE, De Deyn G, de Goede R, Fleskens L, Geissen V, Kuyper TW, Mäder P, Pulleman M, Sukkel W, van Groenigen JW, Brussaard L 2018. Soil quality – a critical review. Soil Biology and Biochemistry 120, 105–125.

Beyer HL, Venter O, Grantham HS, Watson JE 2020. Substantial losses in ecoregion intactness highlight urgency of globally coordinated action. Conservation Letters,13(2): 12692.

Bytnerowicz A, Omasa K, Paoletti E. Integrated effects of air pollution and climate change on forests: a northern hemisphere perspective. Environ Pollut. 2007 Jun;147(3):438–45.

Cameron E, Martins I, Lavelle P, Mathieu J, Tedersoo L, Bharam M, Gottschall F, Guerra C, Hines J, Patoine G, Siebert J, Winter M, Cesarz S, Ferlian O, Kreft H, Lovejoy T, Montanarella L, Orgiazzi A, Pereira H, Phillips H, Settele J, Wall D, Eisenhauer N 2019. Global mismatches in aboveground and belowground biodiversity. Conservation Biology 33(5): 1187–1192.

Cavender-Bares J, Schneider FD, Santos MJ et al. 2022. Integrating remote sensing with ecology and evolution to advance biodiversity conservation. Nature Ecology and Evolution 6: 506–519.

Clapcott J, Young R, Sinner J, Wilcox M, Storey R, Quinn J, Daughney C, Canning A 2018. Freshwater biophysical ecosystem health framework. Cawthron Report No. 3194 prepared for Ministry for the Environment. 89 p. plus appendices.

Clark DE, Hewitt JE, Pilditch CA, Ellis JI 2020. The development of a national approach to monitoring estuarine health based on multivariate analysis. Marine Pollution Bulletin 150: 110602.

Clark DE, Pilditch CA, Pearman JK, Ellis JI, Zaiko A 2020. Environmental DNA metabarcoding reveals estuarine benthic community response to nutrient enrichment–Evidence from an in-situ experiment. Environmental Pollution, 267, 115472.

Clere IK, Ahmmed F, Peter III JG, Fraser-Miller SJ, Gordon KC, Komyakova V & Allan BJ 2022. Quantification and characterization of microplastics in commercial fish from southern New Zealand. Marine Pollution Bulletin 184: 114121.

Creamer RE, Barel JM, Bongiorno G, Zwetsloot MJ 2022. The life of soils: integration the who and how of multifunctionality. Soil Biology and Biochemistry. https://doi.org/10.1016/j.soilbio.2022.108561.

De Bhowmick G, Sarmah AK, Dubey B 2021. Microplastics in the NZ environment: Current status and future directions. Case Studies in Chemical and Environmental Engineering 3: 100076.

Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, Hill R, Chan KMA, Baste IA, Brauman KA, Polasky S, Church A, Lonsdale M, Larigauderie A, Leadley PW, van Oudenhoven APE, van der Plaat F, Schröter M, Lavorel S, Aumeeruddy-Thomas Y, Bukvareva E, Davies K, Demissew S, Erpul G, Failler P, Guerra CA, Hewitt CL, Keune H, Lindley S, Shirayama Y 2018. Assessing nature's contributions to people. Science: 359(6373): 270–272.

Dickie IA, Boyer S, Buckley HL, Duncan RP, Gardner PP, Hogg ID, Holdaway RJ, Lear G, Makiola A, Morales SE, Powell JR 2018. Towards robust and repeatable sampling methods in eDNA-based studies. Molecular Ecology Resources 18: 940–952.

Dominati EJ 2013. Natural capital and ecosystem services of soils. In Dymond JR ed. Ecosystem services in New Zealand – conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand.

Durante LM, Beentjes MP, Wing SR 2020. Shifting trophic architecture of marine fisheries in New Zealand: Implications for guiding effective ecosystem-based management. Fish and Fisheries 21(4): 813–830.

Dymond JR 2013. Ecosystem services in New Zealand: conditions and trends. Lincoln: Manaaki Whenua Press. 539 p.

Eason CT, Fairweather A, Ogilvie S, Blackie H, Miller A 2013. A review of recent non-target toxicity testing of vertebrate pesticides: establishing generic guidelines. New Zealand Journal of Zoology 40: 226–235.

Edgar GJ, Stuart-Smith RD, Thomson RJ & Freeman DJ 2017. Consistent multi-level trophic effects of marine reserve protection across northern New Zealand. PLoS One 12(5): e0177216.

Egan D, Howell E 2001. The historical ecology handbook: A restorationist’s guide to reference ecosystems. Island Press.

Ferreira JG, Andersen JH, Borja A, Bricker SB, Camp J, da Silva MC, Garcés E, Heiskanen A-S, Humborg C, Ignatiades L, Lancelot C, Menesguen A, Tett P, Hoepfner U, Claussen U 2011. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. Estuarine, Coastal and Shelf Science 93(2): 117–131.

Fiore AM, Naik V, Leibensperger EM 2015. Air quality and climate connections. Journal of the Air and Waste Management Association 65(6): 645–685.

Fisheries New Zealand 2022. Aquatic environment and biodiversity annual review 2021. Compiled by the Aquatic Environment Team, Fisheries Science and Information, Fisheries New Zealand, Wellington New Zealand. 779 p.

Fuso Nerini F, Sovacool B, Hughes N, Cozzi L, Cosgrave E, Howells M, Tavoni M, Tomei J, Serriffi H, Milligan B 2019. Connecting climate action with other sustainable development goals. Nature Sustainability 2(8): 674–680.

Fraser RH, Olthof I, Pouliot D 2009. Monitoring land cover change and ecological integrity in'Canada's national parks. Remote Sensing of Environment 113: 1397–1409.

Gladstone-Gallagher RV, Tylianakis JM, Yletyinen J, Dakos V, Douglas EJ, Greenhalgh S, Hewitt JE, Hikuroa D, Lade SJ, Le Heron R, Norkko A 2022. Social–ecological connections across land, water, and sea demand a reprioritization of environmental management. Elementa: Science of the Anthropocene 10(1): 0.00075

Grantham HS et al. 2020. Anthropogenic modification of forests means only 40% of remaining forests have high ecosystem integrity. Nature Communications 11:5978.

Griggs D, Stafford-Smith M, Warrilow D, Street R, Carolina V, Scobie M, Sokona Y 2021. Use of weather and climate information essential for SDG implementation. Nature Reviews Earth & Environment 2: 2–4.

Haasnoot M, Kwakkel JH, Walker WE, ter Maat J 2013. Dynamic adaptive policy pathways: a method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23(2): 485–498.

Hamilton DJ, Bulmer RH, Schwendenmann L, Lundquist CJ 2020. Nitrogen enrichment increases greenhouse gas emissions from emerged intertidal sandflats. Scientific Reports 10: 6686.

Hansen AJ, Barnett K. Jantz P, et al. 2019. Global humid tropics forest structural condition and forest structural integrity maps. Scientific Data 6: 232

Hansen AJ, Noble BP, Veneros J, et al. 2021. Toward monitoring forest ecosystem integrity within the post-2020 Global Biodiversity Framework. Conservation Letters 14(4) p.e12822.

Hewitt JE, Bell R, Costello M, Cummings V, Currie K, Ellis J, Francis M, Froude V, Gorman R, Hall J, Inglis G, MacDiarmid A, Mills G, Pinkerton M, Schiel D, Swales A, Law C, McBride G, Nodder S, Rowden A, Smith M, Thompson D, Torres L, Tuck I, Wing S 2014. Development of a national marine environment monitoring programme (MEMP) for New Zealand. Prepared for Ministry for Primary Industries. New Zealand Aquatic Environment and Biodiversity Report No. 141.

Hoban S, Archer FI, Bertola LD et al. 2022, Global genetic diversity status and trends: towards a suite of Essential Biodiversity Variables (EBVs) for genetic composition. Biological Reviews 97: 1511–1538.

Holdaway RJ, Wood JR, Dickie IA, Orwin KH, Bellingham PJ, Richardson SJ, Lyver POB, Timoti P, Buckley TR 2017. Using DNA metabarcoding to assess New Zealand's terrestrial biodiversity. New Zealand Journal of Ecology 41: 251–262.

Huber S, Prokop G, Arrouays D, Banko G, Bispo A, Jones RJA, Kibblewhite MG, Lexer W, Möller A, Rickson RJ, Shishkov T, Stephens M, Toth G, Van den Akker JJH, Varallyay G, Verheijen FGA, Jones AR (eds) 2008. Environmental assessment of soil for monitoring: volume I indicators & criteria. EUR23490 EN/1, Office for the Official Publications of the European Communities, Luxembourg, 339 p.

Hulme PE 2020. Plant invasions in New Zealand: global lessons in prevention, eradication and control. Biological Invasions 22: 1539–1562.

Hume T, Gerbeaux P, Hart D, Kettles H, Neale D, 2016. In: A classification of New Zealand's coastal hydrosystems. Report prepared for Ministry for the Environment. pp. 120.

Hurd CL, Law CS, Bach LT, Britton D, Hovenden M, Paine ER, Raven JA, Tamsitt V, Boyd PW 2022. Forensic carbon accounting: Assessing the role of seaweeds for carbon sequestration. Journal of Phycology 58 (3): 347–363.

IPCC 2014. Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL editors. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. pp. 1–32.

Jackson MC, Weyl OLF, Altermatt F, Durance I, Friberg N, Dumbrell AJ, Piggott JJ, Tiegs SD, Tockner K, Krug CB, Leadley PW, Woodward G 2016. Recommendations for the next generation of global freshwater biological monitoring tools. In: Dumbrell AJ, Kordas RL, Woodward G eds. Advances in ecological research 55: large-scale ecology: model systems to global perspectives. pp. 615–636.

Jones A, Fernandes-Ugalde O, Scarpa S, Eiselt B 2022. LUCAS soil 2022. EUR 30331 EN, Publications Office of the European Union, Luxembourg., 2021, ISBN 978-92-76-21079-5.

Karr JR 1991. Biological integrity: a long-neglected aspect of water resource management. Ecological Applications 1(1): 66–84.

Leathwick J, West D, Gerbeaux P, Kelly D, Robertson H, Brown D, Chadderton W, Ausseil A 2010. Freshwater ecosystems of New Zealand (FENZ) geodatabase. Users guide. Wellington: Department of Conservation.

Lee W, McGlone M, Wright E 2005. Biodiversity inventory and monitoring: a review of national and international systems and a proposed framework for future biodiversity monitoring by the Department of Conservation. Landcare Research contract report LC0405/122.

Lehmann J, Bossio DA, Kogel-Knabner I, Rillig MC 2020. The concept and future prospects of soil health. Nature Reviews Earth & Environment 1: 544–553.

Lipztin et al. 2022. An evaluation of carbon indicators of soil health in long-term agricultural experiments. Soil biology and biochemistry 172, 108708.

McCarthy JK, Leathwick JR, Roudier P, Barringer JR, Etherington TR, Morgan FJ, Odgers NP, Price RH, Wiser SK, Richardson SJ 2021. New Zealand Environmental Data Stack (NZEnvDS). New Zealand Journal of Ecology 45(2): 1–8.

McGlone MS, McNutt K, Richardson SR, Bellingham PJ, Wright EF 2020. Biodiversity monitoring, ecological integrity, and the design of the New Zealand Biodiversity Assessment Framework. New Zealand Journal of Ecology 44: 3411.

MfE 2022. Urutau, ka taurikura: Kia tū pakari a Aotearoa i ngā huringa āhuarangi Adapt and thrive: Building a climate-resilient New Zealand – New Zealand's first national adaptation plan.

Ministry for Primary Industries (MPI) 2019. Best management practice guidelines for salmon farms in the Marlborough Sounds: Part 2: Water quality standards and monitoring protocols (Version 1.0). New Zealand Aquatic Environment and Biodiversity Report No. 230. Prepared for Ministry for Primary Industries by the Water Quality Standards Working Group (D Elvines, Preece MA, Baxter A, Broekhuizen N, Ford R, Knight B, Schuckard R, Urlich S).

Moebius-Clune BN, Moebius-Clune DJ, Gugino BK, Idowu OJ, Schindelbeck RR, Ristow AJ, van Es HM, Thies JE, Shayler HA, McBride MB, Kurtz, KSM, Wolfe DW, Abawi GS 2016. Comprehensive Assessment of Soil Health – The Cornell Framework, Edition 3.2, Cornell University, Geneva, NY.

Montenegro D, Astudillo-García C, Hickey T, Lear G 2020. A non-invasive method to monitor marine pollution from bacterial DNA present in fish skin mucus. Environmental Pollution 263: 114438.

Morriss GA, Nugent G, Whitford J 2016. Dead birds found after aerial poisoning operations targeting small mammal pests in New Zealand 2003–14. New Zealand Journal of Ecology 40: 361–370.

Norris CE, Bean M, Cappellazzi SB, Cope M Greub KLH, Liptzin D, Rieke EL, Tracy PW, Morgan CLS, Honeycutt CW 2020. Introducing the North American project to evaluate soil health measurements. Agronomy Journal 112: 3195–3215.

O'Brien D, Laikre L, Hoban S, Bruford MW, Ekblom R, Fischer MC, Hall J, Hvilsom C, Hollingsworth PM, Kershaw F, Mittan CS, Mukassabi TA, Ogden R, Segelbacher G, Shaw RE, Vernesi C, MacDonald AJ 2022. Bringing together approaches to reporting on within species genetic diversity. Journal of Applied Ecology 59: 2227–2233.

O'Dea R, Lagisz M, Jennions MD, Koricheva J, Noble DWA, Parker TH, Gurevitch J, Page MJ, Stewart G, Moher D, Nakagawa S 2021. Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. Biological Reviews 96(5): 1695–1722.

O'Neill KP, Amacher MC, Perry CH 2005. Soils as an indicator of forest health: a guide to the collection, analysis, and interpretation of soil indicator data in the Forest Inventory and Analysis program. Gen. Tech. Rep. NC-258. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 53 p.

Overton JM, Walker S, Price R, Stephens RT, Henson S, Earl R, Wright E 2015. Vital sites and actions: an integrated framework for prioritizing conservation actions and reporting achievement. Diversity and Distributions 21(6): 654–664.

Pardo LH, Fenn ME, Goodale CL et al. 2011. Effects of nitrogen deposition and empirical nitrogen critical loads for ecoregions of the United States. Ecological Applications 21(8): 3049–3082.

Parliamentary Commissioner for the Environment 2020. Managing our estuaries. Wellington: Parliamentary Commissioner for the Environment.

Parks Canada Agency 2011. Consolidated guidelines for ecological integrity monitoring in Canada's national parks. Protected areas establishment and conservation branch, Parks Canada.

Payne RJ, Dise NB, Field CD, Dore AJ, Caporn SJM, Stevens CJ 2017. Nitrogen deposition and plant biodiversity: past, present, and future. Frontiers in Ecology and the Environment 15(8): 431–436.

Pereira HM, Ferrier S, Walters M, Geller GN, Jongman RHG, Scholes RJ, Bruford MW, Brummitt N, Butchart SHM, Cardoso AC, Coops NC 2013. Essential biodiversity variables. Science 339: 277–278.

Pérez A, Machado W, Gutierrez D, Stokes D, Sanders L, Smoak JM, Santos I, Sanders CJ 2017. Changes in soil organic carbon accumulation driven by mangrove expansion and deforestation in a Aotearoa New Zealand estuary, Estuarine, Coastal and Shelf Science.

Pinkerton M, Gall M, O'Callaghan J, Thoral F, Swales A 2022. Monitoring coastal suspended sediment in Aotearoa New Zealand: utility of satellite remote sensing. Prepared for Department of Conservation. NIWA Client Report No: 2022106WN.

Pochon X, Wood SA, Atalah J, Fletcher L, Laroche O, Pearman JK, Elvines D, Zaiko A, Biessy L, Thomson-Laing G, Keeley NB 2021. A validated protocol for fish farm monitoring using environmental DNA. ARPHA Conference Abstracts 4: e65421.

Rapport DJ, Costanza R, McMichael AJ 1998. Assessing ecosystem health. Trends in Ecology and Evolution 13(10): 397–402.

Robertson B, Gillespie P, Asher R, Frisk S, Keeley N, Hopkins G, Thompson S, Tuckey B 2002. Estuarine environmental assessment and monitoring: A national protocol. Part A – Development of the monitoring protocol for New Zealand Estuaries: Introduction, rationale and methodology. Prepared for Supporting Councils and the Ministry for the Environment. Sustainable Management Fund Contract No. 5096, p. 93.

Rodil IF, Lohrer AM, Hewitt JE, Townsend M, Thrush SF, Carbines M 2013. Tracking environmental stress gradients using three biotic integrity indices: advantages of a locally-developed traits-based approach. Ecological indicators 34: 560–570.

Rodil IF, Attard KM, Norkko J, Glud RN, Norkko A 2019. Towards a sampling design for characterizing habitat-specific benthic biodiversity related to oxygen flux dynamics using Aquatic Eddy Covariance. PLoS One 14(2): e0211673.

Schallenberg M, Kelly D, Clapcott J, Death R, MacNeil C, Young R, Sorrell B, Scarsbrook M 2011. Approaches to assessing ecological integrity of New Zealand freshwaters. Science for Conservation 307: 84.

Schulte RPO, Creamer RE, Donnellan T, Farrelly N, Fealy R, O'Donoghue C, O'Uallachain D 2014. Functional land management: a framework for managing soil-based ecosystem services for the sustainable intensification of agriculture. Environmental Science & Policy 38.

Schmeller DS, Weatherdon LV, Loyau A, Bondeau A, Brotons L., Brummitt N, Geijzendorffer IR, Haase P, Kuemmerlen M, Martin CS, Mihoub JB 2018. A suite of essential biodiversity variables for detecting critical biodiversity change. Biological Reviews 93: 55–71.

Simberloff D 2019. New Zealand as a leader in conservation practice and invasion management. Journal of the Royal Society of New Zealand 49: 259–280.

Singers NJD, Rogers GM 2014. A classification of New Zealand's terrestrial ecosystems. Science for Conservation 325.

Smit KP, Bernard ATF, Lombard AT, Sink KJ 2021. Assessing marine ecosystem condition: a review to support indicator choice and framework development. Ecological Indicators 121: 107148.

Stephenson F, Rowden A, Brough T, Leathwick J, Bulmer R, Clark D, Lundquist C, Greenfield B, Bowden D, Tuck I, Neill K, Mackay K, Pinkerton M, Anderson O, Gorman R, Mills S, Watson S, Nelson W, Hewitt J 2021. Development of a New Zealand seafloor community classification (SCC). NIWA Client Report No. 2020243WN prepared for Department of Conservation (DOC).

Stewart M, Northcott G, Gaw S and Tremblay LA 2016. An update on emerging organic contaminants of concern for New Zealand with guidance on monitoring approaches for councils. Prepared by Streamlined Environmental Ltd, Northcott Research Consultants Ltd, University of Canterbury, Cawthron Institute and the University of Auckland for Auckland Council, Greater Wellington Regional Council and Environment Canterbury Regional Council.

Stott DE 2019. Recommended soil health indicators and associated laboratory procedures. Soil Health Technical Note No. 450-03. U.S. Department of Agriculture, Natural Resources Conservation Service.

Theobald DM 2013. A general model to quantify ecological integrity for landscape assessments and US application. Landscape Ecology 28:1859-1874.

Thrush SF, Hewitt JE, Norkko A, Cummings VJ, Funnell GA 2003. Macrobenthic recovery processes following catastrophic sedimentation on estuarine sandflats. Ecological Applications 13(5): 1433–1455.

Thrush SF, Hewitt JE, Lundquist C, Townsend M, Lohrer AM 2011. A strategy to assess trends in the ecological integrity of New Zealand's marine ecosystems. NIWA Client Report No: HAM2011-140 prepared for Department of Conservation.

Tierney GL, Faber-Langendoen D, Mitchell BR, Shriver WG, Gibbs JP 2009. Monitoring and evaluating the ecological integrity of forest ecosystems. Frontiers in Ecology and the Environment 7(6): 308–316.

US EPA United States Environmental Protection Agency (US EPA) 2020. Integrated science assessment for oxides of nitrogen, oxides of sulfur, and particulate matter – ecological criteria.

Vitousek PM, D'Antonia CM, Loope LL, Rejmanek M, Westbrooks RG 1997. Introduced species: a significant component of human-induced global change. New Zealand Journal of Ecology 21: 1–16.

Walker S, Bellingham PJ, Kaine G, Richardson S, Greenhalgh S, Simcock R, Brown MA, Stephens , Lee WG 2021. What effects must be avoided, remediated or mitigated to maintain indigenous biodiversity? New Zealand Journal of Ecology 45: 1–12.

Weir SM, Yu S, Knox A, Talent LG, Monks JM, Salice CJ 2016. Acute toxicity and risk to lizards of rodenticides and herbicides commonly used in New Zealand. New Zealand Journal of Ecology 40: 342–350.

Whitehead AL, Booker DJ 2019. Communicating biophysical conditions across New Zealand's rivers using an interactive webtool. New Zealand Journal of Marine and Freshwater Research 53(2): 278–287.

Williams PA, Wiser S, Clarkson B, Stanley MC 2007. New Zealand's historically rare terrestrial ecosystems set in a physical and physiognomic framework. New Zealand Journal of Ecology 31: 119–128.

Wiser SK, Hurst JM, Wright EF, Allen RB 2011. New Zealand’s forest and shrubland communities: A quantitative classification based on a nationally representative plot network. Applied Vegetation Science 14: 506–523.

Wood JR, Burge OR, Bolstridge N, Bonner K, Clarkson B, Cole TL, Davis C, Fergus A, McKeown MM, Morse C, Richardson SJ, Robertson H, Wilmshurst JM 2021. Vertical distribution of prokaryotes communities and predicted metabolic pathways in New Zealand wetlands, and potential for environmental DNA indicators of wetland condition. PLoS ONE 16(1): e0243363.

Wood SA, Blakinship J 2022. Making soil health science practical: guiding research for agronomic and environmental benefits. Soil Biology and Biochemistry 172: 108776.

Wurtzebach Z, Schultz C 2016. Measuring ecological integrity: history, practical applications, and research opportunities. BioScience 66: 446–457.

Zaiko A, Berthelsen A, Cornelisen C, Clark D, Bulmer R, Hewitt J, Stevens L, Stott R, McBride G, Hickey C, Banks J, Hudson N 2018. Managing upstream: estuaries state and values – methods and data review. NIWA Client Report No. 201715HN prepared for the Ministry for the Environment. Wellington:

Zwetsloot MJ, Bongiorno G, Barel JM, di Lonardo P, Creamer RE 2022. A flexible selection tool for the inclusion of soil biology methods in the assessment of soil multi-functionality. Soil Biology and Biochemistry. SBB 108514.

9. APPENDICES

Appendix 1. Lists of compiled potential attributes and associated metadata.

These are attached separately as supplementary files (excel, raw format) and titled as per the following:

- Terrestrial attributes_report format_20220930.xlsx
- Soil attributes_report format_202200930.xlsx
- Freshwater_attributes_report format_20220930.xlsx
- Coastal and Estuaries attributes_report format_20220930.xlsx
- Air attributes_report format_20220930.xlsx

Files containing Web of Science (WoS) literature search results can also be provided to MfE on request.

Appendix 2. This appendix contains additional information relevant to the Air domain.

Description of Attribute classes.

To allow some grouping in the Air domain, attributes were assigned a prevalence level based on usage in the literature and also a class based on common root causes or impacts. Additional information on each of these classes is as follows:

1. Surface pollutants: surprisingly, these attributes were not common within New Zealand studies. Ecosystems are impacted by surface pollutants, particularly sulphur and nitrogen oxides via deposition on water, vegetation and soils generally via wet deposition. Tropospheric ozone also affects the function and growth of vegetation. Acidification related to sulphur and nitrogen oxides affects nutrient cycling in ecosystems. Eutrophication, the process of accumulation of nutrients in water bodies, also often results from air pollution (see reviews by Bobbink et al. (2010), Pardo et al. (2011), Payne et al. (2017), and most comprehensively, US EPA (2020)). Recent international work detailed in Allen et al. (2022) also suggests that the prevalence of airborne microplastics is nearly ubiquitous globally and is therefore a potential threat for the marine-atmosphere environment worthy of monitoring. The general lack of literature in this space potentially highlights a knowledge gap which perhaps needs to be studied more broadly given the international literature.
2. Stratospheric ozone depletion attributes: the impacts of stratospheric ozone depletion on ecosystem function was also a relatively common theme. Metrics such as the concentration of ozone depleting substances allow an analysis of the effectiveness of global limits included within the Montreal Protocol. Note that many of the relevant attributes in this class are already monitored to support the Montreal Protocol.
3. Teleconnection related attributes: teleconnection indices related to El Niño Southern Oscillation, the Southern Annular mode and, less frequently, the Interdecadal Pacific Oscillation have been used by a number of studies as proxies to examine ecological sensitivity to natural climate variability. Note that these indices are already used and disseminated by Statistics New Zealand.
4. Light-related attributes: these attributes were either in the high or medium prevalence categories and some are collected commonly at meteorological observatories, However, many of the studies were at regional and/or local scales and would require additional monitoring for the attributes to be used nationally.
5. Temperature related attributes: temperature was the most commonly detailed abiotic physical feature used within the EI literature, with 68 separate references in the systematic and ad hoc searches combined. Various aspects of air temperature change attributable to human-induced climate change were identified, with indicators of changes in extreme temperatures being an important and high prevalence subset. These attributes must be considered within the EI context given the ecosystem-climate nexus. As for the precipitation class, the existing

climate/weather monitoring networks provide reasonably good coverage of temperature attributes across the country.

6. Precipitation-related attributes: these connect to changing precipitation occurrence and intensity attributable to human-induced climate change and also to changing seasonality of precipitation. This class linked to high or medium prevalence attributes. These attributes must be considered within the EI context given the ecosystem-climate nexus. The existing weather monitoring networks across Aotearoa New Zealand provide a reasonably good coverage of precipitation attributes across the entire country, though the network is reducing in size and there are some areas of limited coverage, such as high elevation areas in South Island. There are also limited long-term time series available, which potentially limits attribution of cause and effect, but overall, long-term baseline data are available for use in identification of human-induced change throughout Aotearoa New Zealand.
7. Greenhouse gas attributes: the impacts and mitigation possibilities related to greenhouse gases and ecosystems was also a common theme, though only carbon dioxide atmospheric concentrations meet the high prevalence criteria. The concentrations of these gases connect to the Paris Agreement and are common drivers used within modelling studies to predict human-induced climate change and thus provide useful attributes. Note that these attributes are already monitored across Aotearoa New Zealand to support climate change agreements.
8. Other attributes: this class defines five other attributes which represent the potential impact of human-induced climate or other confounding factors on EI, namely the changing occurrence of wind extremes and changes in the frequency of weather conducive to wildfires as represented by fire indices. As for the precipitation class, the existing climate/weather monitoring networks provide reasonably good coverage of wind attributes across the country. The fire indices are also derived, collated and distributed via ongoing networks.

Note that the confounding factor classes relate to attributes that are very commonly identified in studies that discuss surface pollutants or stratospheric ozone depletion, or that relate to climate change related attributes which will likely act as threat multipliers.