Chapter 11
Indicators of Ecological Integrity

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Abstract Freshwater Ecological Integrity (EI) incorporates the concepts of ecosystem "health", unimpaired structure, composition and function and a capacity for self-renewal and, as such, it is a holistic advance over standard water quality metrics for assessing lake condition. In the New Zealand freshwater context, EI has been defined as a composite of nativeness, pristineness, diversity and resilience to perturbations. Measurable lake attributes have been proposed and calibrated against pre-impaired "reference" conditions for different lake types. Related to EI, LakeSPI (Submerged Plant Indicator) also assesses lake ecological condition and has been calibrated for a wide range of New Zealand lakes. These EI approaches are thus able to measure departures from reference conditions (or other defined endpoints) and for all these reasons, EI approaches are beneficial for setting lake restoration goals or targets and for tracking the success and progress of restoration activities. Recently, EI approaches have been making inroads with regard to environmental policy and monitoring. This chapter discusses the current development and future possibilities for using EI to help restore degraded lakes.

Keywords Anthropogenic pressures · Reference state · Attributes · Multimetric · LakeSPI

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11.1 Ecological Integrity

When restoring lakes, it is useful to have a restoration goal or endpoint. To date, both management and restoration goals for lakes in New Zealand have focused on water quality and, as a result, lakes are usually monitored for trophic state variables (i.e. chlorophyll *a*, total nitrogen, total phosphorus and, sometimes, water clarity), with little regard to other aspects of lake ecosystems, except sometimes where nuisance species are present. However, popular concepts such as ecosystem "health" and the "life-supporting capacity" of freshwaters (a management target enshrined in the Resource Management Act 1991) indicate that there is an interest in looking beyond trophic state when assessing lake condition and trends, and this is supported by a large body of academic work which has attempted to define and utilise more holistic concepts such as "ecosystem health" (Steedman 1994; Scrimgeour and Wicklum 1996; Rapport et al. 1998), "biotic integrity" (Karr and Dudley 1981; Karr 1996) and "ecological integrity" (Miller 1991; Barbour et al. 2000; Bunn and Davies 2000). Such concepts may be closely aligned to the Māori concept of *mauri*, which can be translated as the embodiment of an "essential life force" (Tipa and Teirney 2006).

Such approaches have been criticised as being subjective and normative (e.g. Peters 1991; Sagoff 2000). However, from a management and restoration point of view, normative, holistic concepts like ecological integrity (EI) may be useful precisely because they incorporate values and value judgements and, as such, can link directly to goals and objectives relating to lake health within policy tools (e.g. catchment management plans, water plans, national policy statements). Furthermore, EI may better reflect how humans perceive freshwater values and condition than trophic state indicators do. Therefore, these more holistic concepts are increasingly being employed at the policy level [e.g. Canadian National Parks Act (2000), Lee et al. (2005), Europe's Water Framework Directive (Boon and Pringle 2009)].

The status of, or change in, lake condition may not accurately track the level of anthropogenic pressures. For example, lakes may show inertia to restoration activities that have reduced or removed major anthropogenic pressures (Scheffer 2004). Such complexities of lake systems can be difficult to understand and predict without a more holistic perspective on lake ecosystem function and restoration. In their formal application of the concept of EI to lakes, Drake et al. (2011) and Özkundakci et al. (2014) reported that, in multi-lake comparisons, environmental pressure gradients (e.g. invasive species, agriculture in the catchments, etc.) only correlated weakly with many common measures of lake condition. In contrast, a gradient of EI (as determined by expert assessments of the lakes after site visits) correlated strongly with many of the pressure gradients tested (Drake et al. 2011). Use of the concept of EI encourages the development and use of multivariate, multi-gradient and multimetric assessments of lake condition which are more likely to track significant ecological responses and help identify aspects of lake ecosystems that may facilitate lake restoration.

11.1.1 New Zealand Definitions of Ecological Integrity

The concept of EI has been developed and refined for New Zealand's terrestrial (Lee et al. 2005) and freshwater environments (Schallenberg et al. 2011). Schallenberg et al. (2011) proposed that, in the freshwater context, EI could be defined 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.

Of the four common types of EI definitions listed by Manuel-Navarrete et al. (2004), the freshwater EI definition above is a "wilderness-normative" definition that places pristineness (i.e. departure from a reference condition) at the core of EI. In addition to both functional and structural pristineness, Schallenberg et al. (2011) also proposed three other quantifiable components of freshwater EI: nativeness, diversity and resilience (Fig. 11.1).

In a global context, New Zealand has a high proportion of endemic species which are vulnerable to predation and competition from invasive species (Howard-Williams et al. 1987; McDowall 2006). Nativeness refers to the degree to which ecosystems are composed of biota indigenous to regions of interest. Thus, a high proportion of indigenous taxa in a lake will contribute to the EI of that lake. Accordingly, the assessment of nativeness requires detailed information on the taxonomic composition of biological communities of a lake. The pristineness component of EI can relate to structural (e.g. presence of macrophytes, food web structure, etc.), functional (e.g. productivity, oxygen depletion, etc.), physico-chemical (e.g. water quality, sediment characteristics, etc.) and connective (e.g. dams, diversions, etc.) aspects of lakes, regardless of whether native or exotic biota contribute to these aspects of lake EI.

Biodiversity is a key ecosystem value as indicated in the global Convention on Biological Diversity of which New Zealand is a signatory. Of all habitats on Earth, anthropogenic impacts are having the greatest negative impacts on the biodiversity of freshwaters (Strayer and Dudgeon 2010). Therefore, the maintenance and enhancement of biodiversity within lakes is of great importance. However, linking diversity to EI is not a simple matter because diversity is often unimodally related to disturbance in ecosystems (Flöder and Sommer 1999). In addition, non-native species contribute to diversity, potentially conflicting with the value of nativeness. Furthermore, diversity is measured in a variety of ways (e.g. species richness, Simpson diversity, Shannon diversity, alpha and gamma diversity, etc.) and is dependent on spatial extent or scale of the study area. Despite these operational complexities, diversity is recognised as an important aspect of EI in freshwaters.

Ecological resilience reflects the ability of an ecosystem to return to its original state after a disturbance or perturbation. Resilience is related to the long-term stability of an ecosystem within the context of varying and changing environmental conditions. As such, the inclusion of ecological resilience as a component of EI extends the concept into the temporal dimension. In the context of lake EI, resilience

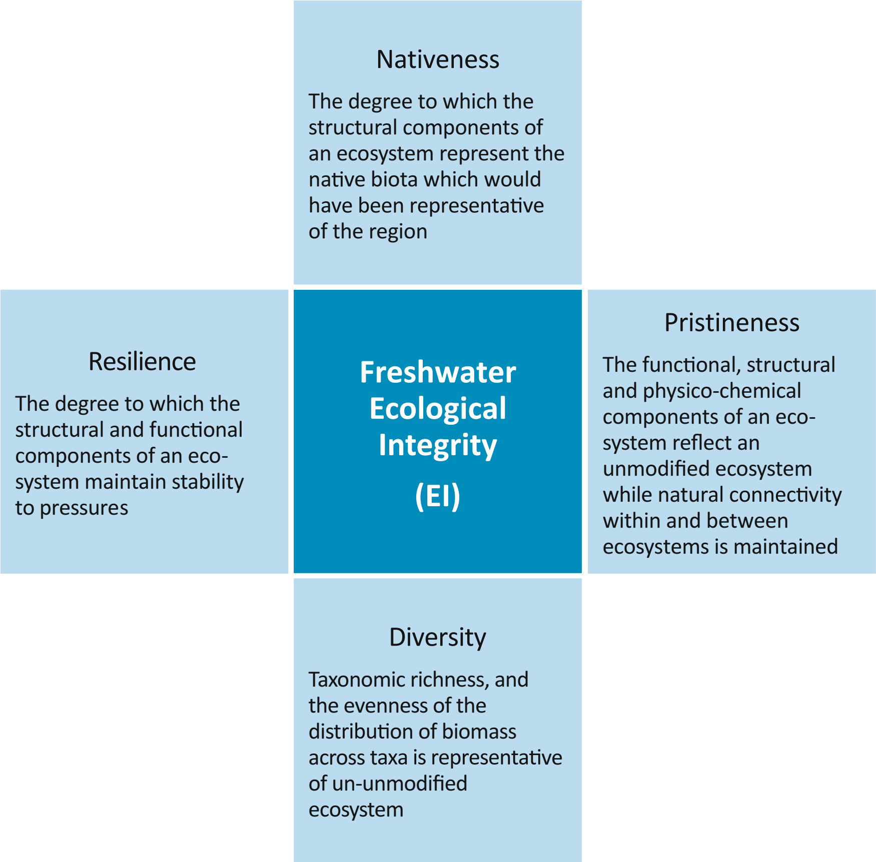

Fig. 11.1 Components of freshwater ecological integrity [after Schallenberg et al. (2011)]

reflects a lake's ability to maintain its structural and functional ecological characteristics despite exposure to environmental variability and change. In this sense, it relates to the presence of beneficial ecological feedbacks within the lake, providing a resistance to (i.e. inertia), and resilience from (i.e. ability to recover), anthropogenic pressures. There are no standard measures of ecological resilience for lakes, so this component of EI may be defined in terms of characteristics which could suggest that a lake is close to an ecological threshold or tipping point (*sensu* Scheffer 2004).

Both Lee et al. (2005) and Schallenberg et al. (2011) calibrated their definitions of EI to a reference condition for terrestrial and lake ecosystems, respectively, emphasising the importance of pristineness within the New Zealand terrestrial and freshwater contexts. In addition to discussing the issue of calibrating EI to reference conditions, Schallenberg et al. (2011) discussed a number of other issues to consider in the implementation of EI, including the scale-dependence and variability (spatial

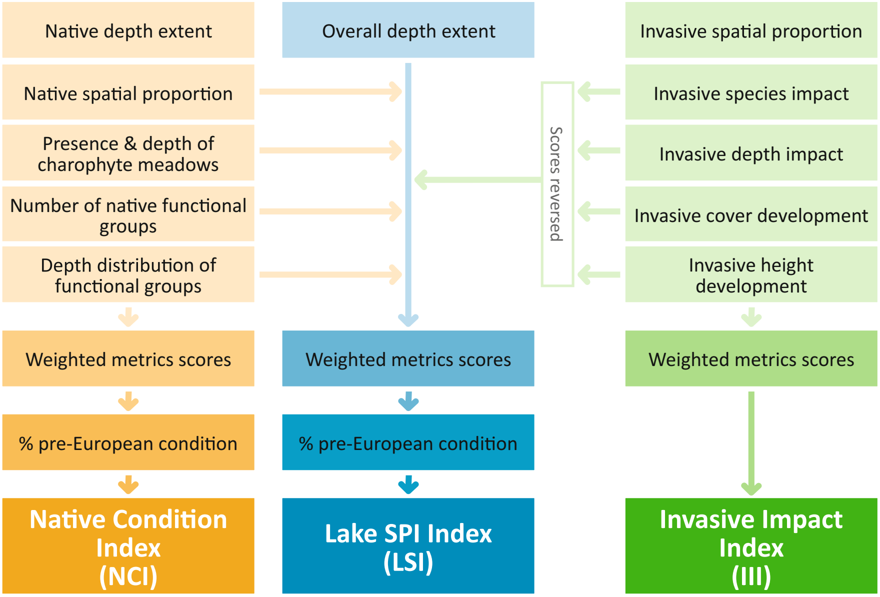

Fig. 11.2 Conceptual overview of the LakeSPI method showing vegetation elements measured and scoring procedure leading to the calculation of three condition indices [modified from de Winton et al. (2012)]

and temporal) of some components of EI and the potential to refine estimates of EI by accounting for different lake types.

Though not specifically designed to assess lake ecological integrity, LakeSPI (Submerged Plant Indicators) is a biological indicator method developed to assess ecological quality of New Zealand lakes (Clayton and Edwards 2006a, b; de Winton et al. 2012). Component metrics were selected for sensitivity to habitat degradation and invasion by alien weeds. LakeSPI metrics assess macrophyte nativeness, diversity and cover (Fig. 11.2) that are related to components of EI (Schallenberg et al. 2011) and could be integrated to a more holistic EI assessment approach for lake restoration (Table 11.1).

In LakeSPI, the emphasis for assessment is on “pristine” vegetation elements that are common to widely varying lake types and geographical locations, so that comparisons between lakes are possible. Nevertheless, LakeSPI does include normalisation for lake maximum depth as an important driver of natural macrophyte depth constraints.

Reference condition of lake vegetation was inferred from a wide range of pristine lakes (from vegetation surveys for >380 water bodies) as well as historical accounts of submerged vegetation (e.g. Kirk 1871; Cunningham et al. 1953). Elements of a pristine (pre-European) lake condition included:

Table 11.1 Examples of LakeSPI indices or metrics, their description, categorisation of metrics within the four components of EI defined by Schallenberg et al. (2011) and relevance for lake restoration

LakeSPI indices/ metric	Definition	EI component	Relevance
LakeSPI index	Integrated measure of % pristine state	Pristineness	Non-vegetated lakes (0% LakeSPI) represent most severely impacted lakes; regime shifts represent major effect on EI (Schallenberg and Sorrell 2009)
Vegetation/native maximum depth/ native distribution	Depth to which plants extend	Pristineness (functional), resilience	Depth extent reduction due to eutrophication (Schwarz et al. 2000) Fluctuations over time indicate instability/possible macrophyte collapse
Charophyte meadows	Depth to which high covers of charophytes extend	Pristineness (structural, functional)	Indicates vegetated area in deeper water Sensitivity threshold to eutrophication (Penning et al. 2008) Potential water quality benefits (Blindow et al. 2014)
Native ratio (note exotic ratio is reciprocal)	Spatial proportion of vegetated area occupied by native plants	Nativeness, resilience	Measure of native plant presence Potential for seed bank formation and maintenance (de Winton and Clayton 1996) Littoral dominance by invasive weeds destabilises system (Champion 2002; Schallenberg and Sorrell 2009)
Nature of invasive cover/invasive maximum height	Measure of invasive performance	Nativeness, pristineness (structural, functional)	Degree of native plant exclusion Change to dense canopy formers Weed impacts on biogeochemical cycles (e.g. Ribaudo et al. 2014)
Invasive species impact	Ranking of species according to invasive ability	Nativeness	Degree of native plant exclusion
Native diversity	Representation by species belonging to up to five functional groups	Diversity	Species richness proxy, structural diversity, depth niche diversity, functional diversity
Native distribution	Key functional group extend >5 m depth	Pristineness (functional)	*Isoëtes* sensitive to combined water clarity and sediment modifications (Brucet et al. 2013)

Note that metrics may span more than one EI component

- Presence of a high number of functional plant groups.
- Development of high cover “meadows” of charophytes, which may extend beyond the depth limits of vascular submerged plants.
- Vegetation development to $\geq$20 m depth or to the lake maximum depth.
- Absence of alien invasive weeds.

It should be noted that LakeSPI cannot be applied to lakes affected by salinity (e.g. coastal lakes and lagoon systems), high altitude (e.g. >c. 1300 m), geothermal water or extremes of pH.

11.2 Key Attributes of Lake Ecological Integrity

Attributes (also known as metrics or indicators) are quantitative measures of EI that are applicable to lakes. Schallenberg et al. (2011) proposed four sets of attributes (referred to as indicators) for measuring lake EI—one set for each of the four components of EI. These attributes were tested conceptually against a set of assessment criteria, and the attributes that appeared most promising in terms of monitoring are presented in Table 11.2.

Lakes and lake habitats are highly diverse, so some specific EI attributes may be better suited to certain lake types than others. Here, the use of a typology divides lakes into three classes that may be useful: (1) polymictic, (2) brackish lakes (including intermittently open and closed lakes and lagoons or ICOLLs) and (3) seasonally stratified lakes (Table 11.3).

Polymictic lakes are lakes which do not thermally stratify on a seasonal basis and are generally fully mixed, but may stratify for short periods of time (e.g. hours or days). In New Zealand, these tend to be shallow lakes (e.g. <10 m maximum depth). Brackish lakes and ICOLLs are generally shallow, coastal lakes with some saline influence through a permanent or intermittent connection to the sea. Seasonally stratified lakes are generally deeper lakes which are thermally stratified for a substantial part of the year, but undergo complete mixing during winter.

Table 11.3 shows that in general, (1) useful nativeness attributes include fish and macrophyte nativeness, (2) pristineness attributes include those typically indicating eutrophication, (3) diversity attributes include species richness of benthic invertebrates, rotifers, macrophytes and phytoplankton and (4) attributes of ecological resilience include cyanobacterial cell density, food chain length and the degree of balance in available N and P (e.g., as indicated by the ratio of dissolved inorganic nitrogen to total phosphorus concentrations).

Özkundakci et al. (2014) analysed the relationships between a range of anthropogenic pressure gradients and EI attributes for 25 seasonally stratifying New Zealand lakes. Instead of applying a typology to the lakes, these authors statistically removed the effects of non-anthropogenic differences in lakes before

Table 11.2 Suggested list of attributes for the assessment of ecological integrity in lakes [from Schallenberg et al. (2011)]

Component of EI	Indicator of attribute	Examples of related stressors
Nativeness	Catch per unit effort (CPUE) of native fish	Invasion by/introduction of exotic species
	Percentage of species native (e.g. macrophytes, fish)	Invasion by/introduction of exotic species
	Absence of invasive fish and macrophytes	Invasion by/introduction of exotic species
	Proportion of shoreline occupied by native macrophytes	Invasion by/introduction of exotic species
Pristineness		
(a) Structural	Depth of lower limit of macrophyte distribution	Eutrophication (benthic effects)
	Phytoplankton community composition	Eutrophication
(b) Functional	Intactness of hydrological regime	Connectedness, abstraction, irrigation, artificial human barriers
	Continuity of passage to sea for migratory fish (potentially indicated by diadromous fish)	Connectedness, artificial human barriers
	Water column DO fluctuation	Eutrophication
	Sediment anoxia (or rate of change of redox state with depth)	Anoxia, eutrophication (benthic effects)
(c) Physico-chemical	TLI (or its components)	Eutrophication
	Non-nutrient contaminants	Depends on pressures
Diversity	Macrophytes, fish, invertebrate diversity indices	Loss of biodiversity
Resilience	Number of trophic levels	Loss of top predators
	Euphotic depth compared to macrophyte depth limit	Macrophyte collapse
	Instance/frequency of macrophyte collapse or recorded regime shifts between clear water and turbid states	Macrophyte collapse
	Compensation depth compared to depth of mixed layer	Potential for light or nutrient limitation of phytoplankton growth
	N:P nutrient balance (DIN:TP)	Risk of cyanobacterial blooms
	Presence of potentially bloom-forming cyanobacteria	Risk of cyanobacterial blooms

analysing the pressure-response relationships. They found that 11 attributes were significantly related to anthropogenic pressure gradients, as shown in Table 11.4.

The information in Tables 11.2, 11.3 and 11.4 suggests that some useful EI attributes are likely to be inter-correlated, supplying redundant information to an assessment of EI. The use of the EI framework should include (if possible) attributes

Table 11.3 Attributes or indicators of components of ecological integrity by lake type

Lake type	EI component	Attribute
Polymictic	Nativeness	• % native fish species • % native macrophyte species • % macrophyte cover attributable to native macrophytes
	Pristineness	• Total nitrogen concentration • Total phosphorus concentration • Trophic level index (TLI) • Chlorophyll *a* concentration • Nitrogen loading rate per unit lake area
	Diversity	• No robust attributes were identified
	Resilience	• Cyanobacterial cell density • Food chain length • Ratio of dissolved inorganic nitrogen to total phosphorus
Brackish and ICOLLs	Nativeness	• % native macrophyte species
	Pristineness	• Chlorophyll *a* concentration • Total nitrogen concentration • Total phosphorus concentration • Trophic level index (TLI) • % of the macroinvertebrate community consisting of (Ephemeroptera + Plecoptera + Odonata) by species counts • Maximum macrophyte depth limit
	Diversity	• Benthic invertebrate species richness • Phytoplankton species richness
	Resilience	• Cyanobacteria cell density
Seasonally stratified	Nativeness	• No robust attributes were identified[a]
	Pristineness	• Maximum macrophyte depth limit • Total phosphorus concentration • Chlorophyll *a* concentration • Total nitrogen concentration
	Diversity	• Rotifer species richness • Macrophyte species richness • Phytoplankton species richness
	Resilience	• Ratio of dissolved inorganic nitrogen to total phosphorus

[a] For nativeness, reference conditions should reflect 100% native communities and, because many non-native species disrupt lake ecosystems (Champion 2002; Closs et al. 2004), a departure from 100% native species composition reflects a departure from reference condition

from all four components while reducing the redundancy (over-representation) of attributes within components (Schallenberg et al. 2011). A robust assessment of EI will contain attributes that are more-or-less evenly spread across all four EI components.

It is also apparent that for some lake types, useful EI attributes have been elusive to date. For example, with respect to ecological resilience and diversity, it has been more difficult to identify attributes that are monotonically related to EI. To identify indicators of ecological resilience, the analysis of long-term data sets covering the responses of lake condition over documented perturbation times is required.

Table 11.4 Attributes of ecological integrity (EI) for seasonally stratifying lakes that were significantly related to anthropogenic pressure gradients [from Özkundakci et al. (2014)]

EI attribute	EI component	Proportion variance explained
Trophic level index	Pristineness	0.80
Total phosphorus	Pristineness	0.68
Total nitrogen	Pristineness	0.67
Rotifer species richness	Diversity	0.55
Soluble reactive phosphorus	Pristineness	0.55
Macrophyte native species count	Nativeness	0.51
Chlorophyll *a*	Pristineness	0.49
Macrophyte total species count	Diversity	0.49
Ammonium	Pristineness	0.41
Macrophyte maximum plant depth	Pristineness	0.38
Macroinvertebrate species richness	Diversity	0.38

Therefore, further work is needed to quantify the relationships between diversity and EI and to identify lake attributes that robustly reflect the ecological resilience, resistance and vulnerability of lakes to anthropogenic pressures.

As EI is a normative concept, one could expect that adding a human interpretive element to the assessment could be advantageous. In a study on 45 shallow coastal lakes, Drake et al. (2011) compared EI assessments based on measured attributes with EI assessments made by three limnologists who had visited the lakes and had ranked the lakes independently in terms of an EI gradient. Not only were the three independent expert assessments of the lakes highly correlated, but they correlated with both measured lake attributes and with four anthropogenic pressure gradients impinging on the lakes. In contrast, the measured lake EI indicators correlated more weakly with the anthropogenic pressure gradients, indicating that expert assessments following site visits can provide useful information to EI assessments that is not easily captured by measuring EI indicators (Table 11.5).

11.3 Implementing Ecological Integrity for Lake Restoration

11.3.1 Reversing the Decline of Ecological Integrity

With the arrival of European settlers to New Zealand in the mid-1800s, the modern era of rapid environmental change was initiated, affecting many lakes (Augustinas et al. 2006; Kitto 2010; Schallenberg et al. 2012; Schallenberg and Saulnier-Talbot 2015). Along with decreases in water quality (Gluckman 2017), many native freshwater fish species have become threatened (Goodman et al. 2014), macrophyte communities have been extirpated or invaded by non-native species (Howard-

Table 11.5 Cross-validated correlations of boosted regression tree models built using WoNI (Waters of National Importance) pressure indices [native catchment vegetation removal, imperviousness, N load and P load) from Drake et al. (2011)]

Measured variable	Cross-validated correlation with four modelled WoNI pressure indices
Native fish species % in this survey	**0.30**
Native fish CPUE (common bully + shortfin eel + longfin eel)	0.24
Benthic invertebrate Pielou evenness	−0.05
Macrophyte weighted Simpson index	0.10
pH	**0.65**
Water colour	0.03
Light attenuation coefficient	0.23
TN:TP/Redfield N:P	0.20
Food web mean distance to centroid	0.12
$\delta^{15}N$ range of consumers	0.06
Chlorophyll *a*	**0.36**
TLI	**0.42**
Expert assessment	**0.77**

Values in bold type are statistically significant at $\alpha = 0.05$

Williams et al. 1987; Kelly and Hawes 2005; Schallenberg and Sorrell 2009), hydrology and hydrological connectivity has been altered (McDowall 2006) and other anthropogenic impacts on lakes have occurred (Weeks et al. 2015). Hence, there is an increasing need to restore the ecological integrity and associated ecosystem services of degraded lakes (Schallenberg et al. 2011).

Shallow lake ecosystems tend to exhibit strong biological interactions, and non-linear responses to changes in ecological drivers are common among such ecosystems because of the implicit importance of ecological feedbacks (Scheffer 2004). Such feedbacks confer inertia, resistance and resilience to perturbations, and while this may confer a surprising amount of assimilative capacity for pollutants in well-functioning lake ecosystems, feedbacks can also impart non-beneficial ecological inertia when they impart resistance to attempts to restore a lake. Accordingly, a lake may respond suddenly to gradual changes in pressures and it may appear recalcitrant toward substantial efforts to restore the lake by reducing pressures on it. For this reason, it is important to understand that ecological feedbacks and inertia may be beneficial for management (by enhancing assimilative capacity), but may also hinder restoration. Embedding EI into lake restoration planning is more likely to identify solutions for overcoming undesirable feedback mechanisms.

11.3.2 Ecological Integrity and Reference Condition

Lake restoration is facilitated by clearly defining the goals of the restoration activities undertaken. These goals can be difficult to establish, especially if relevant information for “reference lakes” (lakes similar to that being lake restored, but in pristine condition) is not available (see Feature Box 11.1 for methods to determine reference conditions). To address this, palaeolimnological studies of degraded lakes allow inferences about the specific historical conditions of the lake prior to its degradation to be made. Carefully interpreted studies of the microfossils and geochemical signatures archived in sediment deposited on the lake bed during historical and pre-historical times provide useful information on reference conditions of the lake. These results, combined with the use of statistical transfer functions relating modern distributions of taxa to environmental conditions, allows quantitative historical inferences about attributes such as phytoplankton biomass, pH, temperature and salinity to be made. Biological proxies of these environmental attributes include chironomids (Woodward and Shulmeister 2006), diatoms (Reid 2005; Schallenberg et al. 2012; Schallenberg and Saulnier-Talbot 2015), pollen (Cosgrove 2011), plant macro-fossil remains (Ayres et al. 2008) and cladoceran remains (Luoto et al. 2013).

Another method for estimating reference conditions is to employ a pressure-response model in a so-called space for time approach. This approach is based on surveys of many lakes spanning a broad gradient of EI. The data from the survey lakes can be used to construct a gradient of EI, which can be used to quantify attributes of the most pristine lakes, thereby providing estimates of the conditions of similar lakes under unimpacted or minimally impacted conditions. Similarly, the use of LakeSPI to determine reference conditions also relies on a large database of lakes sampled in recent times to establish likely macrophyte conditions in minimally impacted or unimpacted lakes. While process-based lake modelling is commonly used to test future scenarios (i.e. climate change scenarios), Hawkins et al. (2010) suggested its use for predicting the historical reference conditions at a site or lake. However, to date, this has not been a typical application of lake deterministic modelling.

Box 11.1 Techniques to Define Reference Conditions in Lakes

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By defining reference conditions, we seek to answer the question “what is the ‘natural’ ecological condition of a lake?” In New Zealand, reference conditions can, therefore, be considered to relate to pristine conditions present prior to human colonisation. Assessing the extent that the present-day ecological integrity of a lake has departed from a reference state provides a useful

(continued)

Box 11.1 (continued)
measure of impairment which can help to set objectives for a lake restoration programme. Reference conditions may be derived for a range of variables. These include: nutrient concentrations, trophic status, primary productivity, phytoplankton community composition, sediment deposition rates, pH and conductivity. A variety of methods has been proposed to define reference conditions (see Table 11.6), and the choice of which method(s) to use will depend on the extent of existing data, the variables of interest, the number of lakes being studied and the resources that are available.

Table 11.6 Summary of key techniques to estimate lake reference conditions

Method	Advantages	Disadvantages	Further reading
Use data for existing undisturbed sites	• Accurate • Uncontentious • Statistical models can be used to extrapolate results to lakes elsewhere based on characteristics such as lake morphology and soil type	• Undisturbed examples of most lake types no longer exist in New Zealand, e.g. lowland lakes	Cardoso et al. (2007) and Herlihy et al. (2013a)
Paleolimnology (analysis of lake sediments)	• A well-developed field of limnology that has led to the development of advanced techniques which can be used for a range of applications • Quantitative and precise	• Requires resource intensive and site-specific sampling and analysis • Diagenesis processes can alter sediment core composition • May not be applicable to variable of interest. Transfer functions that link biotic indicators (e.g. diatoms) with historic water quality can only yield information about variables that limit productivity	Reid (2005) and Herlihy et al. (2013b)
Stressor-response modelling (hindcasting using statistical models that relate current water quality to human pressures and natural factors in lake catchments)	• Quantitative and precise • Can provide information about a range of variables • Can be used to derive additional knowledge using existing monitoring data • Can account for	• Requires a large sample size • Requires detailed data about catchment characteristics • Does not explicitly reflect in-lake processes	Herlihy et al. (2013b)

(continued)

Table 11.6 (continued)

Method	Advantages	Disadvantages	Further reading
	natural variability in factors such as soils and climate • Models can be extrapolated to un-monitored lakes		
Process-based lake ecosystem modelling	• Quantitative and precise • Can account for inherent natural variability of freshwater ecosystems, e.g. due to seasonal cycles • Can simulate a wide range of variables • A tool to formulate new hypotheses and research questions	• High uncertainty with configuring reference state processes • Extensive resource and data requirements, although simple eutrophication models ("Vollenweider models") may provide a parsimonious approach to simulate dominant in-lake processes and provide static predictions of trophic state variables • Largely unproven for estimating reference conditions	See Chap. 3 of this book
Review local oral and written (non-scientific) historical records	• Can help to engage local communities with lake restoration planning • Can provide useful information about historic abundance of *mahinga kai* species	• Unlikely to provide quantitative data • Information does not pre-date start of human disturbance • Issues with "shifting baselines"	Tipa and Nelson (2008)
Calculate upper statistical distribution (e.g. 25th percentile) of monitoring data for a specific lake type	• Straightforward	• Not a true estimate of reference state • Dependent on the sample composition	Herlihy et al. (2013b)
Expert knowledge	• Essential for interpreting the results of other methods	• Subjective • Imprecise	

11.3.3 *Other Ecological Integrity Restoration Endpoints*

Benchmarking lake status relative to a pristine reference condition may not be relevant or achievable in all cases. Duarte et al. (2009) showed that simply reducing key human pressures did not guarantee the return of the system to its pristine state. The differing trajectories and endpoints between degradation and recovery observed in four coastal ecosystems (Duarte et al. 2009) may have been due to biological inertia apparent in systems (discussed above) or to the focus on only single pressure and response variables.

Artificial water bodies, such as hydro-electric reservoirs, present a particular challenge for identifying restoration endpoints because the prior natural state of a reservoir was usually a river and, therefore, the pristine reference state is not relevant in the context of restoring a degraded reservoir. However, EI may still be a useful concept for determining management and restoration endpoints for reservoirs even though the target of reference state is not appropriate. In the case of artificial water bodies, which are constructed predominantly for human purposes, other types of goals (e.g. recreation and sports fisheries) may be deemed more important than ecologically derived endpoints. Nevertheless, the management and restoration of such systems should benefit by holistically considering the EI of the systems and their surrounding aquatic habitats.

Societal perspectives and norms are known to shift over time and, therefore, perspectives concerning which conditions are natural and acceptable can shift (Hawkins et al. 2010). A societally acceptable or desirable lake condition (e.g. open park-like lake margins that allow public access and views) may be one that is quite different from a past state. The past acclimatisation of non-indigenous species can result in alien species being considered as accepted components of lakes, while some invasive species are societally valued (e.g. sports fish) or otherwise utilised (e.g. *Salix* sp.—willows—for erosion control). Therefore, in these cases, desired restoration targets may not reflect a maximisation of EI or a return to a reference condition, and such cases may be problematic for tracking improvements in EI or recognising ecological degradation.

Existing ecological lake values may also deviate from the lake's pristine reference state. Palaeolimnological study of a Norfolk Broad, UK, showed that dredging to restore an earlier reference state was likely to remove contemporary substrate that favoured a valued, nationally rare submerged macrophyte (Ayres et al. 2008). Moreover, Ecke et al. (2010) noted that rare and threatened freshwater species were widely represented in European lakes with lower ecological status scores, and that restoration of the lakes to a more pristine state could produce uncertain outcomes for those species.

In recognition of such issues, Stoddard et al. (2006) identified three additional benchmark conditions that should not be confused with pristine reference state: a "historic condition", the "least disturbed condition" and the "best attainable condition" (Fig. 11.3).

It has been argued that all reference conditions reflect a point in the historical trajectory of a lake because lakes naturally undergo aging and succession over time (Ayres et al. 2008; Kowalewski 2013). Thus, historically based restoration targets should specify relevant historical time frames. For example, both LakeSPI and EI as defined by Schallenberg et al. (2011) calibrate to a pre-European-colonisation (i.e. prior to c. 1850) reference state.

Minimally disturbed reference lakes (Fig. 11.3) are lakes with physico-chemical conditions indicative of low levels of anthropogenic impact, located in catchments with the lowest levels of land-use modification. Stoddard et al. (2006) defined "best

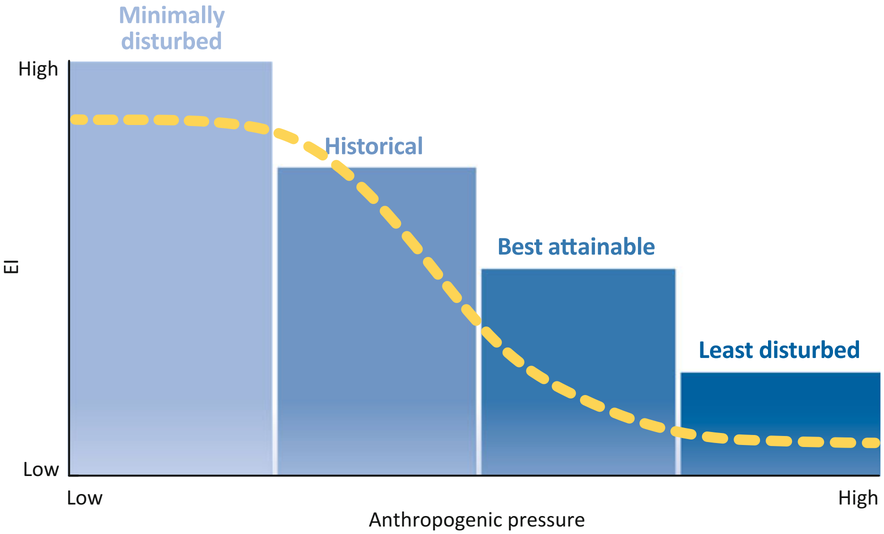

Fig. 11.3 Positions of different restoration target conditions along a gradient of anthropogenic pressure recognising that the targets may be set in relation to (1) a reference (minimally disturbed) condition, (2) a historical condition, (3) a best attainable condition associated with current management practices or (4) to a least disturbed (planned or future) condition [modified from Stoddard et al. (2006)]

attainable condition" as the expected outcome from the application of "best management practice". This is perhaps the most difficult condition to define as it represents an agreed potential, based on current practicable technologies, resourcing and management/societal will. This concept might be applicable to artificial water bodies or those where multiple, often conflicting ecological and human values preclude the attainment of a near-pristine restoration target. Finally, a restoration target set as the best attainable condition may not necessarily preclude further degradation of the water body.

Cultural perspectives can also provide important endpoints for EI. In New Zealand, recent freshwater management reforms have identified the importance of Māori perspectives in freshwater management and restoration (see Chap. 16), in particular for identifying critical components of species composition [harvestable species (*kai*), sacred species (*taonga*)] or function (navigation) (Harmsworth et al. 2013). While the concept of EI is likely to have broad linkages with cultural values and perspectives, so far these have not been specifically considered within an EI framework (e.g. Schallenberg et al. 2011).

Although the European Water Framework Directive (WFD) requires lake assessment to be expressed relative to a minimally disturbed state (see Feature Box 11.2), the endpoint for any restoration is the achievement of "good" ecological status (Brucet et al. 2013). The definition of a good status is contentious, but can best be defined where ecological thresholds in the lake can be quantified (Brucet et al. 2013).

An ecological threshold may occur at a discontinuity in the response relationship of an ecosystem component to a pressure gradient, at a cross-over in the responses of tolerant vs sensitive taxa, or a threshold may result from the breach of a threshold of an attribute having an indirect effect on the response attribute of interest (e.g. a chlorophyll *a* boundary associated with significant retraction in macrophyte spatial extent).

It is important to establish clear and relevant timelines for restoration actions to achieve EI endpoints. For example, where grass carp have been stocked to lakes to eradicate alien weed species for biosecurity reasons, there can be a temporary, unfavourable reduction in water clarity and EI (see Chap. 8). The primary aim of the stocking is to restore native vegetation values by regeneration from seedbanks once invasive species have been eradicated, and the grass carp have been removed. Grass carp browsing during this process could cause some EI attributes to deteriorate (e.g. reduction in plant depth limit, loss of vegetation influence on water quality), while others could indicate improvement (e.g. reduced invasive weed presence and development).

All types of restoration endpoints are likely to benefit from the use of an EI framework, even if the attainment of reference conditions is not the agreed upon goal of a restoration. For a restoration project to be successful, it is helpful for all involved to clearly articulate and agree on the endpoint sought and the timeline for achieving it. In this way, restoration progress can be tracked and the success or otherwise of restoration efforts can be robustly assessed, whatever the goals may be.

Box 11.2 Assessing Ecological Conditions of Lakes Across Europe

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Water is not a commercial product like any other but, rather, a heritage which must be protected, defended and treated as such. This acknowledgement is the cornerstone of the EU's water policy.

The Water Framework Directive (2000/60/EC) is the most substantial piece of water legislation from the European Commission (EC) to date. A core concept of the EU Water Framework Directive is that the structure and functioning of aquatic ecosystems is used to assess the ecological status of surface waters.

Biological communities, such as phytoplankton, aquatic flora, benthic invertebrates and fish fauna, are used to assess the health of aquatic ecosystems. Assessment of quality is based on the extent of deviation from the reference conditions, defined as the biological, chemical and morphological conditions associated with no or very low human pressure. Good status means "slight" deviation from reference conditions, providing sustainable ecosystem

(continued)

Box 11.2 (continued)
and acceptable conditions for human use. The general objective of the WFD is to achieve "good status" for all surface waters by 2015.

Since the adoption of the European Water Framework Directive in 2000, huge progress has been made in the ecological assessment of European waters. Over 90 lake ecological assessment methods are currently in use across Europe. These assessment methods are composed of several metrics (e.g. chlorophyll-*a*, total phytoplankton biovolume and abundance of cyanobacteria), and combination rules are applied to calculate the ecological assessment results for the whole system. The final assessment is expressed as an Ecological Quality Ratio (EQR)—the ratio of the observed assessment value to the expected value under reference conditions. To ensure methods comparability, intercalibration has been carried out by Member States—62 lake assessment methods were intercalibrated and published in an EC Decision (see Table 11.7).

Most of the assessment methods are based on phytoplankton and macrophyte communities, while fewer methods are developed using fish fauna, benthic invertebrates and phytobenthos. Most of the methods focus on the assessment of eutrophication pressure, which is one of the major and the best understood human impacts in Europe, while only a few methods address hydromorpohological alterations and multiple pressures.

For the whole lake assessment, assessment of biological methods are combined using a "one-out-all-out principle", i.e. the worst status of the elements used in the assessment determines the final status of the water body. Still, the validity of this principle has been strongly debated.

The ecological status of more than 19,000 lake water bodies was assessed using the WFD classification tools (European Environment Agency 2012). Of those, 44% are reported to be in less than good ecological status and will need restoration measures to meet the "good status" objective.

11.3.4 Suggested Ecological Integrity Attribute Guidelines

In Sects. 11.1 and 11.2, some suggested attributes for measuring EI in lakes were presented. However, other attributes may also be relevant, especially for specific lakes and lake types. Ecological Integrity attributes useful for lake restoration should meet a number of criteria. Ideally some consideration should be given to the time frame of measurement because some attributes may respond more quickly than others to changes in environmental pressures/drivers. For example, community structure can be sensitive to anthropogenic stressors, whereas changes to ecosystem metabolism (i.e. community productivity, respiration) may be slower to respond (Schindler 1987). In deep New Zealand lakes, physico-chemical attributes of EI

Table 11.7 Overview of lake assessment methods (only intercalibrated methods)

Biological community	Most typical metrics included	Member states	Pressures addressed	Selected references
Phytoplankton	Chlorophyll-*a* Total biovolume Biovolume of cyanobacteria Sensitivity indices	AT, BE, CY, DE, DK, EE, ES, FI, IE, IT, NL, NO, PL, PT, SE, SI, UK	Eutrophication	Carvalho et al. (2013) and Poikane et al. (2010, 2014)
Macrophytes	Colonisation depth Sensitivity indices	AT, BE, DE, DK, EE, FI, FR, IE, IT, LT, LV, NL, NO, PL, SE, SI, UK	Eutrophication	Pall and Moser (2009) and Schaumburg et al. (2004)
Phytobenthos	Diatom trophic indices	BE, DE, FI, HU, IE, PL, SE, SI, UK	Eutrophication	Kelly et al. (2014) and Schaumburg et al. (2004)
Benthic invertebrates	Total taxa richness Shannon diversity Sensitivity indices	BE, EE, DE, FI, LT, NL, NO, SE, SI, UK	Hydromorphological alterations Acidification Eutrophication	McFarland et al. (2010) and Sidagyte et al. (2013)
Fish fauna	Total biomass Biomass of cyprinids Functional indices	AT, DE, FI, IE, IT	Eutrophication Multiple pressures	Kelly et al. (2012) and Olin et al. (2013)

AT Austria; *BE* Belgium; *CY* Cyprus; *DE* Germany; *DK* Denmark; *EE* Estonia; *ES* Spain; *FI* Finland; *IE* Ireland; *IT* Italy; *LT* Lithuania; *LV* Latvia; *NL*, the Netherlands; *NO* Norway; *PL* Poland; *PT* Portugal; *SE* Sweden; *SI* Slovenia; *UK* United Kingdom

were more strongly related to anthropogenic pressures than biological indicators of EI (Özkundakci et al. 2014). Useful attributes have large "signal-to-noise" ratios, are highly sensitive to anthropogenic pressures and are less sensitive to natural environmental variations.

We have defined EI as a multimetric concept, which should consider attributes reflecting the state of a lake with respect to nativeness, pristineness, diversity and resilience. The inclusion of metrics covering four separate components of EI encourages the assessment of EI to be broad in scope, covering multiple ecological gradients. To date, there has been no attempt to combine attributes from the four EI components into an overall EI score for lakes, although this has been conducted for New Zealand rivers (Clapcott et al. 2011). Currently, nativeness, pristineness and diversity can be measured more confidently than resilience, and more work is needed to develop resilience indicators. Similarly, there continues to be debate about how diversity correlates to ecosystem stressors, functioning and integrity. As work progresses on these questions and more robust attributes for EI components are developed, consideration should be given to how each of the four EI components should be weighted within an overall EI index. While the future development of an overall EI index could be useful, examining the four components separately provides a clear picture of the status and trends of the individual EI components—components which may respond differently across anthropogenic pressure gradients. For this reason, it may be advantageous to examine the EI components separately when undertaking lake restoration.

11.4 Ecological Integrity in Lake Management Policy and Restoration Practice

11.4.1 New Zealand

In New Zealand, regional councils generally focus on water quality in lakes, while the Department of Conservation tends to focus on conserving indigenous biodiversity and habitats (Park 2000). The concept of EI encourages a unification of these two approaches, as well as the consideration of lake ecological resistance (inertia) and resilience (recovery) to anthropogenic pressures. The recent development of a New Zealand freshwater definition of EI (Schallenberg et al. 2011) and its subsequent use in assessments of lake EI and reference condition (Drake et al. 2011; Schallenberg and Kelly 2013; Özkundakci et al. 2014; Schallenberg and Schallenberg 2014) encourage more holistic approaches to lake monitoring, management and restoration.

Among regional and national government departments and ministries, a substantial amount of information is being collected on New Zealand lakes that can already contribute to assessments of lake EI. For example, water quality information collected by regional councils, together with information on indigenous biodiversity and non-indigenous species distributions collected by the Department of Conservation and the National Institute of Water and Atmospheric Research (NIWA), and information on cyanobacterial cell densities collected by public health offices and the Ministry of Health, together represent attributes that cover all four of the EI components. Combining of this information would allow assessment of EI at a national scale and could facilitate the development of policies focused on the maintenance and enhancement of lake EI. The Department of Conservation has further considered an amalgamated monitoring programme as part of its biodiversity monitoring strategy which would combine regional councils' monitoring of water quality with focused monitoring on nativeness and biodiversity to inform a broader assessment of EI (Kelly et al. 2013).

LakeSPI bio-assessments are frequently undertaken to complement traditional water quality monitoring. Individual LakeSPI metrics (see Fig. 11.2), indicating departure from an expected or “pristine” reference state, could contribute to a multimetric EI approach for monitoring water bodies. To date LakeSPI assessments are available for >260 lakes (http://lakespi.niwa.co.nz/).

Loosely related to the concept of EI are the concepts of ecological condition and ecological value that have been used by regional councils in prioritisation schemes to identify high quality lakes. For example, ecological condition was one line of evidence used to prioritise lakes for biodiversity management in the Waikato region, central North Island (Reeves et al. 2009), leading to the identification of significant natural areas for protection. Ecological value was used to identify lakes (i.e. moderate-high to outstanding value) for priority management in Northland (Champion and de Winton 2012) and has guided initiatives to protect and restore lakes (Champion and Wells 2014). While restoration potential was also considered for Waikato lakes by Reeves et al. (2009), this was based more on feasibility and time-frame required rather than EI criteria. None of these schemes identified reference conditions or indicated the degree of departure of individual lakes from an expected pristine state, but they have identified some minimally disturbed conditions for lakes in several of New Zealand’s regions.

With the development of the New Zealand lake EI framework (Schallenberg et al. 2011), the opportunity has arisen for regional council lake managers to place their lakes within an EI context. For example, studies commissioned by the Tasman District Council (Schallenberg 2011), Environment Southland (Schallenberg and Kelly 2013) and Environment Canterbury (Schallenberg and Schallenberg 2014) have used the EI concept to assess the ecological condition of lakes in those regions to help define reference conditions for the lakes and to calculate current departures of the lakes from their EI reference conditions (Fig. 11.4).

While the concept of lake EI hasn’t yet been explicitly used to direct lake restoration, the identification of a poor state of an EI attribute could encourage the adoption of specific lake management and restoration actions. The type of information summarised in Fig. 11.4 can help set restoration goals and targets, even if achieving them is aspirational rather than realistic in the short term.

11.5 Future Prospects

Recent government guidance has set some national freshwater guidelines for maintaining or improving ecosystem health, defined as,

> supporting a healthy ecosystem appropriate to that freshwater body type, where ecological processes are maintained, there is a range and diversity of indigenous flora and fauna, and there is resilience to change. (Ministry for the Environment 2014)

This goal appears to be compatible with maintaining and enhancing EI, although current lake attributes are limited to trophic state variables such as nitrogen, phosphorus and chlorophyll *a* concentrations. Thus, the EI framework provides useful guidance for selecting ecological attributes (beyond water quality attributes) which could contribute to more holistic assessments of lake health.

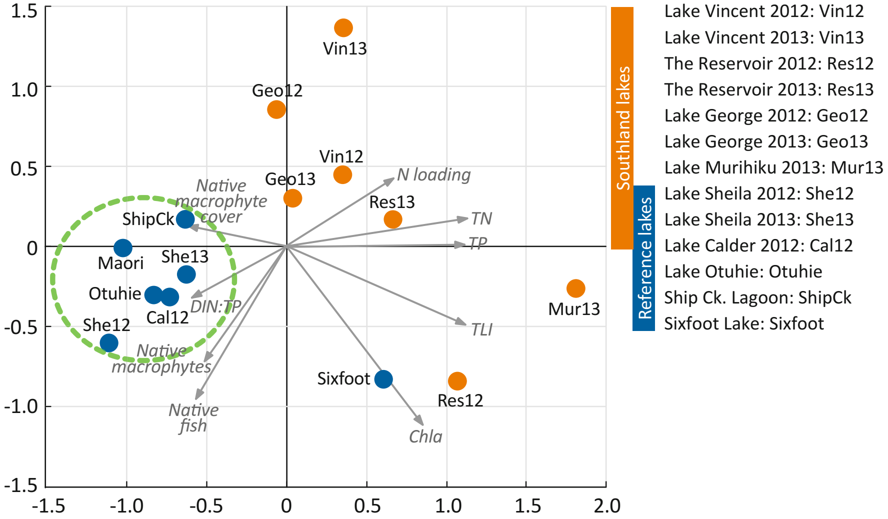

Fig. 11.4 Ordination plot showing relationships between Southland reference lakes (blue circles) and other Southland lakes (orange circles), based on nativeness, pristineness and resilience indicators of EI. Six-foot Lake (Campbell Island) was considered a reference lake although it was eutrophic. The green, dashed circle encloses the other reference lakes. The *x*-axis explains 47% of the variation and can be interpreted as a gradient of pristineness and nativeness. The *y*-axis explains 20% of the variation [from Schallenberg and Kelly (2013)].

Ecological Integrity encourages the adoption of a holistic perspective on lake policy, monitoring, management and restoration. This chapter highlights how EI can be useful for establishing lake restoration goals and targets, whether they be set for the purpose of restoring to reference conditions or to another endpoint along the lake EI gradient. Either way, the EI concept encourages the setting of multiparameter restoration endpoints, resulting in more holistic monitoring of lake health status and recovery. Ecological Integrity encourages progression away from a common restoration perspective which argues that if the physico-chemical environment is restored, then the rest of the ecosystem will necessarily restore itself. It has been shown that restoration strategies that focus only on reductions in nutrient loading (for example) often fail to achieve predicted outcomes (e.g. Duarte et al. 2009). Holistic approaches to restoration that are aimed at restoring diverse ecosystem components are more likely to achieve desired restoration outcomes because some key synergistic interactions among ecosystem components are likely to increase the rate of recovery and the probability of restoration success, while others are likely to hinder these outcomes. In addition, the adoption of an EI approach to restoration encourages the safeguarding and restoration of lake ecological resilience, which should produce more reliable long-term restoration outcomes.

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