The Land Resource Circle: supporting land-use decision making with an ecosystem-service-based framework of soil functions

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Abstract

Land information has in the past focused on the key land and soil properties that physically or chemically support or limit the use of land. With the increasing focus on the environmental, social, and cultural impacts of land-use decisions beyond the boundaries of individual land parcels, there is a growing need for more extensive resource information to support assessments of the benefits, impacts, and trade-offs of land-use decisions. We present a new framework for providing land resource information to support an ecosystem-service-based approach to land-use decision making. The new framework, called "the Land Resource Circle", is first conceptually defined, then its use is explored in a hypothetical example. It draws upon the literature on soil functions and their contribution to ecosystem services. In addition, it recognizes that soils differ in their capacity for resisting the various pressures due to land use and/or climate. It also recognizes that the surrounding landscape provides functionality that can affect the delivery of ecosystem services from a land parcel and its suitability for different land uses. The Land Resource Circle is designed as a flexible and comprehensive information resource that can be used for multiple purposes, including spatial planning, land assessment, and increasing awareness of soil-related constraints to sustainable use of land.

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1 Introduction

There are rapidly growing demands on land-based industries and land managers to balance the need for economic prosperity with a greater focus on the environmental, social, and cultural impacts of land-use decisions beyond the boundaries of individual land parcels (Foley et al., 2011; Renting et al., 2009). Comprehensive land resource information systems that incorporate these wider considerations are needed to assess the benefits, impacts, and trade-offs of land-use decisions at different temporal and spatial scales.

Most existing national-scale land resource information classification systems are based on land evaluation concepts that derive from classification systems from the 1950s to the 1980s (van Diepen et al., 1991); for example, the USDA Land Capability Classification (LCC) (Klingebiel and Montgomery, 1961) or the closely related New Zealand Land Use Capability (LUC) (Lynn et al., 2009) and Tasmanian Land Capability Classification (Grouse, 1999) systems. While these classifications have been, and are, still widely used, they do have some significant limitations that are the focus of increasing attention. Land resource analyses in the 21st century tend to have broader, more holistic criteria than the productivity and erosion focus of last century (Foley et al., 2005; Lavalle et al., 2016). The USDA LCC and NZ LUC classifications, for example, do not consider the impacts of land use on environmental outcomes such as water quality (Lilburne et al., 2016) or the potential consequences of climate change (Orwin et al., 2015). There is also increasing interest in understanding the difference and interaction between inherent and dynamic soil properties (Stevenson et al., 2015). Land evaluation has tended to focus on inherent properties (e.g. topsoil depth, soil texture, slope), whereas soil quality (or soil health) focuses on dynamic properties (e.g. soil organic matter content, aggregation, density), particularly in the surface horizon, where the effects of land management are expressed (Bünemann et al., 2018).

The ecosystem services concept is a more recent development in characterizing the wider benefits or services provided by nature (Costanza et al., 2017). Some researchers have focused on the services provided by soil (Bouma, 2014; Calzolari et al., 2016; Dominati et al., 2010; Greiner et al., 2017). This paper adopts and extends this work to develop a new framework for providing land resource information to support decision making that covers a wide range of issues relating to productivity and environmental outcomes. The new framework, called "the Land Resource Circle" (LRC), is first conceptually defined, then its use is explored in an expert-informed hypothetical example.

2 Background

2.1 Land-use capability/evaluation

There is a long history of formal land evaluation since 1950. The USDA LCC (Klingebiel and Montgomery, 1961) is an interpretative grouping of soils that has been widely used and modified (van Diepen et al., 1991). For example, it has strongly influenced New Zealand's LUC classification (Lynn and Hewitt, 2006). Other US systems include the Storie Index Rating, and a classification for irrigated land used by the U.S. Bureau of Reclamation. The United Nations Food and Agriculture Organisation (FAO) documented standardized principles and methods in *A Framework for Land Evaluation* (FAO, 1976), which is still in use today, particularly in low- and lower-middle-income countries. More recent land evaluation systems include the Müncheberg Soil Quality Rating (Mueller et al., 2010) and the Canadian Land Suitability Rating System (Bock et al., 2018).

In common with other USDA-influenced classifications, New Zealand's LUC classification has three levels. The top level has eight classes, indicating increasing hazard or limitation to use. Class 1 is the most versatile land, capable of a range of agricultural uses; class 8 is the least versatile and most suited to conservation land. Classes 1–4 are classified as "arable" (includes grain and seed crops, process and [outdoor] fresh vegetable crops, perennial horticulture) , 5–8 are "non-arable" (includes pasture and forestry). The second level (subclass) indicates the dominant limitation (erodibility, wetness, soil and climate). The third level (unit) groups area of land by similarities in crop suitability, production level, and management requirements (Lynn et al., 2009). While LUC does have a strong focus on soil conservation, particularly in relation to erosion, other aspects of sustainable use are implicitly covered in its assessment of "long-term sustainable production" (e.g. "suitable for cropping" means that under good management the land is capable of growing at least one of the common, annual field crops normally grown in that region without any permanent adverse soil effects, and with average yields) (Lynn et al., 2009). Unfortunately, this hierarchical limitation-based approach, while easy to understand, is inflexible in terms of supporting analyses of environmental and socio-economic outcomes. It also lacks the flexibility to analyse the impacts of climate change and interactions of climate with environmental outcomes. Our premise is that the ecosystem service approach enables a more comprehensive description of land resources that supports decisions in a wide range of contexts, including food security, climate change, water quality, land-use suitability, irrigation management, sustainability, soil health monitoring, and trade-offs between competing uses.

2.2 Ecosystem services and soil functions

Ecosystem service concepts and frameworks have received considerable attention over the last two decades (Costanza et al., 2017), and have now been adopted by international organizations and government agencies in numerous countries (Baveye et al., 2016). The Millennium Ecosystem Assessment (MEA, 2005) was a major milestone that defined ecosystem services as "the capacity of natural processes and components to provide goods and services that satisfy human needs, directly or indirectly". Four categories of ecosystem services were described: provisioning, regulating, cultural, and supporting. Other initiatives to develop ecosystem service frameworks include The Economics of Ecosystems and Biodiversity (TEEB (2010)) and the Common International Classification of Ecosystem Services (CICES) (Maes et al., 2013). Each has its own particular focus and application, but there is no clear and consistent terminology (Fisher et al., 2009; Schwilch et al., 2016). Indeed Fisher et al. (2009) argue that different decision-making contexts require different classification schemes.

Some researchers have focused on soil ecosystem services and linked these to the older literature on soil functions and soil properties (Baveye et al., 2016; Blum, 2005; Calzolari et al., 2016; Dominati et al., 2010; Tóth et al., 2013). In particular, Dominati et al. (2014a; 2010; 2014b) have presented a framework showing the links between ecosystem services, soil properties, and processes that degrade and enhance soils. In this framework, soil properties (inherent and manageable) underpin the soil's natural capital. Tóth et al. (2013) linked the seven major soil functions listed by the Commission of the European Communities (CEC, 2006) as underpinning the four MEA (2005) ecosystem service categories, in a continental-scale assessment of provisioning soil functions. They developed some productivity indices that could be shown spatially, thus providing information that could assist decision makers. Similarly, Calzolari et al. (2016) developed regional-scale maps of northern Italy showing eight key soil functions that contribute to one or more ecosystem services: 1) habitat for soil organisms; 2) filtering and buffering; 3) contribution to microclimate regulation; 4) carbon sequestration potential; 5) food provision; 6) support to human infrastructures; 7) water regulation; and 8) water storage.

Following Fisher et al. (2009) and Bünemann et al. (2018), we have adopted the following definitions. A *service* is the capacity of natural processes and components to provide well-being to humans, directly or indirectly. There are three broad types of services: provisioning, regulating and maintenance, and cultural. *Soil functions* are bundles of soil processes that are not specifically linked to human benefit. For example, water storage is a soil function that is mediated by a range of measurable soil properties (e.g., pore size distribution, texture, bulk density, stone content) that determine the process of the movement of water in the soil. Water storage function provides ecosystem services, and thus benefits to humans, when, for instance, it is evaluated in connection with supporting food production (provisioning service), or preventing unwanted nutrient leaching, surface run-off or flooding (regulating services). Rather than try to separate functions and processes, or avoid the use of one of the terms (e.g., Schwilch et al., 2016), we have opted to group soil processes and functions together in our framework. Both of these support ecosystem services directly or indirectly.

3 Land Resource Circle framework

Decision making for sustainable use of the land is becoming more holistic and broader in scope than the earlier focus on biophysical impacts on sustainable productivity and economic return (Foley et al., 2005). Degradation of ecosystem services has been observed (Foley et al., 2011; Lautenbach et al., 2011; Schulte et al., 2014), prompting the notion that sustainable use of land should account for impacts on receiving environments. For example, water quality of downstream water bodies has become an important driver in determining appropriate use of land upstream (McDowell et al., 2018). Other drivers include the impact of land use on greenhouse gas emissions and biodiversity.

The desire of a wide range of stakeholders to address the multitude of issues facing society now and in the future calls for the provision of national-scale land resource information to address a much wider range of ecosystem services in land-use decision making. This information needs to support more integrated analyses of trade-offs between environmental, social, cultural, and economic objectives. For instance, landscape-scale methods are now emerging for understanding trade-offs and optimizing land resources to maximize regulating services (e.g. erosion, climate, water regulation) while maintaining food provisioning services (Herzig et al., 2013; Herzig et al., 2016; Seppelt, 2016).

3.1 Interaction of land use, soil, and climate

Climate is a critical factor affecting agricultural production and the capability of land to support different land uses. Climatic conditions (e.g. growing degree days, drought frequency, solar radiation) are important to meeting physiological demands of plants and animals, but they also impose conditions that may increase or reduce the risks of adverse environmental outcomes (e.g., NO_3 leaching, sediment run-off, N_2O emissions, wind erosion) under different land uses. However, the impact of climate on production and the environment under different land uses is also strongly influenced by its interaction with specific soil/landform attributes and constraints at any given location. For example, while climate is an important determinant of the physiological potential of plants to produce biomass, this potential may be constrained by key soil/landform functions. The interaction between climate and soil/landform properties also affects the risk of adverse environmental outcomes from different land-use practices. For example, soil water storage capacity and drainage characteristics, precipitation, and temperature affect the risk of NO_3 leaching, N_2O emission and surface run-off. Another example of interactions between climate, soil/landform, and land use is the effect of extreme rainfall events on soil erosion, where the effect is influenced by soil aggregation, slope and vegetation cover. In general, the level of ecosystem services provided by a land parcel is a function of the land use and management imposed, and their interactions with climate and soil/landform characteristics (attributes and constraints) at that location (Figure 1).

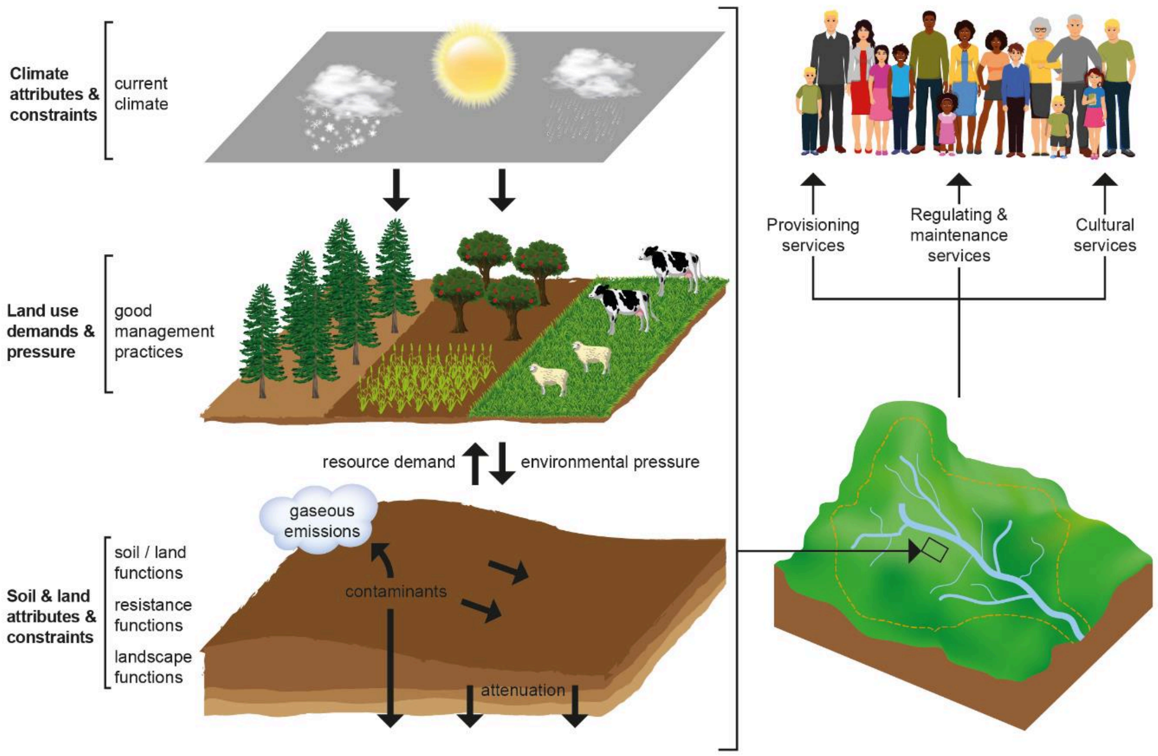

Figure 1. The interactions of soil and land with climate and land use to determine the impacts and outcomes of land-use decisions on ecosystem services.

3.2 Proposed framework

We propose an ecosystem-service-influenced framework for land resource information called the Land Resource Circle (LRC), depicted in Figure 2. The LRC essentially describes the various soil and land processes and functions that are determined by the attributes and constraints of the soil, topography, and wider landscape, and their interactions with climate and land use. The outer rings reflect the three types of ecosystem services (provisioning, regulating and maintenance, and cultural) and indicate some of the more specific ecosystem services and associated benefits. The inner circle has three groupings of land-related functions: key soil and land functions or processes, landscape functions, and land resistance, where all three are influenced by the underlying natural capital of the land system.

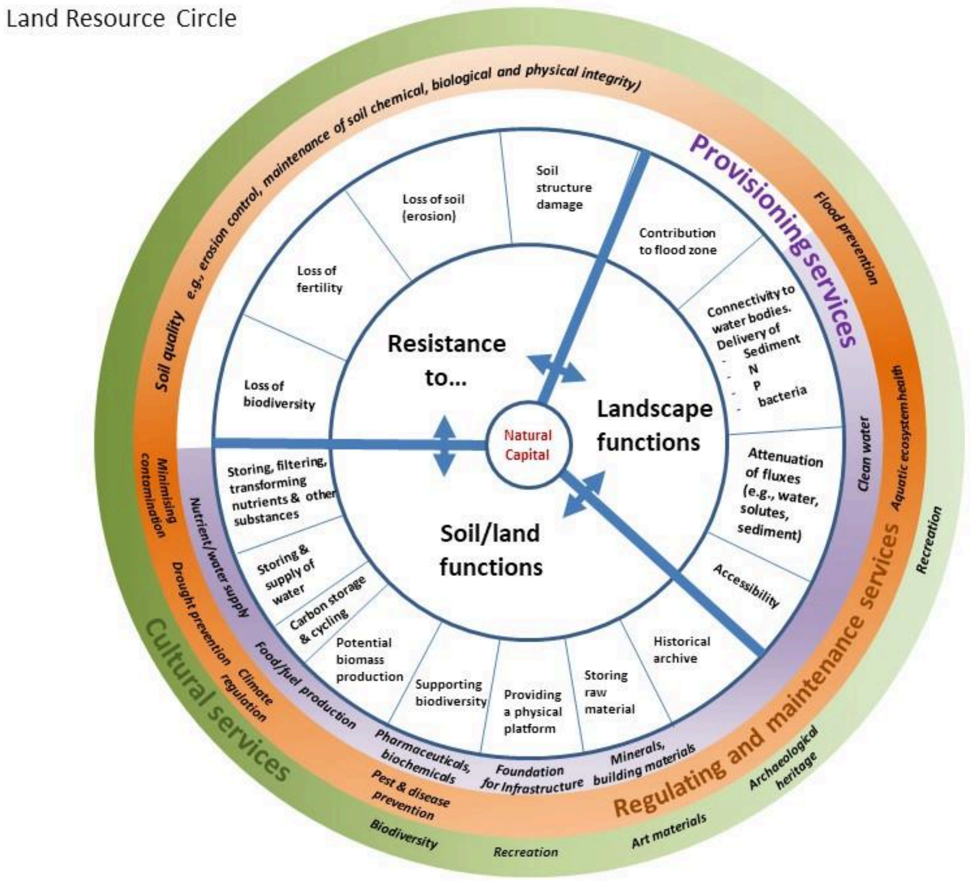

Figure 2. The Land Resource Circle: a framework for describing the key characteristics of a land parcel. The inner core is the natural capital or properties (e.g., geology, mineralogy) of the soil and land system. The inner ring lists functions and processes provided by the land parcel and the broader landscape (catchment), with resistance representing the ability of land to resist external pressures. The three outer rings are the ecosystem services and associated benefits. Climate is considered as a separate layer, which can affect all elements in the circle. See also Adhikari and Hartemink (2016) for a similar circle, but their functions are limited to the soil, and resistance is not considered.

The first grouping of key soil/land functions and processes is adapted from CEC (2006) and Schwilch et al. (2016). We have maintained the seven CEC functions, but relabelled them and separated the nutrient- and water-related functions, resulting in eight soil/land functions that describe the functions of a discrete land parcel immediately above the land surface and below the surface as far as the saturated zone.

The second grouping of landscape functions describes the spatial relevance of processes operating in various parts of a landscape (e.g., catchment) to the land parcel. In effect these are ‘off-site’ functions provided by the surrounding land. The spatial context is particularly important for ecosystem services (such as clean water provision) that are related to transport processes like water or sediment movement along pressure or altitude gradients (e.g., attenuation of NO_3 through denitrification or plant uptake during transport in a shallow aquifer). As such, these landscape functions can occur outside of the soil and land parcel of immediate interest because they are affected by, for instance, groundwater/surface water hydrology and hillslope morphology. These landscape functions may also relate to the human component in a landscape (e.g., existing infrastructure) and include connectivity to surrounding environments, both natural and anthropogenic. For example, a connectivity function that a surrounding landscape might provide for a specific land parcel is connectivity to processing factories through a roading network, or routing of run-off water through a connected wetland.

The third grouping of functions and processes relates to the resistance of land to degradation pressure. Resistance is defined as the ability of the soil to withstand modification under an applied stress (Hewitt and Shepherd, 1997). We further limit this definition to reflect a longer time scale for recovery. Soils with poor resistance also have low resilience (i.e., do not recover quickly after modification). Poor resistance can affect ecosystem function through potential changes in soil and land properties. Since our framework is operating on a human time scale (i.e. years to decades), this change is overwhelmingly a result of direct or indirect actions by humans, including land-use change, intensification of land use, and climate change.

The components of the LRC are now discussed in more detail. As in Dominati et al.’s (2014a) framework, the natural capital of land is the set of properties that are integral to the various land-based ecosystems. The underlying natural capital supports the three types of ecosystem services that provide direct and indirect benefits to humans. For example, soils with high levels of carbon, good aggregate structure, and high capacity for water storage and nutrient retention tend to have a high biomass production function, provide provisioning (food) and regulating/maintenance services (flood control, clean water), and are more resistant to structural deterioration and erosion. The broader landscape can influence the level of ecosystem services through spatial relationships that either enhance or constrain the achievable level of ecosystem services (e.g. attenuation in downstream rivers can enhance the supply of clean water). The link between soil properties and soil function has been tabulated by Adhikari and Hartemink (2016), Greiner et al. (2017), and Dominati et al. (2014b). In general, multiple soil properties affect a single function, and each soil property usually influences multiple functions.

External pressures can influence soil properties and thus functions/processes, ecosystem services, and ultimately humans. Pressures can be imposed by different land uses (type, intensity), climatic conditions, and their interactions. For instance, soil properties can change under various types of pressures, such as frequent tillage (e.g., reduced soil carbon stocks), or use of heavy machinery or animal treading (e.g., reduced soil macroporosity). Some soils are more resistant to pressure than others, so their properties will not change as much. For instance, resistance to land-use-driven detrimental changes in soil structure is strongly affected by clay mineralogy (type and quantity) and organic carbon content in New Zealand soils (Hewitt and Shepherd, 1997).

While the varying capacity of land to withstand different pressures has long been recognised, it has not been explicitly characterized in land evaluation frameworks discussed earlier. We argue that explicit identification of these differences enables a flexible assessment of land resources that incorporates an awareness of the potential for land degradation that may limit the sustained productivity and/or environmental performance (i.e. minimize contaminant losses) of a given land use. It will also assist in identifying management options that may offset or mitigate the specific degradation effects. For example, a land parcel that is susceptible to compaction may still be suitable for intensive cattle grazing if they are housed and fed supplement (e.g. hay or silage) during periods of high soil moisture when the risk of compaction is greatest (Thomas et al., 2008).

As discussed, the interactions between properties and the various soil functions and processes are complex. Many soil properties influence a variety of soil functions and processes so the degradation (or enhancement) of a soil property due to a pressure can impact on the soil's long-term support of multiple ecosystem services.

Figure 3 simplifies this complexity by distinguishing four main soil components (soil physical structure, air/water content, nutrient and carbon levels, and soil biota/habitat) and the key links with four potential land degradation responses to pressure (loss of fertility, damage to soil structure, erosion, and loss of biodiversity). For example, the pressure imposed by a land use (e.g., heavy machinery under intensive cropping or livestock treading damage on pastures) may cause soil compaction (soil structure damage), resulting in a consequent loss of soil aeration, reduced infiltration of water, and restricted root penetration, which can restrict the access of plant roots to water and nutrients and increase the risk of nitrous oxide emissions (Gregorich et al., 2014; Hu et al., 2019; Thomas et al., 2008). The links determine the level of provisioning and regulating services that are supplied by a degraded soil. Land with poor resistance to degradation has "sustainability constraints" for its long-term use under specific high-pressure land uses. Alternative management practices or the addition of built capital (e.g. irrigation, fertilizer) may overcome either the inherent constraints of the land (e.g. low water storage) or sustainability constraints (e.g. propensity to erode or compact), though there is often a real cost associated with doing so.

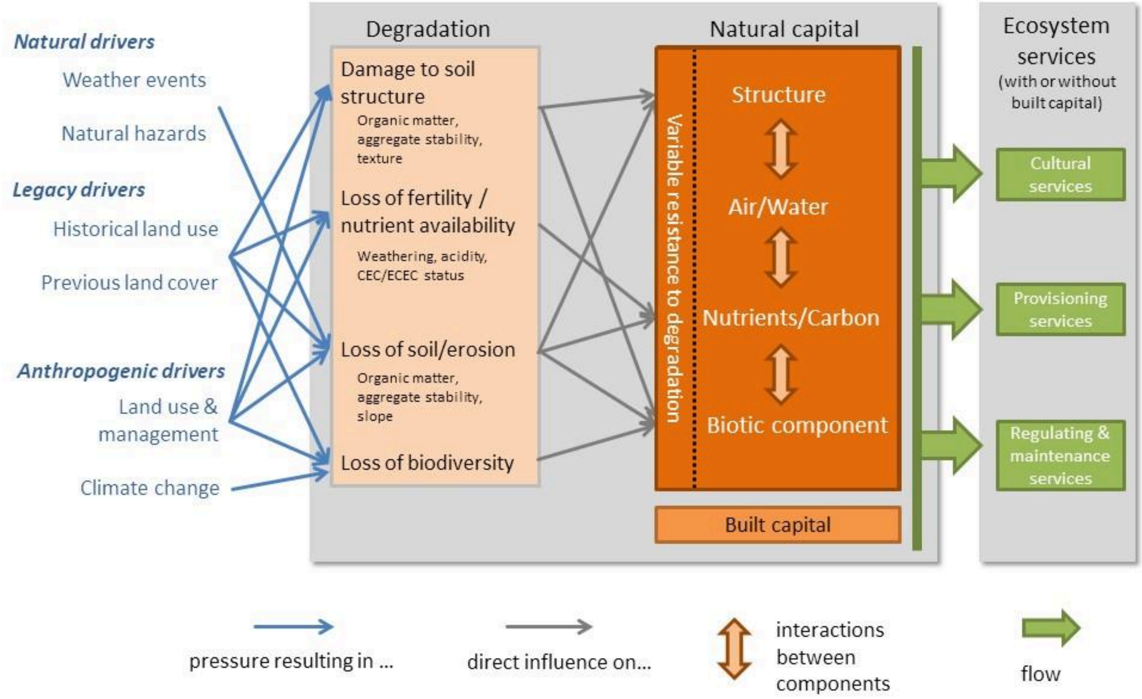

Figure 3. The primary interactions between four key components of the land/soil system and the four main types of land degradation. The natural capital and its variable capacity to resist degradation will constrain the sustainability of a chosen land use. Built capital can help improve the level of service (e.g., installation of artificial drainage in poorly drained soils, liming to alleviate pH decline caused by phosphate fertilizer application).

3.3 Using the LRC

The LRC is a framework to support a comprehensive description of land that spans the range of ecosystem services that the land supports and the functions that it performs. The framework structure provides a set of “building blocks” (or estimates of land functions) that can be combined, as appropriate, to inform a variety of land resource questions. The framework needs to include multiple levels. Some ecosystem services of interest (e.g., food provision) are the synthesis of a number of soil and land processes (i.e. cycling of water, gas, nutrients and organic matter, and soil structure) and their interactions with climate. A characterization of the land’s synthesized capacity for food provision is expected to be useful for some land resource questions. Other questions might best be progressed by focusing on the lower-level functions (e.g., questions related to irrigation or fertilizer application might focus on the more specific functions of the land’s capacity for storing water or cycling specific nutrients). Land can vary in its ability to support different crops (e.g., land may have a high potential yield for ryegrass but a low potential yield for lucerne due to high levels of exchangeable aluminium [Al toxicity] at greater soil depths) (Rechcigl et al., 1988). The framework therefore needs to allow for the characterization of biomass production of specific crops as well as for more generalized crop types. At one level, these characterizations of biomass production might assume current climate. At another level the effect of climate change scenarios on the land’s capacity for biomass production can be explored.

Regulation of nutrients is the capacity of the soil to store, transform, filter, and supply nutrients. While there may be a land resource question that is interested in a high-level generic description of how well the soil retains nutrients, other land resource questions might well require characterization of the individual lower-level soil functions related to nutrient regulation (e.g., risk of loss of specific nutrients via specific pathways: loss of nitrogen, phosphorus, and pathogens by run-off or leaching via bypass flow or matrix flow).

By evaluating and mapping the functions and ecosystem services in the LRC at different levels, an extensive information resource can be developed to support a wide range of applications in the area of land-use assessment and planning to meet defined environmental, social, cultural, and economic objectives, and to identify where changes in management might be targeted to overcome particular constraints or adverse environmental impacts. The LRC framework requires the assessment of each land parcel (i.e., a homogeneous block of land) for each of the various functions (and lower-level sub-functions) in the inner circle of the LRC. Each is given a value from 0 to 1, where 0 is minimal function and 1 is maximum potential function for the area of land where the framework is to be applied. This could be at a national or provincial scale, or perhaps based on broader ecological criteria (e.g. eco-regions).

Using information from the LRC to inform a particular land resource question involves two steps:

1. Select the LRC functions relevant to a land resource question of interest. The selected components should reflect the relevant ecosystem services, the community priorities and values, and could be a mix of higher- and lower-level functions.
2. Integrate the function assessments as appropriate to reflect ecosystem services relevant to the land resource question. This will usually involve a consideration of the effect of pressure (e.g., land use, weather events). Note that this integration may best be done in a multi-criteria decision process (e.g., Moraine et al., 2017), or in a spatial modelling framework that looks at catchment-scale impacts and objectives (e.g., Herzig et al., 2016; Snelder et al., submitted).

For step 1, a simple example of a land resource enquiry aimed at securing food supply from agriculture (food provisioning service) might predominantly focus on the soil function of potential biomass production for selected agricultural crops, augmented by the soil's capacity for storing and transforming nutrients. However, such a single-service consideration is unlikely to be sufficient in long-term land-use planning because it ignores the effect of regulating services beyond the land parcel and the risk to land degradation over time. Hence one could increase complexity by imagining a catchment under intensifying agriculture from the perspective of maintaining water quality in receiving environments. The enquiry might then draw upon and combine information on the LRC components that optimize ecosystem services of contaminant regulation, as well as potential biomass production. The resistance functions are also relevant, as a lack of resistance can reduce the capacity over time of the land parcel to produce biomass and regulate nutrients. In this example, spatial context is also very important for water quality outcomes, which means landscape functions of attenuation and connectivity need to be accounted for. Where cultural services are of particular interest, a more complex evaluation of trade-offs between ecosystem services could be facilitated. In contrast, a much narrower land-use question on heavy metal contamination may only require information about the resistance of the land to toxification (e.g., high/low affinity of the soil to store bioavailable heavy metals) and, potentially, spatial information on past/current land use.

Step 2 considers how to combine the relevant LRC functions and land-use pressures to help inform the land resource decision makers. The function values can be combined by different methods, including simple averaging, fuzzy logic, and using rule-based models. Kidd et al. (2015) use traditional suitability rule sets to derive a set of 20 spatial indices, whereby each describes the capacity of land to produce a specific crop (analogous to LRC biomass production sub-functions). These are then summed to describe agricultural versatility of land, an indicator considered useful for investors looking for land suited to a wide variety of enterprises, and for informing protection of agricultural land from non-agricultural development. Greiner et al. (2018) trialled four methods of aggregating soil function values, noting that different methods suited different purposes. **Error! Reference source not found.** shows the higher level of functions from the LRC and which of the various ecosystem services they contribute to.

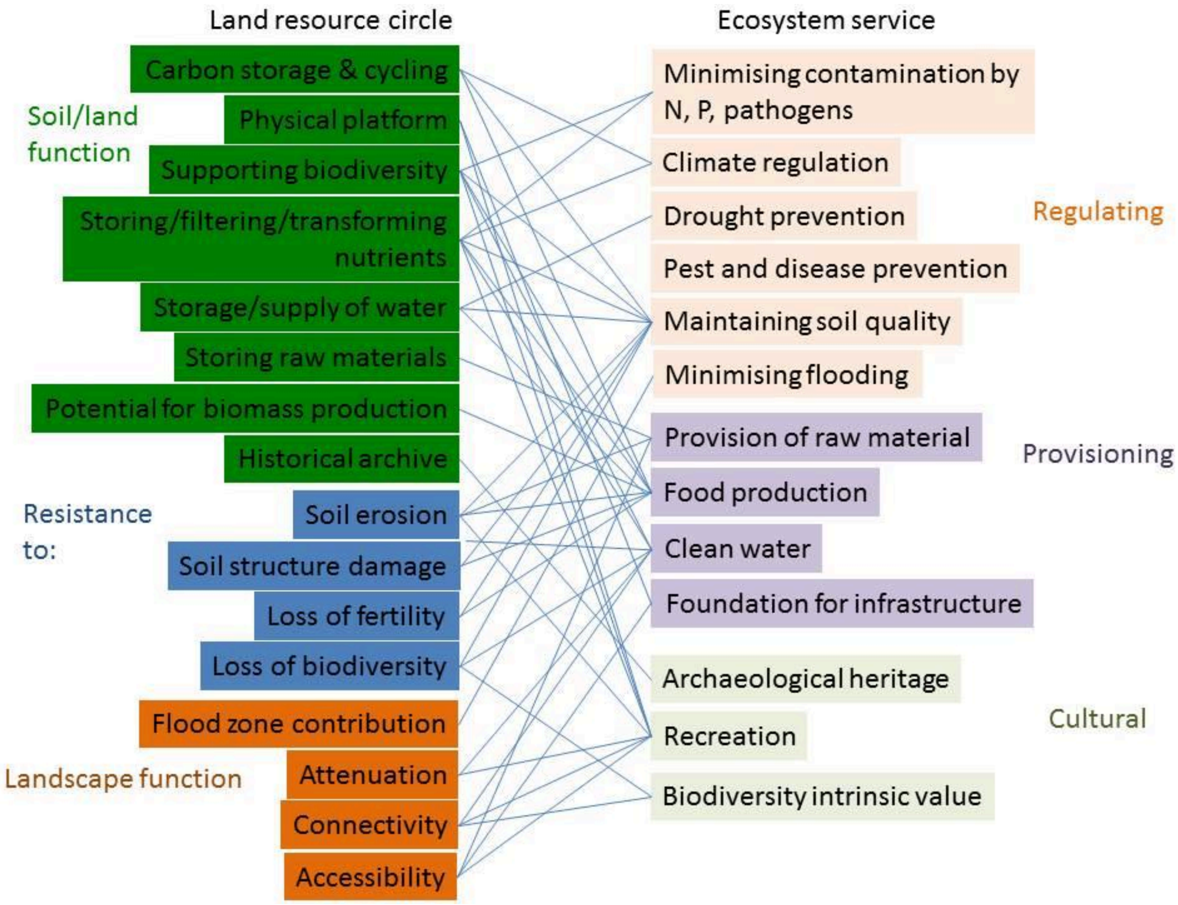

Figure 4. Direct mapping between high-level functions from the LRC and ecosystem services. N = nitrogen; P = phosphorus.

4. Hypothetical example

4.1 Background/context

We now present a hypothetical example to illustrate the two steps above, whereby a decision maker is interested in the suitability of land for different land uses from multiple perspectives (e.g., increasing productivity while remaining within water quality limits and continuing to provide other ecosystem services). We first outline the properties of the soils chosen for the example, the management regime of the different land uses, and the assumed base climatic and topographical conditions for the example. Expert knowledge is then used to score each of the soils and land uses for their ability to influence key functions selected from the LRC. The two scores are then used to calculate a combined score for each soil and land-use combination for each function.

4.1.1 Soil details for the hypothetical example

We selected four soils from the New Zealand National Soil Database with contrasting soil properties to illustrate the application of the LRC. The properties listed in Table 1 largely control soil functions and, consequently, soil ecosystem services and resistance to degradation. We acknowledge that this selection does not comprise all the controls on soil functions and services (e.g., soil carbon as a property is mainly ignored, as are soil biota), but we believe the data are sufficiently complex to illustrate the application of the conceptual framework. The properties are typically mapped in soil surveys, with most properties being directly measured, though some are derived from pedotransfer functions.

The rationale for the selection of the properties in Table 1 is as follows. Soil texture, stone content (particle size >2 mm), and bulk density, as well as other factors (e.g., mineralogy, soil carbon content), influence soil porosity (pore size distribution, pore volume, pore connectivity) and particle packing, and thus soil structure. These properties are linked to water/air transport and storage within the soil. Bulk density directly affects the pore size distribution and the growth of plant roots. Texture is a particularly important property that affects nutrient provision (e.g., via cation exchange capacity, chemically reactive surface area) and the stabilisation for soil carbon through the formation of organo-mineral complexes (Beare et al., 2014; Curtin et al., 2017). These properties can also influence resistance to soil compaction/structural degradation (Drewry et al., 2008), liquefaction (Giona Bucci et al., 2018), and soil erosion (e.g., smaller and lighter particles vs. larger and heavier particles; coherent structure vs. loose particles). Considering these links, texture, stone content and bulk density, and hence structure, affect the services of food production from plants, carbon sequestration, prevention of flooding, and nutrient/sediment loss through surface run-off and retaining contaminants in the soil.

Soil drainage classes are defined by the depth to dominant low chroma colours in the soil; in our examples this depth is related to either a slowly permeable layer that impedes drainage (moderately well-drained, Templeton), and/or a shallow groundwater table (poorly drained, Temuka). While oxygen deficiency is a requirement for denitrification (formation of N_2O/N_2 from NO_3/NH_4) (Balaine et al., 2016; Harrison-Kirk et al., 2015) and inhibits carbon oxidation, slow drainage of soil water also extends the time for potential biogeochemical interactions between the soil particles and water/solutes (e.g., Maher, 2011). The functions that are directly affected by soil drainage are water storage for food production, carbon storage (reducing vs. oxygenated conditions), filtering contaminants as they are transported to fresh water receiving environments, and the production of greenhouse gases (N_2O) (Cameron et al., 2013; Clough et al., 1996; deKlein et al., 2003; Rappoldt and Corre, 1997; Shepherd et al., 2001; Stenger et al., 2008; Velthof et al., 2010). Note that the two functions related to nitrogen will occur most effectively at opposite drainage conditions: well-drained soils show little denitrification and higher-solute NO_3 and ammonium load; poorly drained soils have higher denitrification activity, which reduces the solute N load of already slowly moving soil water. Through its effect on soil water content, soil drainage is also strongly related to risks such as compaction (Drewry et al., 2008) and erosion (e.g., moisture providing cohesion between particles, pre-rain event high soil moisture inhibits infiltration of new precipitation).

Profile-available water (PAW) to 60 cm is the amount of water that can be held by the soil between wilting point (–1500 kPa suction) and field capacity (–10 kPa) in the upper 60 cm of the soil, and hence is accessible by the roots of most cultivated plants. The value is derived from a pedotransfer function using water release data at different suction values from suction plate and pressure vessel experiments (method follows Gradwell and Birell, 1979), soil texture (<2 mm fraction) and coarse fragments, and soil structure variables (aggregation, soil strength) (McNeill et al., 2018). PAW links to water storage and the many services related to this (e.g., food production, flood prevention, contaminant/nutrient retention, regulating greenhouse gases through carbon cycling, and denitrification).

The phosphorus (P) retention is a measure of the affinity of phosphate to adsorb to soil particles (Blakemore et al., 1987) and is a proxy for soil weathering. It is used here as an indicator for positively charged reactive surfaces, which in New Zealand conditions are generally linked to secondary pedogenic oxides (e.g., ferrihydrite) and poorly crystalline soil minerals (e.g., allophane, imogolite) that have a high affinity to bind PO_4^- (Hewitt, 2010; Saunders, 1965). It directly affects the service of minimizing contaminant losses by reducing the risk of P leaching (as PO_4^-) and P surface run-off (P attached to sediment) to freshwater bodies (e.g., McDowell et al., 2003). Indirectly, via its dependence on soil mineralogy, this property has been found to be linked to compaction risk and structural vulnerability (Hewitt and Shepherd, 1997). It also reflects the capacity of soil mineral particles to stabilize soil carbon and therefore minimize the risk of carbon losses (McNally et al., 2017). Therefore, P retention can be associated with functions and resistance processes like those associated with soil structure.

Bypass flow is a categorial variable based on soil drainage, structure, and New Zealand soil type that reflects the tendency of water to follow preferential flow pathways in soil (e.g., pore space between the surfaces of strongly developed coarse soil aggregates, fractures as a result of shrink/swell activity of clay minerals, root channels), often linked to impeded matrix flow (e.g., pedogenic pans) (McLeod et al., 2004; McLeod et al., 2008; McLeod et al., 2003). The fast routing of water by bypass flow may increase the transport of surface-borne contaminants (e.g. microbes in livestock effluent; McLeod et al., 2008).

Structural vulnerability is an index between 0 and 1 (highest vulnerability) derived from a pedotransfer function that incorporates bulk density, P retention, New Zealand soil type, drainage, and clay content (Hewitt and Shepherd, 1997). Structural vulnerability is linked to risk to compaction and soil erosion susceptibility (Hewitt and Shepherd, 1997), and functions that involve water flow/retention.

As evident from the above, relationships between soil properties, functions, and services constitute an extremely complex system because of the inter-relations and feedbacks between many different soil properties and functions. We do not claim completeness in our coverage.

4.1.2 Definition of land uses in the hypothetical example

For the purposes of this example we focused on the land uses of dairy grazing (milking platforms), sheep and beef grazing, and mixed arable cropping (based on a typical rotation of wheat, barley, and peas). These land uses are common in New Zealand and have contrasting management regimes (Table 2), which help illustrate the utility of the LRC. The management assumed for each land use (Table 2) was based on industry-agreed good management practices (Williams et al., 2014), as outlined in the guidelines promoted by participating industry groups. This includes nutrient management recommendations provided by the New Zealand Fertiliser Manufacturers' Research Association for sheep/beef (2018), dairy (2016) and cropping (2009) sectors. Further details for sheep and beef, dairy, and cropping land use were derived from the Sheep and Beef Farm Survey 2017 (https://beeflambnz.com/data-tools/benchmark-your-farm), the 2016/17 New Zealand Dairy Statistics report (Livestock Improvement Corporation Limited and DairyNZ Limited, 2017), and the Foundation for Arable Research (2015), respectively. The data for sheep and beef farms were derived by calculating the national average from the regional means of all surveyed farms of class 4 (North Island) and class 6 (South Island). The classes correspond to a stocking rate of ~10 stock units/ha.

4.1.3 Climatic and topographical assumptions for the hypothetical example

It is important to recognize that the production potential of a given land use and the pressure it imposes on the wider environment is also a function of the climate and topographic conditions at the location of interest. For example, differences in total annual rainfall and its seasonal distribution have important implications for the risk of nitrate leaching, along with variation in soil water-holding capacity, soil drainage class, and bypass flow category. For the purposes of this theoretical example, we have assumed a moderate climate of 1000 mm mean annual precipitation (assuming even distribution, with moisture deficit during summer when evapotranspiration rates increase), 800 growing degree days (GDD_{10}), and low frost risk (180 frost-free days). We assumed that all three land uses were located on gently rolling topography (15^o slope).

Table 1. Basic properties of the four contrasting soils used in the hypothetical example

	Soil taxonomy	Soil family	Dominant texture group	Horizon-weighted, average stone content (%)	Bulk density topsoil (g cm^{-3})	Drainage class[a]	PAW to 60 cm (mm)	P retention (%)	Bypass flow	Structural vulnerability index (0–1)
Typic Immature Pallic	Haplustept	Templeton	silt	stone-free	1.2	Moderately well drained (60–100)	97	23	high	0.64
Typic Orthic Gley	Endoaquept	Temuka	clay	stone-free	0.87	Poorly drained (<30)	128	38	high	0.53
Weathered Orthic Recent	Dystrustept	Eyre	sand	60	1.09	Well drained (None)	49	22	low	0.63
Typic Orthic Allophanic	Hapludand	Dannevirke	silt	stone-free	0.78	Well drained (None)	158	83	low	0.25

[a] Drainage class is derived from the depth (cm) to dominant low chroma where present. This depth is shown in parentheses.

Table 2. Key management details for the three land uses in the hypothetical example. Values are New Zealand-wide averages for the 2016/17 year (see footnotes and main text for specific details and references)

Land use	**Stocking rate**	**Production** **By weight (kg ha^{-1} y^{-1})**	**By energy (MJ $ha^{-1}y^{-1}$)**	**Nitrogen fertiliser (kg $ha^{-1}y^{-1}$)**	**Average Olsen P**	**Dominant vegetation sp.**
Sheep and beef[a]	~10 stock units ha^{-1} [b]	91 kg beef 87 kg lamb	1773	0	25-40[c1]	Ryegrass and white clover
Dairy cattle[d]	2.81 cows ha^{-1} (~22 stock units ha^{-1}	1071 kg milksolids	40,700	100[c2]	25-40[c2]	Ryegrass and white clover
Arable cropping	NA	10 t grain[e]	130,000	100[c3]	25[c3]	Wheat

[a] National average of the regional means of all surveyed class 4 and 6 farms for 2016/17. Class 4 for North Island (8–13 stock units/ha), class 6 for South Island (6–11 stock units/ha) (https://beeflambnz.com/data-tools/benchmark-your-farm).

[b] A stock unit is defined as one ewe (55 kg) weaning one lamb (25 kg) and consuming 550 kg DM per year (Parker, 1998). One cattle equals 8 stock units (jersey = 6.5, Frisian = 8.5. FxJ = 48%, F = 34%, J = 9%) (https://beeflambnz.com/data-tools/benchmarking-tool).

[c1] Recommended rates from: New Zealand Fertiliser Manufacturers' Research Association (2018), Fertiliser Use on New Zealand Sheep and Beef Farms. Pasture production relies on clover fixed-N. Target Olsen P values are lower for low P retention compared to high P retention soils.

[c2] Recommended rates from: New Zealand Fertiliser Manufacturers' Research Association (2016), Fertiliser Use on New Zealand Dairy Farms. Additional N is supplied as clover-fixed N. Target Olsen P values are lower for low P retention compared to high P retention soils.

[c3] Recommended rates from: New Zealand Fertiliser Manufacturers' Research Association (2009), Managing Soil Fertility on Cropping Farms.

[d] New Zealand Dairy Statistics for 2016/17 (Livestock Improvement Corporation Limited and DairyNZ Limited, 2017)

[e] (Foundation for Arable Research, 2015)

4.2 Step 1: assigning and calculating 'scores' for each function, for each soil, and for land use

The ecosystem services (step 2) delivered by a given land parcel are a product of the functions performed by the land, and the pressure imposed on those functions by interactions between land use/management and the local climate. The LRC was used to identify the following land-related functions relevant to understanding the wider ecosystem services provided by land under different land uses: provisioning (potential biomass production), regulating (N, P and pathogen filtering, sediment retention, N_2O emissions, and carbon storage), and maintenance (soil erosion, soil structural degradation).

4.2.1 Soil scores

Following a method similar to that of Hewitt et al. (2015), we used expert knowledge and the soil data in *4.1.3 Climatic and topographical assumptions for the hypothetical example*

It is important to recognize that the production potential of a given land use and the pressure it imposes on the wider environment is also a function of the climate and topographic conditions at the location of interest. For example, differences in total annual rainfall and its seasonal distribution have important implications for the risk of nitrate leaching, along with variation in soil water-holding capacity, soil drainage class, and bypass flow category. For the purposes of this theoretical example, we have assumed a moderate climate of 1000 mm mean annual precipitation (assuming even distribution, with moisture deficit during summer when evapotranspiration rates increase), 800 growing degree days (GDD_{10}), and low frost risk (180 frost-free days). We assumed that all three land uses were located on gently rolling topography (15^{o} slope).

Table 1, combined with the previously defined climatic and topographic conditions (see above), to calculate a score for selected LRC functions for each soil (Table 3). Scores ranged from 0 (minimum function) to 1 (maximum function). In a departure from the Hewitt et al. (2015) method, our rankings were not only relative to the soils used in our example (*4.1.3 Climatic and topographical assumptions for the hypothetical example*

It is important to recognize that the production potential of a given land use and the pressure it imposes on the wider environment is also a function of the climate and topographic conditions at the location of interest. For example, differences in total annual rainfall and its seasonal distribution have important implications for the risk of nitrate leaching, along with variation in soil water-holding capacity, soil drainage class, and bypass flow category. For the purposes of this theoretical example, we have assumed a moderate climate of 1000 mm mean annual precipitation (assuming even distribution, with moisture deficit during summer when evapotranspiration rates increase), 800 growing degree days (GDD$_{10}$), and low frost risk (180 frost-free days). We assumed that all three land uses were located on gently rolling topography (15^{o} slope).

Table 1) but reflect the expert knowledge of the complete range of soils found in New Zealand. Data from S-map (Lilburne et al., 2012) was also used to guide expert assessments (e.g. the range of PAW values and drainage characteristics for New Zealand soils). Scoring was based on inherent soil properties and assumed the soils were not degraded in any way.

4.2.2 Land-use pressure scores

We used a similar expert approach to assess the response to pressure imposed by each of the land-use categories (as characterized in Table 2 under the previously defined climatic and topographic conditions) on the selected LRC functions. All land uses were assumed to have no artificial drainage or irrigation. Scores were again allocated within the range of 0 (maximum pressure; e.g., intensive vegetable cropping with frequent cultivation and fertilization) to 1 (minimum pressure; e.g., natural vegetation succession without human disturbance or external inputs) (Table 3). For the potential biomass production we did not use total biomass but only the product, represented by its energy yield when consumed as food (meat for sheep and beef, milk solids for dairy, wholemeal flour for wheat cropping). We acknowledge that this deviates from the function of biomass production (i.e., raw biomass yield) and directly quantifies a service (i.e., food provision). The reason for this deviation is a consequence of how services are derived from functions. All soil functions in Tables 3 and 4, except biomass production, can be directly combined into services (see below). However, a comparison of biomass production between land uses is not possible since some of the land uses do not use the entire plant biomass to produce a food product. For instance, the typical aboveground dry matter production of grass (15 t ha^{-1} y^{-1}) in a dairy system would typically be equal to or less than the total dry matter (all aboveground biomass including grain) produced from a wheat crop under average New Zealand conditions. Furthermore, in an arable cropping rotation, the wheat crop may not represent all the biomass produced over an annual cycle where other crops are grown in rotation with wheat. In pastoral farming systems the grass is not directly consumed for food provision but converted into milk solids or meat by animals, with associated energy losses. In the cropping system example, the grain component may be directly utilized as a human food source or used as animal feed for the production of animal products (e.g. milk, meat, wool). The non-grain component of the crop (e.g. wheat straw) can also have value as supplementary feed, livestock bedding material, or simply as an additional organic matter input to the soil. For the purposes of this example we have focused on estimating the energy value of the primary food products (i.e., meat, milk and grain) derived from the three land uses. The average yields per hectare for the three land uses as shown in Table 2 were converted into energy values by using the following factors: 1 kg meat = 10,000 kJ

(Sivakumaran et al., 2016); 1 kg milksolids = 38,000 kJ (Wells, 2001); and 1 kg wheat (as wholemeal flour) = 13,000 kJ (Sivakumaran et al., 2016). To derive the relative values in Table 3 we set wheat at 0.9 (i.e., the value is not a maximum but a New Zealand average) and scaled the other land uses in accordance with their absolute values.

The soil limitations and land-use pressures ranked in Table 3 can impose significant limitations on the delivery of ecosystem services. For instance, the actual production potential at a given site will be a function of the local (or assumed) climatic conditions, the land use, the soil limitations, and the land-use pressures. For instance, high production potential is generally achieved in soils with near neutral pH values and high base saturation, low occurrence of anoxia (i.e. drainage class), high PAW, and unobstructed root penetration (i.e. no compaction). Therefore, the deep allophanic soil derived from basic/intermediate volcanic airfall deposits scored high for production potential, whereas the other soils are constrained by one or more of these factors (e.g., lower pH values, more coarse fragments, impeded drainage and/or lower PAW). Also, while some land-use characteristics may be beneficial for one service (e.g. increased N availability from animal deposit), this will affect other functions and services, such as N leaching.

4.2.3 Combined soil-by-land-use scores

Table 4 is the result of averaging the values of Table 3 (soil attribute and land-use pressure) for each soil function for a given soil–land-use combination. This is an over-simplification, because we have only used one climatic scenario, one topographical context, and a very limited number of land uses. We acknowledge that the land-use pressure scores do not necessarily reflect the full range of management conditions that may be applied on a farm within any one land use. However, the application of good management practices to define the pressures imposed by different land uses provides a means of identifying where the soil–land-use interactions (under a defined climate) may not deliver the required soil functions and, therefore, where targeted changes management may be applied to enhance the soil functions or mitigate adverse environmental outcomes. Furthermore, the framework could be extended to include different categories of intensification within each land use.

More detailed scenarios (including multiple interactions) could be explored when the framework is implemented via a formal modelling approach (e.g. APSIM[2]).

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[2] http://www.apsim.info

Table 3. Baseline ranking of key functions for a) different mineral soils, and b) different land uses (0 is the lowest rating and 1 the highest rating). Soil ratings are based solely on inherent soil properties and assuming soils are not degraded. The land-use ratings take into account typical good management practices for that land use (e.g. increased N and P inputs and increased grazing pressure for dairy, requirement of cultivation for cropping, etc.) and can be interpreted as the pressure that a given land use imposes, independent of soil.

Soil & land-use classes	N filtering (minimize N leaching)	P filtering (minimize P leaching)	Pathogen filtering (minimize pathogen leaching)	Minimize P loss by run-off	Resistance to loss of soil (physical erosion)	N filtering (minimize N_2O emissions)	Carbon storage	Resistance to soil structure damage (1-SVI)	Potential biomass production[a]
Soil attribute									
Pallic	0.6	0.2	0.2	0.6	0.4	0.4	0.5	0.36	0.6
Gley	0.9	0.6	0.3	0.3	0.3	0.2	0.6	0.47	0.7
Recent	0.2	0.1	0.5	0.9	0.5	0.9	0.2	0.37	0.3
Allophanic	0.8	0.9	0.9	0.8	0.9	0.7	0.9	0.75	0.9
Land-use pressure									
Drystock	0.9	0.9	0.9	0.9	0.9	0.7	0.9	0.7	0.02
Dairy	0.3	0.4	0.4	0.6	0.7	0.2	0.9	0.5	0.3
Arable crop	0.5	0.6	0.7	0.4	0.3	0.6	0.3	0.1	0.9

[a] See text for details.

Table 4. Calculated delivery of functions for a) low-intensity dryland sheep and beef, b) dairy, and c) cropping on different soil types

Soil & land-use classes	N filtering (minimize N leaching)	P filtering (minimize P leaching)	Pathogen filtering (minimize pathogen leaching)	Minimize P loss by runoff	Resistance to loss of soil (physical erosion)	N filtering (minimize N_2O emissions)	Carbon storage	Resistance to soil structure damage (1-SVI)	Potential biomass production
Drystock									
Pallic	0.75	0.55	0.55	0.75	0.65	0.55	0.70	0.53	0.31
Gley	0.90	0.75	0.60	0.60	0.60	0.45	0.75	0.59	0.36
Recent	0.55	0.50	0.70	0.90	0.70	0.80	0.55	0.54	0.16
Allophanic	0.85	0.90	0.90	0.85	0.90	0.70	0.90	0.73	0.46
Dairy									
Pallic	0.45	0.30	0.30	0.60	0.55	0.30	0.70	0.43	0.45
Gley	0.60	0.50	0.35	0.45	0.50	0.20	0.75	0.49	0.50
Recent	0.25	0.25	0.45	0.75	0.60	0.55	0.55	0.44	0.30
Allophanic	0.55	0.65	0.65	0.70	0.80	0.45	0.90	0.63	0.60
Arable crop									
Pallic	0.55	0.40	0.45	0.50	0.35	0.50	0.40	0.23	0.75
Gley	0.70	0.60	0.50	0.35	0.30	0.40	0.45	0.29	0.80

Recent	0.35	0.35	0.60	0.65	0.40	0.75	0.25	0.24	0.60
Allophanic	0.65	0.75	0.80	0.60	0.60	0.65	0.60	0.43	0.90

4.3 Step 2: Using combined soil/land-use function scores to calculate higher-level ecosystem services.

In this step, the selected functions from step 1 are combined to describe the ecosystem services of interest, by soil type and under key land uses. Services are limited to on-site benefits (catchment attenuation and connectivity of water bodies is not considered in this example). Each of the selected ecosystem services is defined by combining the values of the soil functions in Table 4. The service of minimizing contamination is calculated by taking the minimum value of the four functions of N/P/pathogen leaching and P loss by run-off. Maintenance of soil quality is assessed as the minimum of the two resistance functions (resistance to soil loss, resistance to soil structure damage). The services of climate regulation via N_2O emissions and soil carbon sequestration, and of food provision, are directly carried over from the N filtering (minimize N_2O emissions), carbon storage, and biomass production functions, respectively. The results can be mapped or viewed as spider plots (Figure 5), helping the user to understand the services provided by the different land uses on a given soil and under defined climatic conditions.

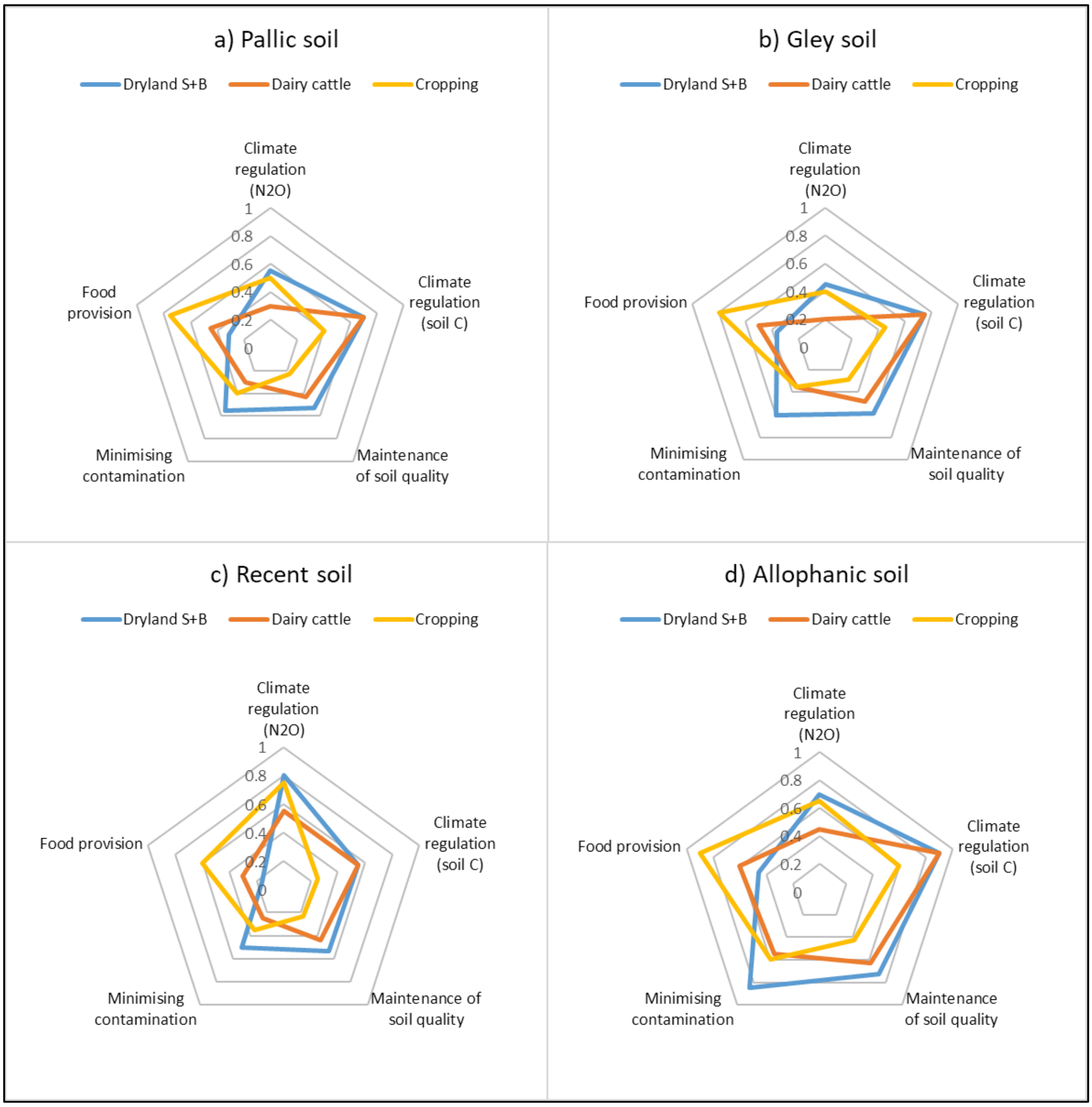

Figure 5. Ecosystem services provided by three land uses on each of the four soils a) Pallic, b) Gley, c) Recent, d) Allophanic. S+B = sheep and beef; C = carbon.

The ecosystem services provided by each soil–land-use combination are shown in Figure 5. Across all soils, differences between land uses are distinct for a range of services. Dryland sheep and beef scores most highly for minimizing contamination, maintenance of soil quality, and climate regulation (= low N_2O emissions), whereas it has the lowest score for food provision of all land uses. This reflects lower land-use intensity (stocking rate), including lower fertilizer use, and the high energy losses when converting autotrophic biomass into biomass of heterotrophs. Dairy farming scores low for minimizing contamination because of greater fertilizer use and higher stocking rates leading to greater returns of nutrients in livestock excreta (increasing the risk of N & P leaching losses) and structural degradation from livestock treading. Both pasture systems – dryland farming and dairy – show the highest service rating for soil carbon sequestration within the climate regulation service. For the maintenance of soil quality, the consequences of higher stocking rates mean dairy land use scores lower than dryland farming. Cropping features the highest rating for food provision but has a low score for maintenance of soil quality and climate regulation (carbon sequestration), reflecting the regular disturbance of the soil with cultivation (e.g., ploughing) and biomass removal after harvest.

These general land-use patterns persist across different soil types. The pedogenically young Recent soils show the lowest benefits for food provision and climate regulation (carbon sequestration) because of the rudimentary development of nutrient and carbon cycles in these soils (comparably low in soil carbon, reactive surface area, plant-available mineral nutrients). Because of lack of soil development and associated formation of pedogenic horizons of low permeability (e.g., argillic horizons, fragipans), soil drainage is generally good and leaching of contaminants potentially high (poor nutrient regulation). In contrast, well-drained soils lack the anoxic conditions necessary for N_2O production and hence Recent soils score most highly in climate regulation (N_2O). Compared to the Recent soil, the Pallic soil in our example shows improved capabilities for most services: minimizing contamination (higher reactive surface area due to more advanced weathering), food provision (higher nutrient status and water-holding capacity), and climate regulation (higher soil carbon content). The imperfectly drained soil hydrology, however, makes the Pallic soil more likely to be a source of N_2O emissions. The latter is more pronounced in the poorly drained Gley soil, with a water table close to the surface, whereas the other characteristics are similar to those of Pallic soils. The overall best service ratings are achieved by the Allophanic soil, most notably for regulating and maintenance services: well drained for low N_2O emissions; high soil carbon content due to a high amount of carbon-complexing minerals (e.g., allophane, ferrihydrite), which is also beneficial for maintaining soil structure (soil quality maintenance) and underpins the high sorption capacity (minimizing contamination).

In summary, there are distinct differences between land uses and soils with respect to their capability to provide ecosystem services in our example. These are grounded in differences in the functionalities between soil types, and the conditions imposed under good management practices for each land use type. Our approach allows for direct comparison of land-use–soil combinations to assess land-use suitability for maximising selected ecosystem services.

5. Discussion & conclusion

We have proposed the LRC as a framework for developing a comprehensive ecosystem-service-based database of land resource information that is more dynamic and flexible than the USDA-based land evaluation classifications. It is a system that combines empirical data, modelled outputs, and expert knowledge to characterize a range of land functions at different levels that can be used in their own right or combined in different ways to address land resource questions. Table 5 shows different functions from the LRC and their relevance for some common land resource questions. By using the LRC framework to explicitly and separately characterize the various ecosystem-based functions provided by land, the benefits, risk, and trade-offs of different land-use options can be assessed by systematically considering, combining, and visualizing their effects across a broad range of ecosystem services. We envisage that outputs will be spatial as well as plots and single value metrics, will incorporate the effect of climate (current or future) as required, and will be used for different purposes and in a range of spatial planning tools (e.g., the LUS concept for assessing land-use suitability) (McDowell et al., 2018).

Table 5. LRC functions (higher level) and their relevance for a range of land resource questions

Type	Function	Land resource question						
		Soil health monitoring	Water quality in a lake	Suitability for urban development	Suitability for forestry	Food security	Eco System trade-off evaluation	Irrigation suitability in area with nutrient limits
Soil / land functions	Biomass production			✓	✓	✓	✓	✓
	Carbon storage & cycling				✓	✓	✓	
	Nutrient filtering/ storage/transformation		✓			✓	✓	✓
	Water storage & supply		✓			✓	✓	✓
	Supporting biodiversity					✓	✓	
	Storing raw materials						✓	
	Historical archive			✓			✓	
	Providing physical platform			✓			✓	
Landscape function	Attenuation		✓				✓	✓
	Connectivity		✓				✓	✓
	Flood zone contribution			✓			✓	
	Accessibility			✓	✓		✓	✓
Resistance to	Loss of soil (erosion)	✓			✓	✓	✓	
	Soil structure damage	✓				✓	✓	✓
	Loss of fertility	✓				✓	✓	✓
	Loss of biodiversity	✓				✓	✓	

In conclusion, the LRC is the first step in a new characterization of land resources. The framework recognizes that soils differ in their capacity to resist the various pressures due to land use and/or climate. It also recognizes that the surrounding landscape also provides functionality that can affect the delivery of ecosystem services from a land parcel and its suitability for different land uses. This landscape functionality includes whether the parcel is hydrologically connected to rivers and lakes, attenuation of nutrients en route, and the accessibility and availability of key infrastructure to the land parcel. These functions can control the effects of a land use on distal receiving environments (e.g., contamination of lakes) and the suitability of a potential land use (e.g., transport to a processing plant, irrigation water availability).

We anticipate that the framework will aid in providing a wider appreciation of the varying contributions of soil and land across the range of ecosystem services. Expert knowledge was used in our hypothetical example to quantify the functions. Further development and implementation of LRC would focus on improving and verifying the soil and land-use function ratings based on quantitative relationships wherever possible. These might be simple equations derived from experimental observations, through to advanced mechanical models. We recognize that one area where there is limited knowledge is the quantification of the resistance of the different soils to the many different (and often opposing) feedbacks between land management and soil functions. For instance, increased N fertilizer inputs increase biomass production for forage systems, but the soil physical effects (compaction and changes in porosity) of intensive livestock grazing can have negative impacts on production (Drewry et al. 2008). The extent of the various feedback mechanisms is likely to be controlled by the resistance functions.

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