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Soil natural capital quantification by the stock adequacy method

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ABSTRACT

A method is presented for assessing soil natural capital based on the principles of land evaluation. Policymakers are adopting concepts of flows of ecosystem services, and the natural capital stocks that support them, to provide more integrated analyses of the trade-offs between environmental, economic, social and cultural outcomes from land use. Soil is frequently overlooked in these analyses. Techniques are needed to quantify and map soil natural capital and their potential to provide ecosystem services to enable the soil science community to more effectively engage with decision-makers. To support this engagement, these techniques need to use available soil survey maps and databases to provide extensive geographic coverage of soil natural capital estimates. The method presented estimates the adequacy of soil natural capital stocks to support the soil processes behind the provision of ecosystem services under a specific land use. A stock adequacy index estimates the degree to which the provision of services is limited by soil natural capital stocks or advantaged by a stock surplus under a given land use. Reference values are derived from a curve of the response of the provision of the service to key soil stocks for a specified land use. These curves are determined from land evaluation and soil quality literature, or by modelling. The method is essentially an extension of land evaluation in which the evaluations are calibrated using an ecosystem approach. The output indices provide information about potential ecosystem services provision, land-use suitability, soil resource use efficiency, and environmental performance. Outputs from the method are demonstrated for a range of soils under pastoral dairy land use in Wairarapa, New Zealand.

1. Introduction

The recognition that soil should be counted as a component of the earth's natural capital (Costanza et al., 1987) opens new avenues for the integration of soil science with other environmental sciences and economics. Soil natural capital (SNC) is emerging as a useful concept for analysing environmental and resource management problems (e.g. Bristow et al., 2010; Millennium Ecosystem Assessment, 2005; Robinson et al., 2009). It needs to be defined and quantified so it can be used to its potential as a tool in guiding the development of land resource policy and management from local to global scales (McBratney et al., 2014; Robinson et al., 2012). Dominati et al. (2010) assisted this process by providing a framework that helps to reveal the relationships between SNC as represented by soil properties, and flows of ecosystem services coming from soil functioning (soil processes), and how external drivers such as climate and land use, impact on the whole soil system.

Samarasinghe et al. (2013) made an inventory of methods for valuing soil ecosystem services and Dominati et al. (2014) demonstrated the application of appropriate methods for the economic valuation of 14 services provided by one soil under a dairy use. Samarasinghe and Greenhalgh (2013) demonstrate that specific SNC stocks can be valued, using data on market land values under specific land use. This is an important result but it is desirable to develop more direct measures that are less affected by the many factors that drive land prices.

Soil natural capital needs to be quantified in such a way that it can be integrated into environmental policy and land management decision-making to inform the provision of ecosystem services. Most of the messages that soil science needs to communicate to other disciplines can already be expressed using existing nomenclature. The natural capital and ecosystem service terminology, however, allow soil science to translate its knowledge into language that is better understood by ecologists and ecological economists. Soil science insights can then be integrated into wider system analyses that involve other components of natural and built ecological infrastructure (Bristow et al., 2010).

The goal of this study is to present a method to quantify and map SNC that directly uses information available in soil survey databases, with results that may be applied to extensive geographic areas. Furthermore the goal is to develop a method that yields an index as a measure of the capability of a soil to provide a service for a specific land use. There is a need to value soil natural capital in monetary terms (McBratney et al., 2014) to be effectively included in environmental accounting. However, this isn't the only way the importance of soils can be recognised. We propose an index for four reasons. First, it

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is important to clarify the relationships between SNC and the dependent soil services under a use. Second, the index provides a quantity that may be used as an objective measure of SNC capability from which monetary values might be derived if needed from a specific use. Third, monetary values can become an impediment in some forums. Non-monetary values, however, are useful for policy and planning professionals in framing regulatory instruments (Samarasinghe et al., 2013). Fourth, monetary valuation can be technically challenging, including issues of non-commensurability, price volatility, double counting, assumptions made by use of proxies, and the effect of choice of valuation methods, time scale and discount rates.

2. Definitions

We define SNC as soil stocks having the capacity to support the provision of ecosystem services required by a specified land use in which sustainable land management practices are assumed (adapted from Dominati et al., 2010). The ecosystem services required by a land use include services relevant to the off-site environment, for example, filtering of nutrients which determines outcomes such as nitrate leaching into rivers, as well as on-site services of more immediate relevance to the land use enterprise, such as, biomass production. Soil natural capital is a natural asset and the soil profile (pedon) is regarded as the basic unit of this asset. We interpret the soil profile as comprising a bundle of soil stocks. Soil stocks are the soil properties that enable soil processes to operate. The stocks are either measured directly or estimated by pedotransfer functions. Soil stocks include inherent stocks that vary over long timescales (e.g. clay content), and manageable, dynamic stocks that vary over short timescales (e.g. soil water content) (Dominati et al., 2010). Soil carbon stocks are familiar for their use in soil carbon inventory, but stocks also include such non-material soil properties as energy (e.g. stored heat) and soil fabric (e.g. total porosity). These directly relate to the mass, energy and organisational components of SNC identified by Robinson et al. (2009). From these stocks and the functioning of the soil ecosystem, flow ecosystem services which are directly useful to humans.

For practical application SNC needs to be quantified across extensive areas of land. The proposed method for estimating SNC is therefore designed to use commonly available information on soil attributes and from spatial databases and normal soil mapping techniques. This approach facilitates the mapping of SNC stocks. Maps of SNC may be presented as soil maps, in either polygon or raster formats. The analysis is made in the context of the soil ecosystem services framework of Dominati et al. (2010), which brought together soil science concepts and the Millennium Ecosystem Framework for ecosystem services (Millennium Ecosystem Assessment, 2005).

The term 'soil services' is used in this paper to refer to the ecosystem services provided directly by soils. The difference between functions and services lies in the context of the analysis. A 'soil function' (Karlen et al., 1997) is the output of a soil process, or set of soil processes, where the context is the soil system. The concept of 'function' describes a combination of "structure and processes, but also represents the potential that ecosystems have to deliver a service" (Braat and de Groot, 2012, p. 6). By contrast, an 'ecosystem service' represents 'something good' the soil does that, together with other non-soil factors, confers some significant human benefit in the context of the wider ecosystem (Braat and de Groot, 2012; Dominati et al., 2010). We ascribe to the recommended terminology of processes, functions and ecosystem services (Braat and de Groot, 2012; Dominati et al., 2010; Robinson et al., 2009).

3. Method

3.1. Approach

The stock adequacy method for quantification of SNC is based on the principles of land evaluation (FAO, 1976; Rossiter, 1996) and soil quality evaluation (Karlen et al., 1997; Sparling et al., 2004). The proposed method (Fig. 1) is an extension of land evaluation and is quantified relative to the requirements of a specified land use type (FAO, 1976). It is presumed that for adequate sustainable production, the land use type requires the sustainable provision of a specific set of soil services. For effective operation, the soil services need to draw upon a specific set of soil stocks. If these stocks are adequate then the provision of soil services may be sustained, and the specified land use can operate to its potential. The analysis considers soil attributes, but does not consider external drivers such as management or climate. We include measures of the soil water and soil temperature regimes as soil attributes. If the soil stocks are not adequate for the current land use then the soil services provided will be limited and may not prevent or mitigate environmental impacts. A measure of the SNC at a site is derived from an aggregate of adequacy values of the soil stocks under a specific land use.

We make the following conventions. First, that we can identify the appropriate key soil services required by a specific land use and the key soil stocks that support those soil services. Second, the focus of the analysis is the soil — its stocks and soil service outputs. Many factors influence the effective productive output from a land use (Dominati et al., 2010), but wherever possible non-soil limiting factors are not considered. Third, because the focus is natural capital, it is necessary to distinguish natural capital assets provided by nature from the assets added by management by such interventions as irrigation, artificial drainage, or addition of fertilisers and counted as built capital. Fourth, because our goal is to estimate SNC over extensive geographic areas, we have to use existing soil survey data. These data are by necessity classified and mapped using predominantly inherent soil properties (soil capability, McBratney et al., 2014). Manageable soil properties (including the changes caused by additions of built capital) (soil condition, McBratney et al., 2014) vary across the landscape according to the history of land use impacts and the vulnerability of the soil classes to those impacts (Sparling and Schipper, 2002, 2004). This variability is not captured at the scale of regional soil mapping so spatial distinction between manageable properties and inherent properties is not normally possible over extensive areas. We must work with what we have. Until it is possible to predict the dynamic range of manageable soil properties from land use and management practices and map their status and spatial variability, SNC mapping must be based on data that includes both inherent properties with an imprint of manageable soil properties, as provided by a database. Where suitable data on the status of manageable properties are available then the proposed SNC quantification method may be estimated for soil phenoforms (Droogers and Bouma, 1997) based on management data.

1. Define the land use type (LUT). The definition needs to be specific as it influences the choice of soil services required for productive output and sustainable management. Land management practices need to be considered in the definition of land use types. For example, high-intensity, heavy-animal grazing will require specification of the soil's resistance to treading damage, as this is a service required for animal health, the health of the soil, and the quality of pasture production.
2. Select and quantify the soil services required to support and manage the LUT goals of production, as well as maintain natural capital stocks and environmental quality both on-site and off-site.
3. Determine the soil stocks, represented by the soil properties, needed to sustain each soil service. These may be fundamental soil properties measured directly in the field, indirectly by proximal sensing, from laboratory analysis, or derived properties calculated using pedotransfer functions.

   The soil properties that are appropriate for defining the stocks needed to provide a specific soil service may be determined by examination of the interactions between soil properties, the soil processes they influence, and how these processes contribute to the soil service. The identities of such drivers are suggested in the land evaluation literature where mainly inherent stocks have been identified as 'land qualities'

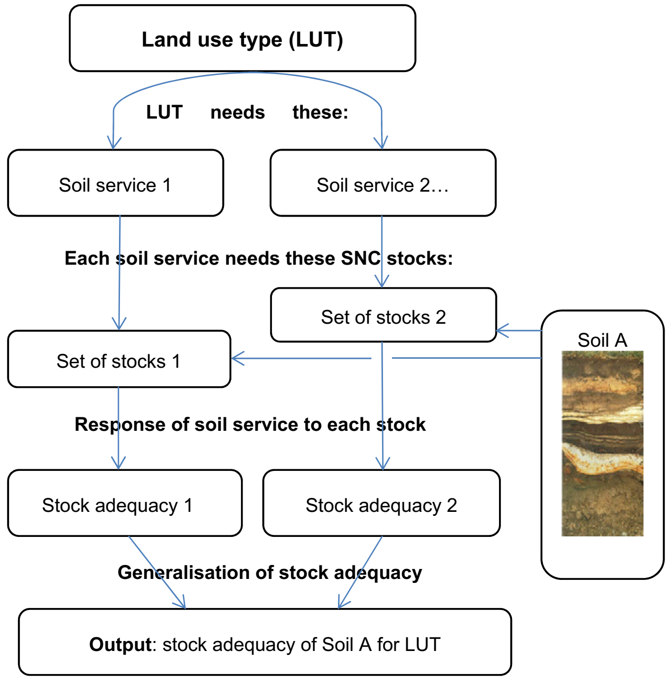

Fig. 1. Outline of procedure for evaluating soil natural capital (SNC) for a specified soil and land use type. The stock adequacy indices may be summed over all services to derive an overall SNC index for the soil/land-use-type combination.

for specific LUTs (e.g. FAO, 1976; Sys et al., 1993; Webb and Wilson, 1995). Similarly, they are also suggested by the monitoring indicators (manageable attributes) identified in the soil quality literature (e.g. Sparling et al., 2008). Where a soil service is represented by a soil process model, the appropriate stocks for the soil service are the soil properties used as inputs to the model. Stocks will often support more than one soil service. In deciding the number of stocks needed to represent the SNC, the usual modelling strategy of parsimony is appropriate.

4. Determine the 100% and 0% adequacy for each stock for each soil service. The measure of adequacy of a stock is characterised as an index in a percentage scale. Its estimation requires that both the 100% and 0% adequacy stock limits be established, as well as the curve of the soil service response to the level of soil stocks (soil service response curve).

   An index of 100% indicates stock levels of sufficient quality to satisfy soil service needs for a fixed level of intensity (based on specific management) within the LUT. An index above 100% would indicate a stock surplus. An index below 100% indicates insufficient stock quality to deliver an optimal soil service. For example, phosphorus nutrient stocks will be less than 100% adequate in sites where fertility testing indicates a fertiliser requirement. There will also be sites where phosphorus reserves are high where there is no fertiliser requirement and stocks are in surplus. Where a stock supports two or more services then separate stock quality estimates are made for each soil service. The 100% stock adequacy level is established for the combination of each stock, soil service, and LUT, by stock levels in soils that are capable of supporting land use goals and environmental performance. These levels can be assessed from the maximum known stocks in low-input systems or by use of appropriate soil management or environmental process models, for example the OVERSEER® Nutrient Budget model (Monaghan et al., 2007).

   Stocks that are relatively easily augmented by management, for example the fertility stocks required for provision of animal pasture feed, by fertilisers, will be highly dependent on soil management technologies. It is useful here to distinguish the part of each service (yield for example) that derives from built capital (e.g. artificial drainage or irrigation) verses natural capital (Dominati et al., 2010) (see the discussion below on built capital). The 0% stock adequacy level is also established for the combination of each stock, soil service, and LUT. For some stocks, the zero stock level may simply be zero. If the stock exists in a wide range of availability from labile to a highly recalcitrant mineral reserve then a decision has to be made about whether the stock includes the total soil content or only an available pool. The decision must be communicated as part of a stock description. For a fabric stock, such as available water capacity, zero can be meaningless if it requires that the soil is totally comprised of pores. We have defined the minimum stock for soil profile available water capacity (PAW) at 20 mm, as based on soil survey data in New Zealand. Another rationale for setting a zero stock value is the point where the soil service response curve flattens and change in service becomes much less sensitive to stock level. The question of what geographic area of soil is valid for setting stock limits, or calculating soil service response curves, has not been investigated.

5. Estimate the soil service response curve. The curve describes the adequacy of the stock at a site, for a specified soil service and LUT, where the independent variable is the stock, and the dependent variable is the soil service output, expressed as a percentage scale between stock levels of 0% and 100%. The adequacy of stock levels may be available from land evaluation literature where stocks have been identified as 'land qualities', and intercepts on the soil service response curves have been provided as land suitability evaluation 'ratings', for each land quality (e.g. FAO, 1976; Sys et al., 1993; Webb and Wilson, 1995). The adequacy of manageable stocks may be available in the soil quality literature where target ranges are provided for levels of soil quality monitoring data (e.g. SINDI, 2012; Sparling et al., 2008). Soil service data for calculation of response curves may also be derived from published simulation modelling

studies (e.g. Lilburne and Webb, 2002; and in Fig. 2), or derived directly from soil process models.

6. Derive an aggregated stock adequacy across all stocks and services assessed at a site. The simplest output is to report the adequacy of all stocks for all services for each soil in matrix form. This displays the soil natural capital status in full. If summary information is desired then some form of aggregation is needed. Using conventional land evaluation analysis, aggregation across several soil services for each soil can use the maximum limitations approach where the soil as a whole is characterised by the level of the least adequate stock. This emphasises the stock that may be limiting the use of the soil, and which may be in greatest need of investment of ecological, added or built capital. Another common generalisation is the Land Index (Rossiter, 1996) or specifically the Storie Index (Storie, 1933), in which each of the stock adequacies across the range of soil services may be combined using an additive, multiplicative, or geometric function. Generalisation of stock adequacies carries the disadvantage of masking low stock values in the averaged result.

We have not considered applying weights to stocks or soil services. It is possible that where production is the emphasis there may be a desire to weight the provisioning services in the aggregation, and the Land Index method is well suited to applying weights. Such weighting, however, is what traditional agriculture has done by neglecting environmental factors, which has led to our current water quality and climate regulation issues. The great strength of the ecosystem services approach is to consider the bigger picture and systems in their entirety to avoid the negative consequences associated with overemphasis on only one service. Non-weighted analysis enables the estimation of stocks and their service outputs to be as transparent as possible. Ecological, added or built capital can then be planned to address stock inadequacies. Where a stock supports more than one soil service for a soil, it is likely that the stock adequacy will differ between the two services. It is suggested that the lowest adequacy value is used in aggregation.

7. Quantify the soil stocks at each evaluation site. Stock values are derived for the field area by soil survey or from existing soil resource information. An evaluation site may be represented on conventional soil maps as a soil map polygon or a component of a soil map polygon, or on digital soil maps as a soil pixel.

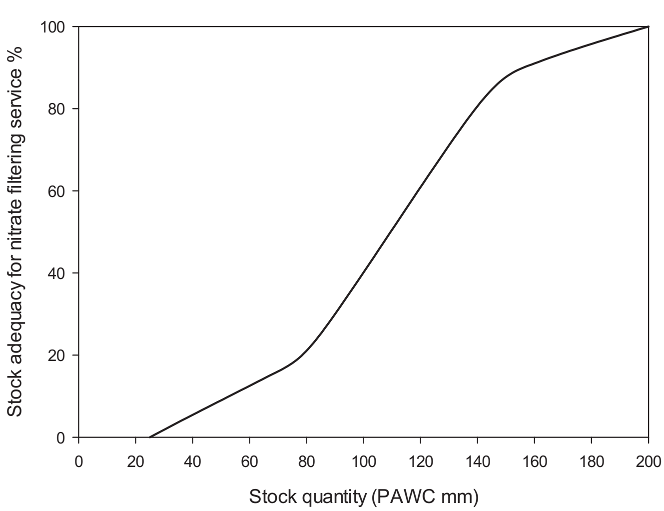

Fig. 2. Soil service response curve for the nitrate filtering service under rain-fed pastoral dairying. The *x*-axis is stock quantity (PAW), and the *y*-axis is stock adequacy for nitrate filtering. Data derived from Lilburne and Webb (2002).

4. Application

We applied the stock adequacy method to estimate SNC for soils in the basin of the Wairarapa Plains, east of Wellington City, New Zealand. This was a test area to demonstrate the mapping of SNC over an extensive geographic area and to explore the utility of the information. The soil data were extracted from a recent soil survey available in the national soil map information system 'S-map Online' (http://smap.landcareresearch.co.nz/home) (Lilburne et al., 2011a). The target land use type was intensive dairy production. Our focus was to map four soil services — nitrate storage, nitrate reduction, phosphorus filtering, and microbial filtering — that contribute to the soil-filtering-regulation ecosystem service. The rationale for each soil service, the choice of key SNC stocks, and the determination of soil function response curves follow.

4.1. Nitrate filtering

The nitrate filtering service was adapted from the nitrogen leaching vulnerability index described in Webb et al. (2010). Vulnerability is the negative expression of a soil service where it estimates the propensity of a soil to leach nitrogen as a potential contaminant. The soil service is the positive expression of the soil's ability to withhold nitrate from leaching. Nitrate vulnerability includes two components: (1) nitrate storage in soil solution within soil pores where it is stored and available for extraction by plant roots, and (2) biological reduction of nitrate under reducing conditions, with release of gaseous elemental nitrogen gas and nitrous oxide to the atmosphere. In this study we have recognised these two components as the nitrogen storage and nitrogen reduction services.

4.2. Nitrate storage service

Lilburne and Webb (2002) used the Gleams model to predict nitrate leaching of four soils in a depth sequence from stony loamy sand to deep silt loam. The key input stock controlling nitrate storage is the profile available water capacity for each soil horizon, summed over the profile to 1 m depth (PAW). The same amount of nitrate was applied to each soil to show the amount of storage and leaching differences between the soils. Nitrate filtering is the amount of nitrate retained by the soil, rather than the nitrate being leached. The leaching results were transformed into the response of nitrate filtering to the PAW stock by fixing the regionally least nitrate retentive soil (the stony soil) as 0% adequacy and the most nitrate retentive soil (deep silt loam soil) as 100% adequacy. The adequacy values were then plotted against the PAW for the four soils of interest (Fig. 2).

4.3. Nitrate reduction service

Nitrate reduction was adapted from the nitrate leaching vulnerability index described in Webb et al. (2010). Biological reduction of nitrate occurs under reducing conditions. These conditions are not measured directly in soil survey but are inferred from soil colour indicators of the soil drainage status. The key input soil stock for the reduction process available for the region is therefore soil drainage class with accessory information on soil parent material, and soil taxonomic class. This is defined in terms of the depth from the soil surface of dominant redox segregations and grey matrix colours (Milne et al., 1995). Because drainage is mapped as classes, the relationship of stock adequacy to nitrate reduction is categorical.

4.4. Phosphorus filtering service

Similar to nitrate filtering, the phosphorus filtering function was adapted from the phosphorus leaching vulnerability index described in Webb et al. (2010). The key stock input is a phosphorus retention class (derived from soil taxonomic class means) adjusted for percent fine earth for each soil horizon, soil horizon thickness, and summed to 100 cm depth. The relationship of stock adequacy to phosphorus filtering class is categorical and estimates the inherent potential for the soil to adsorb phosphorus (dominantly in the form of phosphate anions).

4.5. Microbial filtering service

Microbial filtering is also based on a microbial vulnerability classification (Webb et al., 2010). It recognises four classes of relative microbial retention on the basis of results from lysimeter bypass flow studies (McLeod et al., 2008). The key stock input is a microbial retention class (4 classes) based on soil taxonomic class, depth to slow permeability and soil functional horizons (Lilburne et al., 2011b). The relationship of stock adequacy to microbial filtering class is categorical.

4.6. Mapping SNC adequacy

One soil attribute or class was identified as the key soil stock for each of the soil services. For each soil, the estimated soil stock level was used to read the SNC stock adequacy from the relevant soil service response curve. This process was implemented as a pedotransfer function within the inference engine of S-map (Lilburne et al., 2011a) and values downloaded to GIS. The output was designed to provide the values in S-map soil factsheets available online.

For each soil map polygon, two levels of generalisation were provided by the map database. First, for each soil taxonomic class the SNC stock adequacy values were provided for each soil service. Second, the stock adequacy indices for each of the four soil services were generalised by calculating a mean. Where more than one soil taxonomic class as was assigned to a polygon, the first and second data sets were calculated from soil area-weighted mean.

5. Results

We focused on a portion of the Wairarapa soil map. A sequence of five soils from very shallow stony soils to deep loamy soils, and an associated soil with poor drainage status, are common in this area. The association is common for New Zealand soils derived from alluvium particularly in eastern alluvial basins and plains of both North and South Islands. The fine-earth fraction of these soils is the most functionally active component of the soil and the hard indurated stones reduce the soil volume available for filtering processes. Pertinent soil properties are listed in Table 1.

Soil stock adequacy estimates for the four soil functions for the five soils are given in Table 2. Values are generalised across soil services as an expression of the overall soil nutrient and contaminant filtering ecosystem service. Generalisations have been calculated using means, but alternative strategies can be used for a particular purpose. For example, contaminant risk may be highlighted by identifying minimum stock values for selected soil services.

The five soils are differentiated by stock adequacy for nitrate storage because of the contrasting effect of stoniness and related lower PAW. Nitrate reduction is minimal in the well-drained soils but very high in the poorly drained soil where reduction processes are active. Phosphorus filtering is low in all soils because they are all weakly weathered with low phosphate retention values. Microbial filtering ranges from high to moderate because the drainage in young alluvium with poor structure is dominated by matrix flow, which enhances filtering rather than bypass flow (McLeod et al., 2008). The overall values for mean stock adequacy across the four soil functions are dominated by the nitrate storage trend. An understanding of the overall ecosystem service would require the assessments of the individual soil services to reveal the range of potential contaminant filtering behaviour in the ecosystem, and to reveal the vulnerability of the soils to pose specific contamination risks.

6. Discussion

6.1. Utility

The study demonstrates that SNC can be quantified using a non-monetary index that expresses differences between soils on the basis of their functional efficacy. The estimates may be calculated from soil survey database information, and can be provided for extensive areas where adequate soil survey and land use cover information is available. The vital inputs are knowledge of the LUT soil service requirements, and data that define the key SNC stocks. These stocks are identified as the soil variables that strongly influence the soil processes that represent soil services and contribute to ecosystem services.

Of the soils in the Wairarapa soil sequence, the generalised stock adequacy index points to the better functional performance of the Flaxton and Waimakariri soils for dairy use. The soils though are not perfect and the stock adequacy of the individual soil services provides the detail needed to plan the management requirements for optimising their use and minimise environmental impacts. For land managers, these are the soils on which a dairy enterprise is best able to capitalise on the natural advantages of the land. These advantages include the minimised costs of nutrient and contaminant management interventions, and limited risks to the environment. In contrast to the Flaxton and Waimakariri soils, dairy enterprises on stony soils must compensate for lack of natural capital by added built capital investment in a mix of development, maintenance, mitigation inputs, or investment in ecological infrastructure such as planted riparian margins. The results raise questions about the soil use efficiency of low-PAW stony soils for intensive land uses such as dairy where there is a need for high performance nutrient and contaminant filtering services.

Because the stock adequacy index expresses the adequacy of stocks it is reasonable to suggest that the value of (100 - % SNC adequacy) is an expression of the inadequacy the stocks to support a given soil service. It is an estimate of the service inefficacy that must be tolerated in less than optimal LUT performance, or that needs to be corrected by investment in ecological or built capital. The inadequacy may be used as an indicator of the ecological or built capital required to develop and maintain stocks for optimum performance, for example, standoff pads for soil conservation or improvement of soil carbon C stocks.

The need to increase the environmental performance of land use, particularly under intensive management, has spawned many

Table 1
Wairarapa Plains soil sequence properties, and classification. Soil Taxonomy (Soil Survey Staff, 1999), NZ Soil Classification (Hewitt, 2010).

Soil family	Flaxton	Waimakariri	Barrhill	Eyre	Rangitata
Soil type	Deep silt loam	Deep silt loam	Moderately deep silt loam	Shallow silt loam	Stony sandy loam
Soil Taxonomy	Endoaquepts	Haplustepts	Haplustepts	Haplustepts	Ustorthents
NZ Soil Classification	Orthic Gley	Recent	Recent	Recent	Recent
Depth to >35% stones (cm)	100	100	70	35	0
PAW	220	206	148	76	46
P adsorption	200	100	75	50	25
Drainage class	Poor	Well	Well	Well	Well

Table 2
Soil natural capital estimate (by stock adequacy %) for four soil services, for five soils.

Soil service	Key soil stocks	Flaxton	Waimakariri	Barrhill	Eyre	Rangitata
Nitrate storage	Available water capacity	100	100	32	32	4
Nitrate reduction	Drainage class	42	0	0	0	0
Phosphate filtering	Phosphate retention	16	7	7	7	0
Microbial filtering	Microbial retention class	30	90	70	90	70
Mean SNC stock adequacy supporting the filtering of nutrients and contaminants ecosystem service		98	51	42	32	18

environmental risk mitigation management technologies (e.g. Monaghan et al., 2007). Mitigation technologies have become the major management strategy for environmental protection. A supporting strategy is to choose enterprise location by finding a good fit between LUT needs and soil capability. Where a good fit is located then there is a likelihood of good environmental performance (McBratney et al., 2014).

The following approach is proposed for locating enterprises by using the stock adequacy index as a measure of goodness of fit between LUT requirements and soil capability. Given the knowledge of the ecosystem requirements of a specific LUT, a set of soil services may be defined, and SNC adequacy indices calculated and mapped for each service. The generalised mean stock adequacy including all soil services considered may be mapped with maximum values used as a measure of goodness of fit between the LUT and the SNC. Where goodness of fit is poor, levels of inadequacy may be used to compile a set of soil service profiles to indicate management issues.

A natural-capital-based measure of goodness of fit may be useful for land resource policy and planning. Where established enterprises are poorly fitted to their natural capital, mitigation may not be their only strategy. With the availability of goodness-of-fit information land managers may identify options for adjusting their enterprises to increase the fit and gain the benefits of their natural capital. Greater value may be gained by using appropriate policy instruments to encourage goodness-of-fit-based location of newly establishing enterprises.

These conclusions are no surprise to those who are familiar with relationships of soil type and land use management, and would be evident from a good conventional land evaluation analysis. What is new about an SNC stock adequacy approach is that (1) the stock adequacy estimates are calibrated against objective analysis of soil services, (2) the soil evaluation attributes are directly related to soil processes, and therefore (3) the stock estimate is an indicator of the efficacy of the service it supports. This (4) indicates the performance of ecosystem services under different land use scenarios and (5) enables policy and planning professionals to better understand and integrate production and environmental concerns.

We have chosen to express stock adequacy as an index for the reasons given earlier. The index may be used as a non-monetary-value measure of soil assets, for a farm or region that is calibrated to soil ecosystem services. Expression of soil ecosystem service results in monetary terms has been demonstrated by Dominati et al. (2014). When monetary values of SNC can be estimated robustly, are accepted by economists, and mapped then the results will have added power in assessing the soil assets of a given area. Our expectation is that the stock adequacy method may provide an input to valuation.

6.2. Taking account of added or built capital

The SNC evaluation method is an appropriate tool for evaluating land assets, because it recognises the portion of soil capital assets that is provided freely by nature, and differentiates this from added or built capital. Built capital is the sum of improvements to the soil made by management inputs. These improvements include both initial soil development inputs, for example irrigation system installation costs, and continuing maintenance inputs, for example water application costs. Built capital is important because it represents the costs of developing and maintaining the utility of a soil that wasn't providing the adequate level of ecosystem services for the required land use and management intensity. It is important economically to appreciate the magnitude of built capital and to assess the degree to which land use choice, location, or development considers the prior soil capital assets provided by nature.

Ideally, SNC is what the first land managers started with. Added and built capital represents the net improvements. However, the history of land use and environmental change is highly complex, and determining the individual contribution of natural capital versus added and built capital to soil services is challenging. To distinguish the two, an option is to recognise a historical benchmark in the history of land use and development for an area. This approach was contemplated in New Zealand but it proved complex to unravel. If this is difficult in a country with a short history of human occupation and land management then it would not be appropriate globally. A second option was to use indigenous vegetation land reserves as benchmarks, but suitable benchmarks are rare for many soils and have themselves undergone change related to management of adjacent land. A third and expedient approach is to accept that current soils incorporate components of added capital and to set a benchmark by recognising long-term additions to soil capital that are relatively stable in time. Variation of these improvements in time can be accepted as part of the dynamics of SNC, where the improvements can be said to be 'naturalised'. It is of great pedological interest to identify the historical natural, or genoform state of a soil (Droogers and Bouma, 1997), but it is the soil we are delivered with by the acts of land use history that remains for us to use. Suitable naturalised benchmark soils are most likely found in areas supporting low-input agriculture. It is important that in any study of SNC that the natural capital benchmark is stated. A fourth option is to accept that humans are natural and comprise one of the many actors in a particular landscape that contribute to the overall state of the soil. This approach would accept that SNC is an amalgam of its prehuman state and human impacts. It is what we observe today.

In this study we chose the third option in which the 'naturalised benchmark' was the low-intensity clover-based, rain-fed, pastoral grazing system that was extensive on the Wairarapa Plains and similar New Zealand land in the mid-20th century. Profitable dairy farming on seasonally dry land now requires intensive inputs of irrigation, fertiliser and drainage.

6.3. Stock quantity and quality

Robinson et al. (2009) presented an approach for quantifying stocks by defining stock quantity and stock quality. Stock quantity distinguished inherent (or use-invariant) soil attributes and manageable soil attributes. Stock quality was described by characterisation of the stock composition. For example, the quality of stocks of sand, silt or clay might be characterised in terms of mineralogy or other qualitative components. The stock adequacy method suggests that there are two aspects to stock quality. First is the quality in terms of stock-level that is plotted in the soil service response curve. This is the quality as judged by the requirements of the soil process that provides the service. Second is the quality in terms of the stock-composition. This is not relevant to the example presented in this paper where all soils have similar mineralogical and organic composition. A case where composition is relevant would be for a soil service providing physical support for grazing heavy animals. The service is provided by the resistance and resilience of the wet soil material to treading pressure. A soil structural vulnerability index devised by Hewitt and Shepherd (1997) related soil resistance and resilience to mineralogy, organic carbon, clay and wetness. This compositional quality would need to be expressed by providing a set of curves for a range of structural vulnerability indices on the soil service response plot.

6.4. Relationship to land evaluation

Rossiter (1996) developed a unified land evaluation framework to describe the wide scope of land evaluation analyses. In this framework, the simple example presented in this paper conforms to a static land evaluation model, based on a static resource base, and not sensitive to location. The framework also suggests more sophisticated analyses of SNC For example, dynamic modelling of changes in the soil-stocks' resource base would be possible by tracking change in erosion and sedimentation of material stocks, or change in soil quality. Location sensitivity would be introduced by inclusion of stocks of heat or water content that are inherently sensitive to location and time.

There are several ways in which quantification of SNC may serve the development of land evaluation. First, it displays relationships between current land uses and SNC, levels of sustainability of use, and the goodness of fit between land use and land type. Second, it provides a calibration for the suitability levels of soil qualities based on soil services. Third, Rossiter's (1996) review of land evaluation included complex analyses such as the land allocation problem, which involves optimisation of land allocation. Soil natural capital quantification may assist in the allocation of land where optimisation is based on soil resource use efficiency, judged by land use choices that maximise the use of natural capital for the range of ecosystem services it provides. Fourth, it may provide for quantified land evaluations, employing monetary or non-monetary values that express environmental as well as production values. Fifth, it may integrate land evaluation with its emphasis on static inherent soil profile characteristics, with soil quality with its emphasis on manageable soil properties.

7. Conclusions

- Because the stock adequacy method is compatible with normal soil mapping, land evaluation techniques, and soil resource databases, it has potential for development as an operational tool that can provide practical information on SNC across extensive terrain. This information in turn has potential to introduce insights from soil science into a more holistic ecosystem analysis.
- The soil science sub-disciplines of land evaluation and soil quality have been largely independent branches of soil science. Because the stock adequacy method of SNC quantification can be used to integrate both inherent and manageable soil data, it provides a point of convergence of land evaluation and soil quality.
- Because the method of quantification is standardised as an index, and is calibrated against estimates of the shape of the soil service response by land use, it has potential for universal application.
- Estimation of the soil service response curve for the nitrate storage service used a soil process model. The most commonly available models for this purpose are designed for use as land management tools. Frequently, the models do not differentiate between some of the soil profile characteristics that significantly affect soil processes and services. Neither do they differentiate between important subprocesses. For example, models that predict nitrogen regulation usually include the filtration processes related to storage in pores and plant root uptake. The processes of biological denitrification under anaerobic conditions are commonly not included. There is a need for the development of soil process-based models for the purpose of making transparent the impacts of variation in soil stocks and processes on the provision of ecosystem services from soils.
- The method quantifies SNC with respect to a defined land use. A common usage of the term 'soil natural capital' expresses the natural capital of land irrespective of how it is used. We suggest that a generalised universal soil natural capital evaluation could be designed for regional or national stock inventories. Similar to the method for the estimation of a cost price index from the prices for a standard set of commodities, it would be based on the average stock adequacy for a standard set of soil services across land uses.

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