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Developing an indicator of productive potential to assess land use suitability in New Zealand

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ABSTRACT

The Land Use Suitability (LUS) concept informs decision-making by stakeholders with information about the economic and environmental consequences of land use choices. LUS is composed of three indicators describing the inherent productive and economichttps://mail.niwa.co.nz/owa/- _msocom_1 potential of land parcels (productive potential), the contribution of a land parcel to lose contaminants relative to other land parcels (relative contribution), and the load of contaminants lost compared to the load that ensures that environmental objectives are met (pressure). This paper outlines an improved indicator of productive potential (PP). We outline the four layers of information that comprise PP for a land parcel: (1) Feasibility, which defines whether the productivity and quality of a crop is enough to allow the land use to be undertaken; (2) Yield, which is the amount of a product or crop that can be grown; (3) Economic returns, given the yield and other requirements for the land parcel; and (4) Economic Importance, which combines information about the economic returns and the probability of a land use being undertaken. These layers can be combined into a single PP indicator of the value of the land for economic use. The PP indicator can be expressed continuously or categorically and mapped at a national scale. When combined with the Relative Contribution and Pressure indicators in the LUS system, it allows for identification of areas which are most suitable for intensification by providing for a direct comparison of the economic and environmental outcomes.

1. Introduction

To meet the food and fibre demands and economic desires of a growing and more prosperous population, primary production is intensifying. However, intensification can degrade land and water quality, reducing ecosystem function, biodiversity, and resilience to factors like climate change (Foley et al., 2011; Meyfroidt, 2018). Decisions about the trade-offs of intensification and environmental quality have economic, environmental, social, and cultural impacts that go beyond the farm gate (Goldstein et al., 2012; Liebig et al., 2017; Renting et al., 2009). To help inform land use decisions around intensification and environmental impact across scales, McDowell et al. (2018) developed the Land Use Suitability (LUS) concept. One application of the LUS concept assesses the potential of boosting productivity while achieving a water quality objective; informing questions such as will productivity and water quality objectives be met with the current land use and if not then how should land use and land use practices change? LUS contains three indicators: 1) productive potential (PP), describing the inherent productive and economic potential of land parcels; 2) relative contribution, describing the potential for a land parcel to contribute contaminants downstream relative to other land parcels; and 3) pressure, describing the contaminant load delivered to a receiving environment compared to the load that ensures that water quality objectives are met. The three indicators can be expressed continuously or categorically, mapped across scales, and used to support strategic land assessments and plan land development and investment.

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Of the three LUS indicators, the PP indicator is the least developed. Internationally, the closest analogue of PP is the decades-old concept of land evaluation sometimes also known as land use suitability. There are many examples of assessments that have built on the USDA (Klingebiel and Montgomery, 1961) and Food and Agriculture Organization (Food and Agriculture Organization, 1976) classification frameworks for land suitability (Van Diepen et al., 1991). The principles behind these frameworks include assessing the capability of the physical environment, such as climate, relief, soils, hydrology, and vegetation, to support a given land use. More recent versions have included assessments of adaptation to climate change of single crops (Gasser et al., 2016), or focused on using mathematical approaches that combine quantitative and qualitative data in assessments of suitability of specific crops (El Baroudy, 2016; Lara Estrada et al., 2017; Seyedmohammadi et al., 2019). Seldom have they considered incorporation of socio-economic goals. Of the few examples that do exist (Dunnett et al., 2018), many of the measures of socio-economic goals cannot be transferred to other jurisdictions. Reasons include different policy instruments such as subsidies that may reward one aspect like production, but inadvertently cause poor water quality or a loss of biodiversity (MacLeod and Moller, 2006; OECD, 2017), or legal structures that focus on short-term gain, neglecting indigenous land rights and ownership who may make different decisions based on gains over centuries (Kingi, 2013).

If LUS is to be used to inform questions associated with land use and water quality, it must be used by multiple stakeholders across national or regional scales, catchments, and on-farm. Confidence to recommend or implement change, some of which may mean moving operations between regions, requires the underpinning data and regional policy information to be consistent and as accurate as possible. A common approach is to use freely available data that are applicable to land management units within farms across regions, if not countries (Bock et al., 2018; Coriolos, 2016; Mazahreh et al., 2019). In New Zealand, a national land evaluation framework was developed in 1952 and has been refined since then to define biophysical constraints that may limit sustained productivity within farm management units (Lynn et al., 2009; Mueller et al., 2010). This framework, called land use capability (LUC) focuses on production constraints like soil properties (e.g., depth, water holding capacity, erodibility) and climatic conditions (e.g., rainfall, growing degree days) to classify the versatility of land on a scale from 1 to 8. Class 1 land may be highly suitable for many land uses, whereas higher numbered classes are limited to a few land uses.

To inform LUS and the debate around land use and water quality, the PP indicator must not only incorporate likely yields of different crops (e.g., arable, pastoral, forestry, fruit), it must also, as mentioned above, include an assessment of the socio-economic context in which the land use is to occur. However, a key limitation to using LUC classes as a PP indicator is that as the LUC classes were designed to reflect the high-level constraints to production and, therefore land use versatility. Thus, it does not directly address the economic productive potential of different land use options, and therefore is not ideal for the purposes of the LUS. For example, the Gimblett Gravels in the Hawke's Bay Region of New Zealand have a LUC class of 7, considered to be highly constrained for many crops, but are some of the most prized soils in New Zealand for viticulture (Bloomer, 2011).

This paper outlines the testing and development of the PP indicator. For the purposes of this paper, we define land use as an enterprise or groups of enterprises that reflect different biophysical, social, and economic conditions on land. Specifically, we aim to use readily-available data and models that operate from farm to national scales to assess land parcels and enterprises to: 1) define the conditions and constraints of representative crop typologies using biophysical and management data; 2) estimate the feasibility of land parcels to produce product of sufficient quality to meet market demands; 3) spatially define the yield, economic value and importance of land uses according to different scenarios and 4) incorporate these factors into a single PP indicator. For brevity we present our aims in the context of a simplified national case study that will derive a PP indicator based on six major land uses in New Zealand. Although we focus on a PP indicator of the land for economic purposes, it is acknowledged that there are a range of other values supported by land, including socio-economic (e.g., employment) and non-economic (e.g., biodiversity) that could be included in the LUS approach that are not addressed by the PP indicator. These other values will be addressed in more detail in future iterations of the approach.

2. Method

2.1. Overview

The calculation of the PP indicator uses four ***layers*** of information: feasibility, yield, economic returns, and economic importance. There is one set of layers for each land use included in the analysis, and each layer uses inputs from the preceding layer. To inform decisions, users can extract information relevant to them from each layer or they can use the integrated PP indicator. The six land uses in the analysis are sheep and beef, forestry, dairy, arable (systems where broadacre cropping is the main component of the farm system), horticulture (including flat-land viticulture), and viticulture on land that is not suitable for other horticulture (termed "Other Viticulture"). We envisage future iterations further subdividing these land uses, particularly arable and horticulture which cover a large range of potential crops. For arable we used wheat in the South Island and maize in the North Island, and for horticulture we used the most prevalent land use (vegetable, pipfruit and viticulture) in an area as representative crops.

The layers are all generated under the same ***scenario*** as defined by their biophysical, input, and socioeconomic context. Examples of scenarios might include the current state, a maximum output derived from high fertiliser inputs, a climate change projection, or a projection where infrastructure and labour bottlenecks for certain land uses were removed. For each scenario we define the:

- **Biophysical context** – factors such as temperature, altitude, aspect, dry periods, frosts, hail, soil depth and type. These are included as variables so that changes in the PP indicator can be assessed under different scenarios of climate change.
- **Input context** - what variable inputs will be utilised by each land use, such as fertiliser, irrigation, frost protection etc. The input context is included so that different management responses or mitigations to biophysical constraints, environmental impacts of a land use and climate change can be explored in the wider context of the LUS assessment system.
- **Socioeconomic context** – wider non-biophysical factors that affect the land use, such as labour availability, infrastructure present in a location, market demand, input costs, etc. The inclusion of the socioeconomic context allows for the exploration of different market conditions, but also of policy responses to the need for development in some locations – for example, skills training or development of infrastructure.

The layers use the same pixel size of 200 m by 200 m to represent land parcels. A schematic of the PP indicator calculation is shown in Fig. 1, with the definition and approach for each layer discussed below.

2.2. Feasibility layer

The feasibility of a land use is determined by whether the productivity and quality of a crop is enough to allow the land use to be undertaken on a parcel of land. Feasibility is determined by biophysical constraints, and by any inputs that are defined in the scenario to alleviate those constraints. For example, nutrient levels can be altered by fertilisers, some soil properties can be overcome by artificial drainage, frosts can be mitigated by frost protection, hail can be overcome by covering crops, irrigation can compensate for rainfall deficits etc.

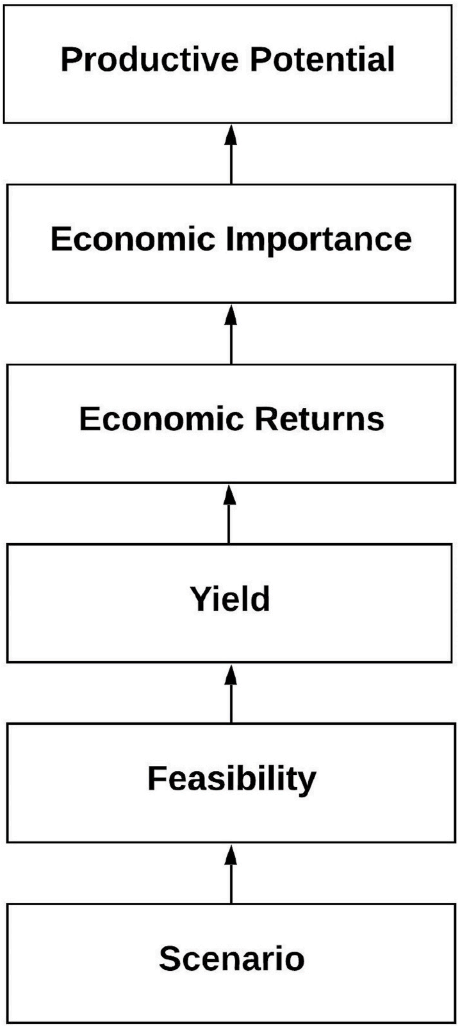

Fig. 1. Schematic of productive potential indicator approach.

Factors such as soil salinity and alkalinity which can be significant limitations internationally (e.g., Russ et al., 2020) are not normally considered limiting constraints in the New Zealand context. The likelihood of a biophysical constraint occurring on a land parcel can be determined by using rule-based, process or statistical models or by other methods like multi criteria decision analysis (MCDA) (e.g. Renwick et al., 2019). The likelihood of a land use is represented as a Feasibility layer in which a binary TRUE/FALSE variable is used to define for each land parcel whether the land use is realistic from a biophysical perspective.

In this, the first development of the PP indicator, feasibility relies on a set of simple definitions as applied in our New Zealand case study. Sheep and beef was assumed to be feasible everywhere currently used for agriculture, forestry was assumed as suitable everywhere not prohibited by the National Environmental Standard for Plantation Forestry (New Zealand Government, 2017), dairy land was a subset of sheep and beef land with slope less than 15°, for arable crops a specific set of rules was developed separately for the North Island (NI) where maize was assumed to be the dominant crop, and the South Island (SI) where more traditional wheat based mixed cropping was assumed to occur. The rules for both wheat and maize were based on growing degree days (>1100 SI, >1200 NI), soil depth (>30 cm), soil drainage (imperfect or better), slope (<15°), and additionally for maize, soil temperature at sowing (>10 °C) and spring and autumn frost (less than 2 years in 5). For horticulture LUC classes 1–2 were used, and for other viticulture we all current viticulture land and land with similar slope and soil characteristics outside LUC classes 1–2 were assumed to be feasible. Climate constraints were included by the applying different crop types to represent the arable and horticulture land uses.

2.3. Yield layer

2.3.1. Pasture yields for pastoral land uses

Dairy and sheep/beef typologies were created from combining spatial datasets of temperature, rainfall, slope, and soil attributes with real farm management information as outlined in Monaghan et al. (2021). Briefly, dairy typologies were based on 431 nutrient budget files sourced from DairyBase records for the 2015/16 production season (DairyNZ, 2017). These nutrient budgets were prepared using the Overseer® Nutrient Budgeting software version 6.3.1 (AgResearch, 2016). Based on expert opinion and previous sensitivity analyses of Overseer components (McDowell et al., 2015) the typologies contained a hierarchy of biophysical attributes that were likely to influence productivity, namely temperature, wetness, drainage, and slope. Soil fertility management (e.g., pH, Olsen extractable phosphorus, potassium) was set to optimal levels for each typology according to (Roberts and Morton, 2009). However, for dairy pastures a fixed level of annual nitrogen fertiliser (200 kg N ha^{-1}) was used, and no added nitrogen was used for sheep and beef pastures.

After accounting for interactions there were potentially 96 dairy farm typologies (2 × 4 x 3 × 4). Because some combinations covered little land area, we restricted our analysis to the 20 combinations that covered the greatest area. The top 20 typologies represented 76% of the land used for dairy farming in New Zealand.

Sheep/beef typologies were based on farm classes used in the Beef and Lamb New Zealand (BLNZ) Economic Service Sheep and Beef Farm Survey (Beef and Lamb New Zealand, 2018). This national survey questions about 500 sheep and beef farmers annually and has been doing so since the 1950s. The survey has eight farm classes and six production regions to represent a total of 17 primary sheep/beef farming combinations (i.e. typologies), each with 5–10 variations accounting for different land management units (e.g. tree or forage crop blocks). These typologies and their variations represented >90% of land in sheep and beef production across New Zealand. Like dairy typologies, soil fertility management (e.g., pH, Olsen extractable phosphorus, potassium) in sheep and beef typologies was set to optimal levels according to Morton and Roberts (2016).

Irrigable typologies for sheep and beef and dairy were set where >50% of the area was deemed irrigable according to Dark et al. (2017). Yield information for each typology was generated utilising daily time step simulation models via the Agricultural Production Systems Simulator (APSIM) (Holzworth et al., 2018). Additional information on the typologies, how APSIM outputs were generated, and the regression equation used to interpolate the yield information to non-represented areas are provided in the Supplementary Information.

2.3.2. Yield from arable and horticulture land uses

Three crop typologies were developed for the South Island based on rainfall zones 650 mm, 750 mm, and 850 mm, and one for the North Island based on the crop production types typically associated with the East Coast. The crop production data for each typology was sourced from Bright et al. (2018). In these data, crop production is simulated using the FAO water production function described by Doorenbos and Kassam (1979) and a proprietary model (Irricalc) (Aqualinc, 2009) across three profile available water classes: 35 mm, 60 mm, and 120 mm. IrriCalc's crop yield model operates on a daily time step and outputs crop yield at the user specified harvest date. Crop yields modelled by IrriCalc were tuned to match yields being achieved on irrigated farms in the relevant typologies.

Horticultural yields were based on the same data source (Bright et al., 2018). Three vegetable production models were used for each of the Canterbury rainfall zones (650 mm, 750 mm, and 850 mm), a single pipfruit (apples) model for the East Coast of the North Island, and viticulture models for Marlborough and Inland South Island basins. These were extrapolated to similar rainfall classes for the vegetable production typology.

Arable and horticultural typologies were assigned to climate zones described in New Zealand Meteorological Service (1983) with some refinements (Bright et al., 2018). Additional information relating to the defined conditions and constraints for each typology, the climate zones, and the assignment of typologies to climate zone are provided in the Supplementary Information.

2.3.3. Yield from forestry land use

Yield estimates for forestry follow the methodology of Watt et al. (2017) predicting volume by log grade using indexes of forestry production: Site Index (SI) which expresses the height of dominant and (or) co-dominant trees at a given index age; and 300 Index (I300), which is the stem volume mean annual increment at age 30 years for a reference regime with a final stand density of 300 stems·ha^{-1}. I_{300}. and SI are defined as described in Kimberley et al. (2017). The results were resampled to 200*200m grid for use in the PP indicator, and at this scale the accuracy for production estimates is expected to be ±2 – $3\text{m}^3\text{ha}^{-1}\text{year.}^{-1}$

2.4. Economic returns

Land uses at each location have different economic values attached to them, which is a function of the amount of product produced and the value of the product in that location. Including a layer of economic returns allows a comparison between the ability to grow a low production level of high value crops with a higher productivity level of a low value crop. All economic data are calculated in New Zealand dollars (2018).

2.4.1. Economic returns for pastoral land uses

Pastoral operating profit (revenue less working expenses and depreciation) were derived from Beef and Lamb NZ survey data (Beef and Lamb NZ 2018) and Dairy NZ survey data (DairyNZ, 2019) using five year averages from 2013/14–2017/18. These survey data provide estimates for 7 sheep and beef farm classes and 8 dairy survey data regions. The economic returns for sheep and beef classes were assigned to climatic zonation (New Zealand Meteorological Service, 1983), while the dairy farm survey data regions were assigned to local government regions most appropriate for the DairyNZ survey region data. The economic returns were adjusted linearly to reflect the relationship between the estimated sheep and beef and dairy pasture yield for a land parcel (section 2.3.1) relative to the mean of the estimated yields from the locations in a typology where those land uses currently occur. This estimate assumes that the survey data reflects the mean returns from all the surveyed land use in a specific area, and that the economic returns are directly related to yield as shown in Eq. (1).

$$Economic\ Return_{LU,\ LP} = \frac{Yield_{LU,\ LP}}{Mean\ Yield_{CLU,\ TP}} \times Economic\ Return_{SD,\ TP} \qquad \text{Eq. 1}$$

Where: LU = Land Use; CLU = land which is currently in a specific land use; LP = Land Parcel; TP = Typology; SD = Survey Data of returns for a given land use in a specific typology.

The capital associated with the land use in each location was estimated from the same survey data sources and subtracted from the operating profit using a cost of capital of 2.9% which reflects the average national return on equity (excluding capital gains) for dairy farms. Additional information on the survey classes and their assignment to climate region are shown in the Supplementary Information.

2.4.2. Economic returns from arable and horticulture land uses

The arable and horticultural financial estimates used data from Bright et al (2018). For arable crops, a financial estimate was generated based on the '*standard arable rotation with > 10% of time in forages/fodder*' used for the arable production in the Matrix of Good Management (Plant and Food Research et al., 2015). Revenue was driven off the single crop yields calculated in the yield section above. Expenditure was set as a fixed cost (on a per hectare basis (Bright et al., 2018)), therefore changes in yields had no impact on expenditure but did impact on revenue.

Bright et al. (2018) uses vegetable, viticulture and pipfruit economic models where revenue and harvesting costs are directly proportional to yield, but other expenditure is fixed. Capital costs for arable and horticultural land uses (like pastoral) were deducted at the same 2.9% cost of capital used for the pastoral land uses.

2.4.3. Economic returns from forestry land use

Forest economic production was calculated as an annualised present value of a standard structural regime of *Pinus radiata d. don* for timber production using the Forest Investment Framework (FIF) (Yao et al., 2016). The calculation of roading and transport costs was modified within the framework to operate nationally rather than within pre-defined forest areas (polygons). Roading was calculated using Euclidean distance (straight-line) from each cell to the nearest line segment of New Zealand road centrelines (Land information New Zealand, 2018). Transport costs were calculated using a cumulative distance from that line segment following the road network to New Zealand ports and sawmills (processors). It was assumed large diameter saw logs (S1 and S2) and pulp were transported to sawmill locations for domestic processing, while small diameter saw logs (S3) were transported to ports for international export as unprocessed logs.

The FIF operates spatially on a 25 m pixel resolution subtracting the discounted value of forest administration, establishment, management, harvesting, internal forest roads and landings, and log transport costs from discounted forest revenues from log sales (see Supplementary Information for forestry operating costs). A 4.9% discount rate was used over a 28-year forest rotation, with one waste thinning operation. This rate has been selected to be consistent with the analysis used on other land uses included in the PP indicator and includes an additional 2% discount rate penalty because of the financial risk profile of forest investment. Large saw logs were valued at \$140 m^{-3}, small saw logs at \$130 m^{-3}, and pulp logs at \$50 m^{-3}. Alternative forms of revenue such as carbon sequestration or other ecosystem services were excluded. Costs were assigned by slope class, enabling cost estimates to be differentiated across landscape types.

2.5. Economic importance

Economic importance is a layer of economic returns that also incorporates the socio-economic constraints operating on a land use. These are generated using the economic returns from a land use on a parcel, multiplied by the probability of the land use occurring on that parcel in the scenario of socio-economic conditions used for the analysis.

For the results generated here we have utilised a scenario that represents the current context of social, labour, infrastructure and market conditions operating at any location (Current scenario). Scenarios can also be used to explore other opportunities that may arise from policy or market changes. For example, under the Current scenario the availability of labour and skills may limit the amount of labour-intensive horticulture that could be undertaken despite its high returns. Users may wish to explore the change in Economic Importance and PP indicator of land parcels in a catchment that benefitted from some policy interventions to increase the supply of labour and provided training opportunities to overcome skills deficits. Another scenario might explore the effect of changes in market and other social-economic conditions due to climate change. The range of scenarios can be refined according to user needs.

Although certain land types may be feasible for a land use, because of various socio-economic constraints a given land use will not occupy all a land type. In this study, the socio-economic constraints are represented by a probability that a given land use will occur in its feasible area. We use the current area of each land use within a New Zealand Territorial Local Authority (TLA) to estimate that probability, i.e. it is assumed that the current area of a particular land use reflects the capacity of the market to absorb the produce, the capacity and capability of the local labour force etc. All land parcels that are biophysically feasible for a land use have equal probability of that land use. For example, if there is twice as much feasible area as current area of a land use, then all the feasible land has a probability of 0.5 for occurrence of the land use.

However, the probabilities for each land use also need to account for other alternate feasible land uses. Some land has many feasible land uses, but other land is more biophysically constrained in its land use options. Where the probability of a high value crop on its feasible area is high because of the ratio between its scenario area and its feasible area, then the probabilities of occurrence on that feasible land must take into account that it cannot occur elsewhere, while alternate land uses may do so. To maintain the potential for the scenario land use areas (and the socio-economic assumptions of the scenario), a hierarchical set of layers of each unique combination of land use feasibilities is defined, where the highest level of the hierarchy has the most combinations of possible land uses, and the lowest has only one possible land use. In our case study there are 7 hierarchical layers (see definitions in Supplementary Information). This hierarchical approach allows the calculation to account for the occurrence of the higher value crops on the limited area of land within a TLA district where these land uses are feasible. The calculation of economic importance then involves solving a series of linear algebra equations for each land use in turn, that ensure the total area of a land use in a TLA matches the scenario area, and all feasible land parcels have equal probability of a land use (Fig. 2). For each land parcel the sum of the probabilities for each land use must sum to 1, and where a land use is not feasible on a land parcel its probability is 0.

$$\begin{array}{l} 1,\ 1,\ 1,\ 1 \\ \frac{1}{C_1},\ \frac{-1}{C_2},0,0 \qquad a_1 \qquad Q_{LU} \\ \left[0,\ \frac{1}{C_2},\ \frac{-1}{C_3},0\ \right]\left[\begin{smallmatrix}a_2\\a_3\end{smallmatrix}\right]=\left[\begin{smallmatrix}0\\0\end{smallmatrix}\quad\right] \\ \qquad\qquad\qquad a_4 \qquad 0 \\ 0,\ 0,\ \frac{1}{C_3},\ \frac{-1}{C_4} \end{array}$$

The economic returns of the land parcels are multiplied by the derived probabilities to get the Economic Importance value of each land use.

$$\begin{bmatrix} 1,1,1,1 \\ \frac{1}{C_1},\frac{-1}{C_2},0,0 \\ 0,\frac{1}{C_2},\frac{-1}{C_3},0 \\ 0,0,\frac{1}{C_3},\frac{-1}{C_4} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} Q_{LU} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Fig. 2. An example of the matrix algebra used in this case study to find the land use probability of each land parcel in a TLA. In this example there are four unique combinations of feasibility that include the land use. c_i is the area in the TLA in the ith combination layer that is feasible for a land use (accounting for any priority higher-value-land uses), Q_{LU} is the area in the TLA that is currently in the land use, and a_i are derived by solving the matrix. The required probabilities are a_i/c_i.

2.6. *Productive potential*

The Productive Potential indicator represents an integration of all the feasible land uses on each land parcel. This differs to standard approaches to Land Suitability which only consider the highest value land use (Food and Agriculture Organization, 1976; Mazahreh et al., 2019) regardless of whether this is practical from a socio-economic point of view, e.g., market demand, labour availability. In our schema, the PP indicator is equivalent to the probability weighted average returns for that land parcel where the land use options are equally distributed across all feasible land after allowing for more spatially constrained, higher value land use options. It is calculated by summing the Economic Importance layer for all feasible land uses on a land parcel, with the proviso that a land use is only included in the PP indicator calculation if its economic returns are higher than the probability weighted average return of land uses that are lower in the feasibility hierarchy. Conceptually this can be represented as ensuring that for increasingly versatile soils (i.e. supports more land use options) any additional feasible land use with lower economic returns does not decrease the value of PP indicator for that class relative to a less versatile soil. The need for this rule arises because the PP indicator calculation is valuing potential returns but not versatility, and it prevents the situation where the additional land uses that a soil is capable of supporting would otherwise result in a lower PP indicator.

3. Results

The results for each step in the process are binary for feasibility, and a set of continuous indices for the other steps. For Production and Economic Importance relative classes were used because units differed between land uses in the case of Production, and because the probabilities differ between classes and locations for the Economic Importance. These relative classes divide the production into five equal area classes. The continuous indices have been divided into classes for presentation purposes, with five classes used for the relative indices (Yield and Economic Importance) and ten classes for the absolute indices (Economic Returns and PP indicator).

3.1. *Feasibility*

The feasibility maps for each land use are shown in Fig. 3. They show a total of 17 million ha for sheep and beef, 15.6 million ha for forestry, 9.3 million ha for dairy, 7.1 million ha for arable, 0.9 million ha for horticulture (including flatland viticulture), and 2.3 million ha for other viticulture (Table 1). Current land uses occupy between 3% (other viticulture) and 47% (sheep and beef) of their feasible area.

3.2. *Yield*

In Fig. 4 we show Yield as relative production with each of the land uses divided into five production classes of equal area. Dairy and sheep and beef show pasture production, arable shows wheat yield, other viticulture shows grape yield, and horticulture varies spatially between yields for vegetable, pipfruit and viticulture in kg of product/ha. The yields generally correlate well with known current yields for horticulture, arable, viticulture and forestry, although the regression equation for pasture results in overestimation of pasture yields in high rainfall areas such as the West Coast of the South Island, indicating that further work is required to calibrate this function.

3.3. *Economic returns*

Fig. 5 shows the potential economic returns (operating profit after capital/ha) from each land use across their feasible area. The maps indicate the relatively higher returns from the horticulture/viticulture and dairy land use.

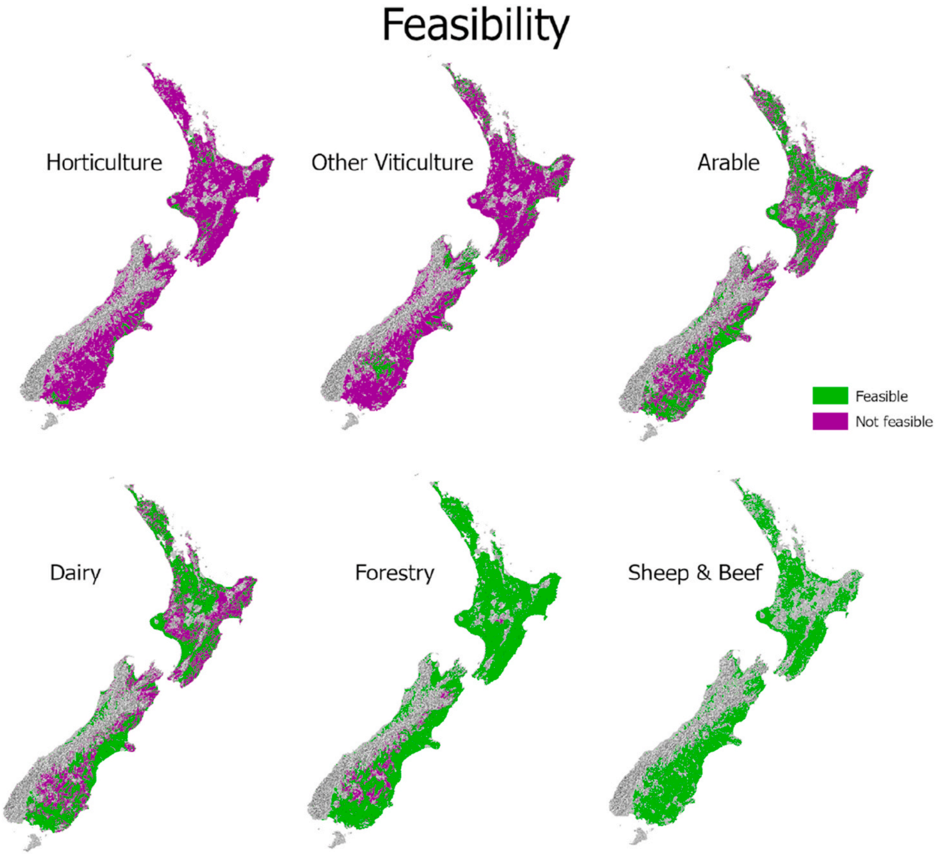

Fig. 3. Feasibility by land use. Grey areas are national parks and reserves and other locations with no data.

Table 1
Area of feasible area and current area for each land use.

Land Use	Feasible Area (ha)	Current Area (ha)	Proportion of feasible land occupied
Arable	7,096,350	271,975	4%
Dairy	9,275,125	2,058,425	22%
Forestry	15,592,750	2,077,250	13%
Horticulture	938,375	211,325	23%
Other viticulture	2,321,250	64,000	3%
Sheep and beef	17,025,875	7,987,550	47%

Table 2 shows the estimated mean economic returns for each land use as estimated in this paper, compared with the mean from national industry survey data, adjusted for capital charge. This shows that for arable, other viticulture and dairy the mean return across the feasible area is less than the mean economic returns from industry survey data, while for sheep and beef the inverse is true. This suggests that the former land uses are focused on the more productive areas within their potential feasible range, while the sheep and beef land use is excluded from the better part of its feasible range by higher value land uses. The only national data on variability of economic returns was obtained from Dairy (2020) for 2018/2019. These data (Table 3) indicate that the industry survey national range in quartile average returns (standardised for capital) is much wider than of the estimated economic returns from this analysis. This is likely to be because the estimated data assumes average management with a range of biophysical conditions, while the industry survey data reflects both the range of management and biophysical conditions.

3.4. *Economic importance*

Maps of relative economic importance divided into five classes are shown in Fig. 6. These show that those land uses which tend to be more prevalent are of higher economic importance than land uses which are of low prevalence in an area, even though the returns from low prevalence land uses may be high. Dairy is economically very important to the Waikato (mid-upper North Island) and Taranaki (west coast of the North Island). Horticulture has pockets of land where high returning land uses occupy a large proportion of their feasible area, and where the economic importance is high. Because horticultural areas are generally small relative to other land uses, they do not appear prominently on the graphic, but are apparent for other viticulture in the north of the South Island (Marlborough) and inland parts of the southern areas of the South Island (inland Otago).

Apart from sheep and beef, the current area for each land use tends to be in the Medium to High areas of economic importance for that land use (see Supplementary Information). This is partly a reflection of the way Economic Importance is calculated in this scenario, which is calculated using current area/feasible area as a probability of occurrence. However, the prevalence of current land use in areas of high Economic Importance also reflects the underlying biophysical drivers of that provide for high productivity and returns to the land use in those locations. There may also be some contribution from the co-location of specialist land uses for infrastructure or labour force reasons.

3.5. *Productive potential*

The estimates of Productive Potential divided into 10 classes of equal area are shown in Fig. 7 below. In our analysis calculation of the PP indicator produces a range of values between 0 and 25,380 with a mean of 594 and a median of 437 indicating some skewness to the data. The

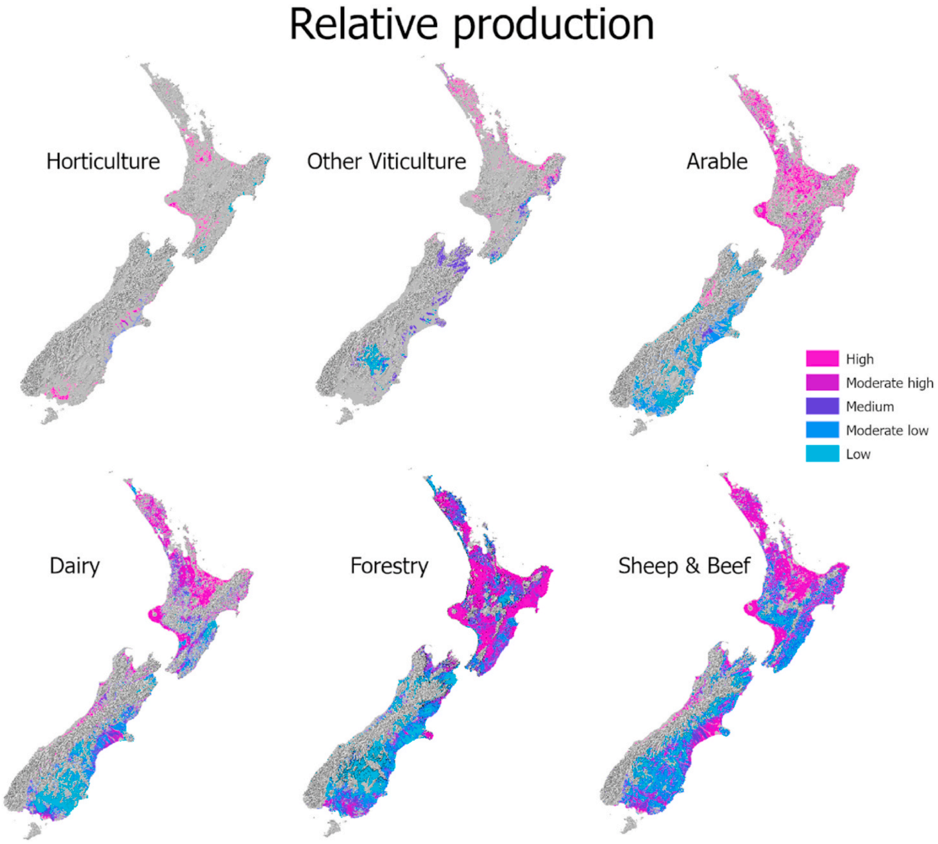

Fig. 4. Index of yield (Relative production) estimates by land use. Grey areas are national parks and reserves and other locations with no data. The dryland yield is shown for dryland areas and the weighted mean irrigated/dryland for irrigable areas. Class definitions and units are provided in the Supplementary Information.

incidence of Class 1 is driven strongly by the prevalence of horticulture, which is the highest value land use, particularly in regions such as the Bay of Plenty, Hawke's Bay and Canterbury where horticulture and viticulture has high Economic Importance – high value and high probability of occurrence. Class 3 may include some areas where horticulture occurs, but it appears to be dominated by areas which are capable of very high production and returns for dairy land use (which is typically the next most profitable land use), and have a high prevalence of dairy, for example Taranaki and Waikato. Areas such as inland Otago have a greater prevalence of lower PP indicator Classes 9 and 10, representing the dominant potential of the land for low production dryland sheep and beef, but the pockets of very high PP indicator in Otago reflect the land with potential for viticulture in the key wine growing areas.

Current land use for horticulture is mainly located in PP indicator Classes 1–4, while dairy is mainly located in PP indicator Classes 3–7 (Table 4). Forestry and sheep and beef occur mainly in the lower half of the PP indicator classifications (5–10). Arable requires highly productive soils but occurs mainly on PP indicator Classes 5–8. This appears to be driven by ~70% of arable land use being in Canterbury. Canterbury has some high-quality soils suitable for arable, but its location on the east coast of the South Island means it experiences dry summers and requires irrigation for full productivity. Because irrigation is in limited supply, and because arable is a relatively (to dairy and horticulture) low value land use, the assigned value of the high-quality soils, which incorporates both its dryland and irrigated productivity, is lower in Canterbury than the equivalent soil in the wetter North Island. This illustrates a key feature of the PP indicator approach which incorporates a wide range of biophysical and socioeconomic factors.

4. Discussion

4.1. Validity

Testing the validity of the PP indicator and its constituent layers is not straightforward because they do not necessarily correspond directly to conditions that are observable through available data. The PP indicator correlates well with the pattern of current land use. Horticulture, which is higher returning and tends to require more specialised conditions, tends to be concentrated on higher PP indicator classes, and the remaining land uses occur in a pattern that we would expect given their requirements and returns. Only for arable land use, which has become concentrated in one region of New Zealand for climatic, market, infrastructure and expertise reasons, does current land use not correlate with the higher PP indicator values that might be expected from its more specialised growing requirements. Further consideration that includes the utility of the indicator in different contexts will be required before a conclusion on its validity can be reached.

However, some of the other layers were not able to be validated beyond simple comparisons. These include: the Feasibility and Productivity layers because the available data was used to calibrate the model; the Economic Returns layer because the indicator covers all feasible land while existing economic data tends to be derived from the higher performing parts of the feasible land; and Economic Importance because there is no comparable data against which to validate the indicator. The analysis did identify areas where the modelling has not performed well, and these will be improved through future iterations.

4.2. Utility

The process outlined here specifies a method for estimating the PP indicator that we believe is appropriate given data constraints, at least in

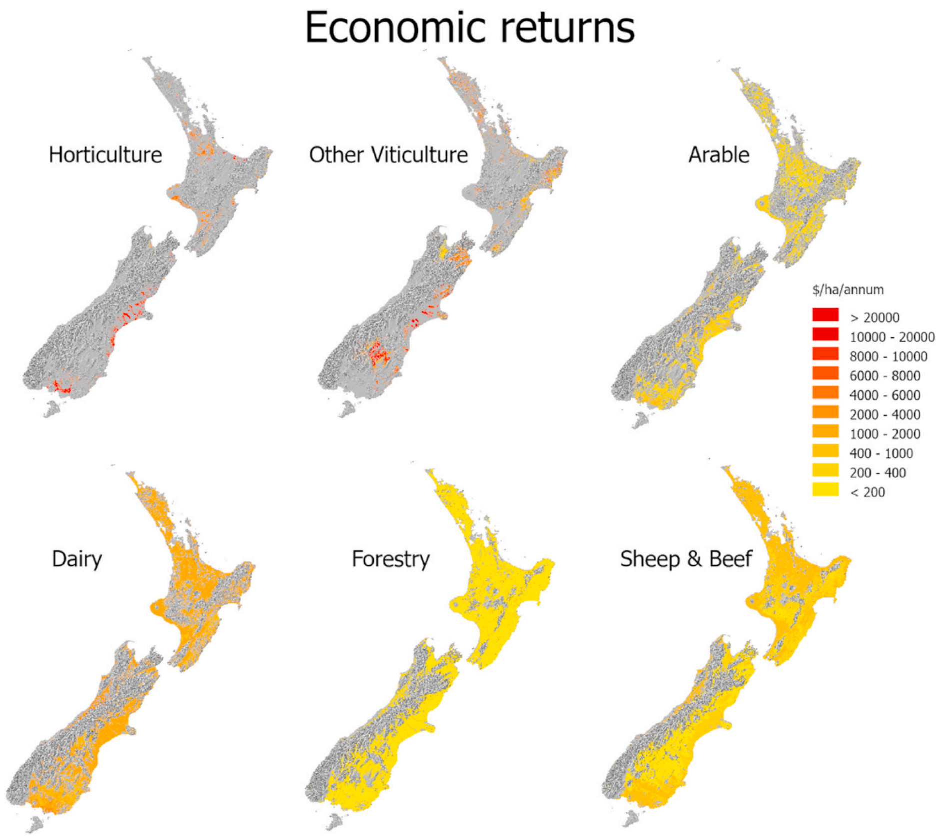

Fig. 5. Economic returns by land use (operating profit after capital charge $/ha/annum). Grey areas are national parks and reserves and other locations with no data.

Table 2
Comparison of estimated economic return with survey data ($/ha/year).

Land use	Estimated mean from Economic Return layer ($/ha/year)	Estimated post capital mean from industry survey data ($/ha/year)
Arable	60	349
Dairy	1274	1561
Forestry	94	
Horticulture	5196	
Other viticulture	4142	8943
Sheep and beef	363	−29

Table 3
Comparison of *variability* in dairy economic returns ($/ha/year).

Comparison of estimated economic return with survey data ($/ha/year)Quartile	Estimated mean from Economic Return layer ($/ha/year)	Estimated post capital mean from dairy industry survey data ($/ha/year)
Bottom quartile	887	240
Lower bottom quartile	1152	1081
Lower upper quartile	1316	1749
Upper quartile	1758	2763

this New Zealand example. It attempts to understand the land parcel's potential for economic contribution independently of activities currently undertaken on a parcel of land. It also generates a set of layers of information that have utility in addition to the integrated PP indicator. For example, the Yield and Economic Return layers may appeal to investors seeking to identify the best place to undertake a specific activity, while a combination of Feasibility, Yield, and Economic Return layers could be used by a landowner to identify potential activities on their property.

The Economic Importance layer and eventual PP indicator are likely to be more suited to strategic and planning purposes than for individual landowners. We envisage Economic Importance being used by planners to understand where land could be protected for specific land uses, particularly when combined with scenarios such as climate change. An issue being actively considered by central government in New Zealand (Ministry for Primary Industries and Ministry for the Environment, 2019; Parker, 2018) is the protection of soils suitable for horticulture from urban encroachment. Identifying the Economic Importance of land for horticulture under future scenarios of climate change and demand would greatly assist in identifying where they should be protected.

In New Zealand it is difficult for planners to direct where specific land uses should occur, as the planning regime is permissive rather than prescriptive. In this context the PP indicator is likely to be of highest utility in identifying where the greatest returns could be achieved by allowing for intensification of land use rather than where specific intensive land uses could occur. When combined with the Relative Contribution and Pressure indicators in the LUS system (McDowell et al., 2018), it would identify areas which are most suitable for allowing intensification by providing for a direct comparison of the economic and environmental outcomes (Cox et al., 2013; Duhon et al., 2015). This has been attempted using the LUC (Horizons Regional Council, 2007), but was based solely on pasture as a potential land use. Furthermore, because LUC measures versatility not productivity or impacts, and because it is non-metric and categorical, its use is problematic in this context.

The PP indicator approach here extends the categorical approaches of land suitability which use a set of rules to define where a land use can be undertaken (Klingebiel and Montgomery, 1961). Kidd et al. (2015) converted the suitability categories to a gross margin value. A quantitative map of potential gross margin was achieved by doing this for twenty crops and taking the median gross margin value. However, this

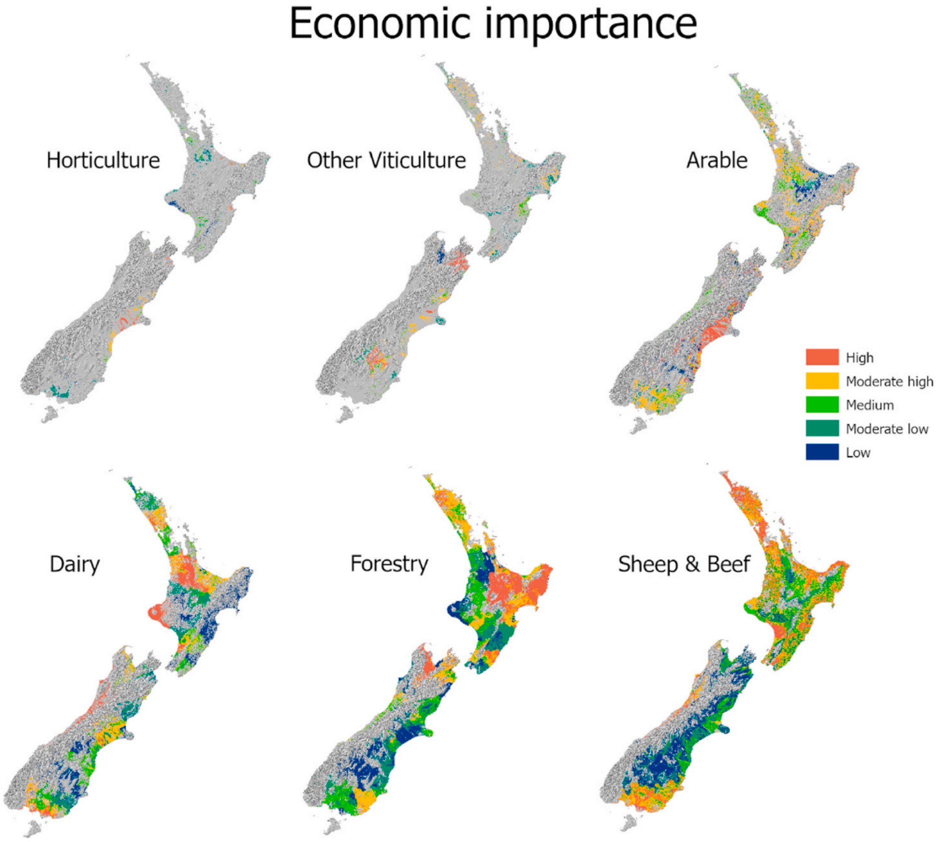

Fig. 6. Index of relative Economic importance by land use. Grey area are national parks and reserves and other areas with no data. Class definitions are provided in the Supplementary Information.

approach is not continuous because it uses a categorical approach to suitability to underpin the classification, does not allow for detailed differentiation between parcels, and does not account for any socio-economic limits or constraints on land use options.

4.3. Future modification

The PP indicator calculation approach is preliminary, and we envisage further development of the concept. Next steps are to change the scenario assumptions, allowing the impact of changes in climate, future market, or policy conditions to be explored. We have consulted with landowners, councils, rural lenders and central government, and the alternate scenario that most stakeholders have shown an interest in is the impact of climate change on the productive potential of a land parcel. However, other scenario examples may be relevant such as the impact of changes to labour availability or availability of processing infrastructure. The alternate scenario(s) would also be applied to the other LUS indicators so that production and environmental trade-offs can be assessed.

The quantitative approach to the PP indicator outlined here also enables additional metrics to be calculated. For example, the expression of PP indicator/Relative Contribution provides an index of the contribution to economic welfare per unit of contaminant delivered at a point of interest, with greater PP indicator/Relative Contribution being more desirable. Economic-environmental metrics already exist such as $ or kg of milk solids produced per kg of nitrogen or phosphorus lost to surface water (McDowell, 2014; Monaghan and De Klein, 2014). However, these do not consider that losses in different locations have different impacts on, for example, waterbodies, nor do they consider the potential for alternative land uses on a land parcel and within a catchment.

The approach and definitions tested here do not represent the value of versatility in soils, just of the potential land uses. The PP indicator definition must compensate for the fact that additional land uses on more versatile soils might have lower value. In New Zealand this arises because arable land uses, which are often lower profit than dairy land use, requires a more versatile soil than does dairy. We should consider the possibility that the ability to undertake more land uses has a value that is independent of the value of the currently highest-value land uses. This additional value may arise from the potential for alternative options if conditions change in the future, or from the portfolio effect of multiple land uses providing a diversification that reduces the variability of income streams. Versatility may provide resilience that is valuable for society as it deals with an increasingly uncertain future, such as in a changing climate (Bock et al., 2018; Dunnett et al., 2018). We need to investigate this further to understand and, if necessary, represent its value. In contrast, the NZLRI LUC categorisation is defined primarily by the versatility of the land and soil, but also provides no indication of the value attached to that versatility.

4.4. Limitations

The example provided here is a prototype exercise and relies on data that is spatially coarse. This is suitable for national to catchment scale assessment, but more work would be required to provide the level of certainty required to make land uses changes at an enterprise scale. Further refinement and improvement of the feasibility classification, and the production and economic data, will improve the accuracy of the PP indicators and enable their use at finer scales of resolution. In particular, the arable, and horticultural land uses are based on a limited number of typologies and need further refinement. Broadening the factors considered in the calculation of the PP indicator or generating new indicators to include measures of social and cultural wellbeing along with the other indicators of LUS will further improve the usefulness to a range of stakeholders and decision makers.

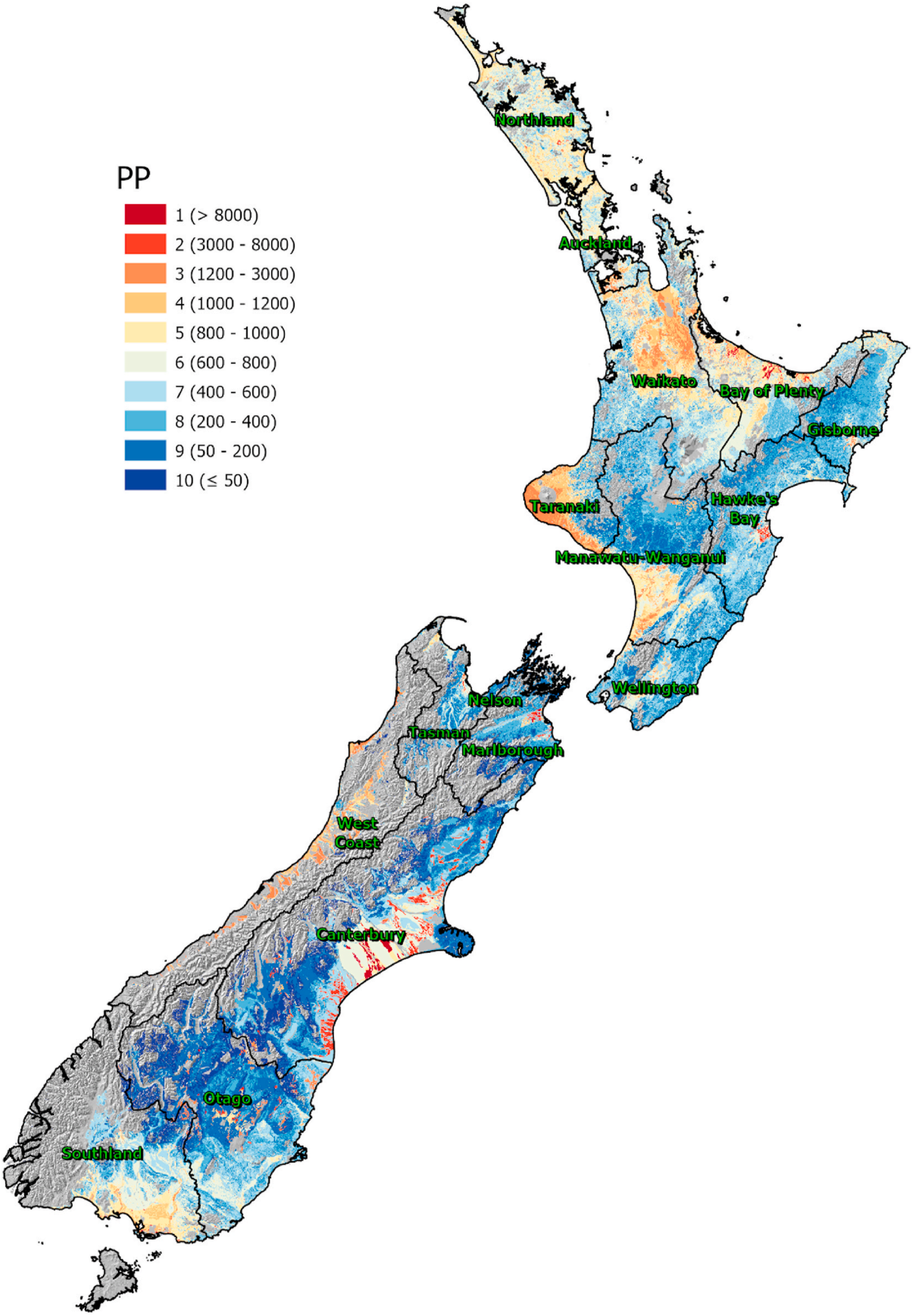

Fig. 7. Estimation of PP indicator. Grey area are national parks and reserves and other areas with no data.

The Economic Returns, Economic Importance and PP indicator layers are dependent on information that will change over time as market and socio-economic conditions. While we have used longer term averages as a way of smoothing year to year variability, these indicators will require regular updating to remain relevant. The Feasibility and Production layers rely on more stable biophysical factors, but because technologies and climate changes over time, these will need to be updated over a longer time scale.

5. Conclusions

The PP indicator provides a mechanism whereby the economic value of land can be represented in a way that is compatible with the other indicators in the LUS system, and within the constraints of the study has shown some validity. It also allows socio-economic constraints or opportunities of different land use options to be included. The approach tested here provides for flexibility to meet the needs of several users and

Table 4
Proportion of current land use by PP indicator class.

Land Use	1	2	3	4	5	6	7	8	9	10	Total area (ha)
Arable	2%	5%	1%	2%	11%	40%	26%	9%	4%	0%	271,975
Dairy	0%	1%	13%	20%	23%	24%	12%	5%	1%	0%	2,058,425
Forestry	0%	0%	0%	2%	11%	22%	22%	27%	14%	1%	2,077,250
Horticulture	24%	39%	17%	6%	4%	6%	3%	0%	0%	0%	211,300
Other Viticulture	0%	1%	0%	16%	16%	24%	24%	12%	6%	1%	64,000
Sheep and Beef	0%	1%	2%	3%	8%	16%	20%	24%	21%	5%	7,987,550

of different contexts. We consider that the PP indicator is likely to be most useful as a general indicator of productive potential, but the full range of layers represented in the PP approach provides information that will be useful for a range of situations and decision contexts. The PP approach overall requires expansion beyond the prototype phase in data terms, and potentially can be broadened to include social and cultural indicators of wellbeing that arise from the productive use of land.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.indic.2021.100128.

Code and data availability

The non-proprietary code and data used to generate the PP indicator are available at www.figshare.com (https://doi.org/10.6084/m9.figshare.14691624.v1).

References

AgResearch, 2016. OVERSEER® Nutrient Budgets, 6.2.2. AgResearch - Fertiliser Association of New Zealand - Ministry for Primary Industries, Hamilton, New Zealand.

Aqualinc, 2009. Estimation of Seasonal Irrigation Water Use. Prepared for Irrigation New Zealand.

Beef and Lamb New Zealand, 2018. Farm classes, Wellington, New Zealand. https://beeflambnz.com/data-tools/farm-classes.

Bloomer, D., 2011. Versatile Soils - Productive Land: Report for Hawke's Bay Regional Council. Page Bloomer Assocaties Ltd, Hastings, New Zealand, p. 37.

Bock, M., Gasser, P.-Y., Pettapiece, W.W., Brierley, A.J., Bootsma, A., Schut, P., Neilsen, D., Smith, C.A.S., 2018. The land suitability rating system is a spatial planning tool to assess crop suitability in Canada. Front. in Env. Sci. 6.

Bright, J., Ford, S., Irving, C., 2018. Water Allocation Economic Analysis: Land/Water Use Modelling. Aqualinc Research contract report prepared for Ministry for the Environment C17020, Christchurch.

Coriolos, 2016. Growing the North: Market Opportunities for Irrigated Agricultural Produce from Northern Western Australia Perth, WA, p. 150.

Cox, T.J., Rutherford, J.C., Kerr, S.C., Smeaton, D.C., Palliser, C.C., 2013. An integrated model for simulating nitrogen trading in an agricultural catchment with complex hydrogeology. J. Environ. Manag. 127, 268–277.

Dairy, N.Z., 2017. Dairy NZ Economic Survey 2015-16. Dairy NZ, Hamilton. Retrieved June 15, 2019, from. https://www.dairynz.co.nz/media/5791415/dairynz-economic-survey-2017-18.pdf.

Dairy, N.Z., 2019. Dairy NZ Economic Survey 2017-18. Dairy NZ, Hamilton. Retrieved June 15, 2019, from. https://www.dairynz.co.nz/media/5791415/dairynz-economic-survey-2017-18.pdf.

Dairy, N.Z., 2020. Dairy NZ Economic Survey 2018-19. Dairy NZ, Hamilton. Retrieved November 11, 2020., from. https://www.dairynz.co.nz/media/5791415/dairynz-economic-survey-2018-19.pdf.

Dark, A., Birendra, K.C., Kasima, A., 2017. National Irrigated Land Spatial Dataset: Summary of Methodology, Assumptions and Results. Aqualinc, Wellington, New Zealand, p. 48.

Doorenbos, J., Kassam, A.H., 1979. Yield Response to Water, Irrigation and Drainage Paper No. 33, Rome, Italy, p. 374.

Duhon, M., McDonald, H., Kerr, S., 2015. Nitrogen Trading in Lake Taupo. Motu Economic and Public Policy Research, Wellington, New Zealand, p. 57.

Dunnett, A., Shirsath, P.B., Aggarwal, P.K., Thornton, P., Joshi, P.K., Pal, B.D., Khatri-Chhetri, A., Ghosh, J., 2018. Multi-objective land use allocation modelling for prioritizing climate-smart agricultural interventions. Ecol. Model. 381, 23–35.

El Baroudy, A.A., 2016. Mapping and evaluating land suitability using a GIS-based model. Catena 140, 96–104.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O/'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Food and Agriculture Organization, 1976. A Framework for Land Evaluation. Food and Agriculture Organization, Rome, Italy, p. 66.

Gasser, P.Y., Smith, C.A.S., Brierley, J.A., Schut, P.H., Neilsen, D., Kenney, E.A., 2016. The use of the land suitability rating system to assess climate change impacts on corn production in the lower Fraser Valley of British Columbia. Can. J. Soil Sci. 96, 256–269.

Goldstein, J.H., Caldarone, G., Duarte, T.K., Ennaanay, D., Hannahs, N., Mendoza, G., Polasky, S., Wolny, S., Daily, G.C., 2012. Integrating ecosystem-service tradeoffs into land-use decisions. Proc. Natl. Acad. Sci. Unit. States Am. 109, 7565–7570.

Holzworth, D., Huth, N.I., Fainges, J., Brown, H., Zurcher, E., Cichota, R., Verrall, S., Herrmann, N.I., Zheng, B., Snow, V., 2018. APSIM Next Generation: overcoming challenges in modernising a farming systems model. Environ. Model. Software 103, 43–51.

Horizons Regional Council, 2007. One Plan: the Consolidated Regional Policy Statement, Regional Plan and Regional Coastal Plan. Prepared by Horizons Regional Council (The Trading Name of the Manawatu-Wanganui Regional Council). http://www.horizons.govt.nz/publications-feedback/one-plan. (Accessed 4 December 2020). for the Manawatu-Wanganui Region.

Kidd, D., Webb, M., Malone, B., Minasny, B., McBratney, A., 2015. Digital soil assessment of agricultural suitability, versatility and capital in Tasmania, Australia. Geoderma Regional 6, 7–21. https://doi.org/10.1016/j.geodrs.2015.08.005.

Kimberley, M.O., Watt, M.S., Harrison, D., 2017. Characterising prediction error as a function of scale in spatial surfaces of tree productivity. NZ J. For. Sc. 47, 19, 2017.

Kingi, T., 2013. Cultural bastions, farm optimisation and tribal agriculture in Aotearoa (New Zealand). In: Michalk, D.L., Millar, G.D., Badgery, W.B., Broadfoot, K.M. (Eds.), Proc. 22nd Intl Grassland Congress. Revitalising Grasslands to Sustain Our Communities. New South Wales Department of Primary Industry, Orange, NSW, pp. 1898–1904.

Klingebiel, A.A., Montgomery, P.H., 1961. Land-capability Classification. Soil Conservation Service. USDA, Washington D.C.

Land information New Zealand, 2018. New Zealand Road Centrelines. Land Information New Zealand, Wellington, New Zealand.

Lara Estrada, L., Rasche, L., Schneider, U.A., 2017. Modeling land suitability for Coffea arabica L. in Central America. Environ. Model. Software 95, 196–209.

Liebig, M.A., Herrick, J.E., Archer, D.W., Dobrowolski, J., Duiker, S.W., Franzluebbers, A.J., Hendrickson, J.R., Mitchell, R., Mohamed, A., Russell, J., Strickland, T.C., 2017. Aligning land use with land potential: the role of integrated agriculture. Agric. & Env. Letters 2.

Lynn, I.H., Manderson, A.K., Page, M.J., Harmsworth, G.R., Eyles, G.O., Douglas, G.B., Mackay, A.D., Newsome, P.J.F., 2009. Land use capability survey handbook. In: A New Zealand Handbook for the Classification of Land, third ed. AgResearch, Landcare Research, GNS Science, Hamilton, Lincoln, Lower Hutt.

MacLeod, C.J., Moller, H., 2006. Intensification and diversification of New Zealand agriculture since 1960: an evaluation of current indicators of land use change. Agric. Ecosyst. Environ. 115, 201–218.

Mazahreh, S., Bsoul, M., Hamoor, D.A., 2019. GIS approach for assessment of land suitability for different land use alternatives in semi arid environment in Jordan: case study (Al Gadeer Alabyad-Mafraq). Inf. Proc. Agric. 6, 91–108.

McDowell, R.W., 2014. Estimating the mitigation of anthropogenic loss of phosphorus in New Zealand grassland catchments. Sci. Total Environ. 468–469, 1178–1186.

McDowell, R.W., Lucci, G.M., Peyroux, G., Yoswara, H., Brown, M., Kalmakoff, I., Cox, N., Smale, P., Wheeler, D., Watkins, N., Smith, C., Monaghan, R., Muirhead, R., Catto, W., Risk, J., 2015. An assessment of MitAgator: a farm-scale tool to estimate and manage the loss of contaminants from land to water. Transactions of the ASABE 59, 537–543.

McDowell, R.W., Snelder, T., Harris, S., Lilburne, L., Larned, S.T., Scarsbrook, M., Curtis, A., Holgate, B., Phillips, J., Taylor, K., 2018. The land use suitability concept: introduction and an application of the concept to inform sustainable productivity within environmental constraints. Ecol. Indicat. 91, 212–219.

Meyfroidt, P., 2018. Trade-offs between environment and livelihoods: bridging the global land use and food security discussions. Global Food Security 16 (March), 9–16. https://doi.org/10.1016/j.gfs.2017.08.001.

Ministry for Primary Industries, Ministry for the Environment, 2019. Valuing Highly Productive Land: A Discussion Document on a Proposed National Policy Statement for Highly Productive Land, Wellington, New Zealand, p. 72.

Monaghan, R.M., De Klein, C.A.M., 2014. Integration of measures to mitigate reactive nitrogen losses to the environment from grazed pastoral dairy systems. J. Agric. Sci. 152, 45–56.

Monaghan, R., Manderson, A., Smith, C., Eikass, H., Burger, D., McDowell, R.W., 2021. Quantifying contaminant losses to water from pastoral landuses in New Zealand I. Development of a spatial framework for assessing losses at a farm scale. N. Z. J. Agric. Res. 64 (3) https://doi.org/10.1080/00288233.2021.1936572.

Morton, J.D., Roberts, A.H.C., 2016. Fertiliser Use on New Zealand Sheep and Beef Farms, fifth ed. Fertiliser Manufacturers' Research Association, Auckland, New Zealand. New Zealand.

Mueller, L., Schindler, U., Mirschel, W., Shepherd, T.G., Ball, B.C., Helming, K., Rogasik, J., Eulenstein, F., Wiggering, H., 2010. Assessing the productivity function of soils. A review. Agron. for Sust. Dev. 30, 601–614.

New Zealand Government, 2017. Resource Management (National Environmental Standards for Plantation Forestry) Regulations 2017. New Zealand Government, Wellington, New Zealand.

New Zealand Meteorological Service, 1983. Climate Regions of New Zealand. Publication No. 174., Wellington, New Zealand.

OECD, 2017. Reforming Agricultural Subsidies to Support Biodiversity in Switzerland. OECD Environment Policy Paper No. 8. ISSN 2309-7841.

Parker, D., 2018. April 19). Environment report highlights serious land issues. Wellington, New Zealand. Retrieved June 9, 2019, from. https://www.beehive.govt.nz/release/environment-report-highlights-serious-land-issues.

Plant, Food Research, 2015. Foundation for arable Research, AgResearch, landcare Research, DairyNZ, beef and Lamb NZ, deer industry NZ, New Zealand pork, horticulture NZ, environment Canterbury. Overview Report: Canterbury Matrix of Good Management Project, Christchurch, New Zealand, p. 379.

Renting, H., Rossing, W.A.H., Groot, J.C.J., Van der Ploeg, J.D., Laurent, C., Perraud, D., Stobbelaar, D.J., Van Ittersum, M.K., 2009. Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. J. Environ. Manag. 90, S112–S123.

Renwick, A., Dynes, R., Johnstone, P., King, W., Holt, L., Penelope, J., 2019. Challenges and opportunities for land use transformation: insights from the central plains water scheme in New Zealand. Sustainability 11, 4912. https://doi.org/10.3390/su11184912.

Roberts, A.H.C., Morton, J.D., 2009. Fertiliser Use on New Zealand Dairy Farms. New Zealand Fertiliser Manufacturers' Research Association, Auckland, New Zealand, p. 52.

Russ, J., Zavheri, E., Damania, R., Desbureaux, S., Escurra, J., Rodella, A.-S., 2020. Salt of the Earth: Quantifying the Impact of Water Salinity on Global Agricultural Productivity. Water Global Practice 9144. Policy Research Working Paper. World Bank, New York. https://documents1.worldbank.org/curated/en/284971581348972217/pdf/Salt-of-the-Earth-Quantifying-the-Impact-of-Water-Salinity-on-Global-Agricultural-Productivity.pdf.

Seyedmohammadi, J., Sarmadian, F., Jafarzadeh, A.A., McDowell, R.W., 2019. Development of a model using matter element, AHP and GIS techniques to assess the suitability of land for agriculture. Geoderma 352, 80–95.

Van Diepen, C.A., Van Keulen, H., Wolf, J., Berkhout, J.A.A., 1991. Land evaluation: from intuition to quantification. Adv. Soil Sci. 15, 139–204.

Watt, M.S., Kimberley, M.O., Dash, J.P., Harrison, D., 2017. Spatial prediction of optimal final stand density for even-aged plantation forests using productivity indices. Can. J. of For. Res. 47, 527–535.

Yao, R.T., Harrison, D.R., Velarde, S.J., Barry, L.E., 2016. Validation and enhancement of a spatial economic tool for assessing ecosystem services provided by planted forests. For. Pol. Econ. 72, 122–131.