Motu

Land-use modelling in New Zealand: current practice and future needs

Jo Hendy, Anne-Gaelle Ausseil, Isaac Bain, Élodie Blanc, David Fleming, Joel Gibbs, Alistair Hall, Alexander Herzig, Patrick Kavanagh, Suzi Kerr, Catherine Leining, Laëtitia Leroy, Edmund Lou, Juan Monge, Andy Reisinger, Jim Risk, Tarek Soliman, Adolf Stroombergen, Levente Timar, Tony van der Weerdan, Dominic White and Christian Zammit

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Author contact details

Levente Timar

Motu Economic and Public Policy Research

levente.timar@motu.org.nz

Dominic White

Motu Economic and Public Policy Research

dominic.white@motu.org.nz

Jo Hendy

Interim Climate Change Commission

jo.hendy@ICCC.mfe.govt.nz

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Motu Economic and Public Policy Research

PO Box 24390	info@motu.org.nz	+64 4 9394250
Wellington	www.motu.org.nz	
New Zealand		

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Abstract

New Zealand faces the challenge of using our land in ways that are not only resilient to future pressures and sustain our rural communities but also enhance our natural environment. For the public and private sectors to make robust land-use decisions under uncertainty, high-quality modelling tools and data are essential. The drivers of land-use decisions are complex and models provide a structured methodology for investigating these. While New Zealand is fortunate to have a range of different modelling tools, these have historically been used in a sporadic and ad hoc way, and underlying datasets are deficient in some areas. As the foundation for more strategic development of New Zealand's modelling capability, this paper profiles the main land-sector and farm- and production-related models and datasets currently applied in New Zealand. It also explores priority policy areas where modelling is needed, such as achieving emission reduction targets; managing freshwater, biodiversity and soil quality; and understanding the distributional impacts of policy options as well as climate change. New Zealand's modelling capability could be strengthened by collecting and sharing land-use data more effectively; building understanding of underlying relationships informed by primary research; creating more collaborative and transparent processes for applying common datasets, scenarios and assumptions, and conducting peer review; and conducting more integrated modelling across environmental issues. These improvements will require strategic policies and processes for refining model development, providing increased, predictable and sustained funding for modelling activity and underlying data collection and primary research, and strengthening networks across modellers inside and outside of government.

JEL codes

C31, D58, Q4, Q54

Keywords

Land-use, modelling, data management, policy analysis

Summary haiku

Land-use modelling
needs research, data, networks
and sustained funding

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1 Introduction

Both the public and private sectors face important strategic decisions about future land use. Globally, between 2013 and 2050, the demand for food is expected to increase by 50 percent (Food and Agriculture Organization, 2017). Over the same period, agricultural production systems will be coming under increasing pressure from a changing climate, changing global consumer preferences, and the emergence of potentially disruptive new technologies. The challenge in New Zealand is to use our land in ways that are not only resilient to those future pressures and sustain our rural communities, but also enhance our natural environment. The state of our water, biodiversity and soils depends on how we use our land, and all three areas have come under increasing pressure in the past decades (Ministry for the Environment & Stats NZ, 2015).

To make robust decisions in the face of an uncertain future, high-quality modelling tools and data are essential. New Zealand has a suite of "stand-alone" land-use-related models. These have been developed over time by government, research organisations and private-sector entities in different contexts and to address a range of environmental and economic issues and regulatory/reporting needs. However, when it comes to applying these tools to assess land-related issues and potential policy options, we have a history of using many of these tools in a sporadic and ad hoc way.

Motu Economic and Public Policy Research convened a workshop in Wellington, New Zealand, on 30 April 2018 that brought together some of the country's most expert researchers in the field of agricultural and resource economics from government, research institutions and the rural sector. The intent of the workshop was to begin designing a more strategic approach across the land-use modelling community. The workshop involved:

- sharing information on recent empirical research and modelling efforts relevant to assessment of land-use, agricultural and resource management issues;
- identifying further research and modelling needs for evidence-based decision-making on these issues by government and business, including gaps in the current suite of tools; and
- proposing priorities for future work.

Building on earlier work and workshop outcomes, as well as inputs from expert modellers across New Zealand, this report profiles land-use models and datasets in New Zealand and provides recommendations for strengthening the country's land-use modelling capability to better address key policy challenges. A companion report profiles energy- and cross-sector models relevant to the assessment of climate change mitigation policy options across the economy.

The structure of the report is as follows. Section 2 provides background information on why it is important to model land-use changes. It builds from an earlier report, *Understanding the practice of land use modelling*, which was based on a previous workshop and funded by the Parliamentary Commissioner for the Environment in 2013 (Anastasiadis et al., 2013). Section 3 provides a stocktake of some of the core land-use models in New Zealand and key datasets. Section 4 summarises the discussions relating to where the modelling community should focus its future efforts and how to improve the process of modelling in New Zealand. Finally, section 5 concludes with key insights.

While noting the critical importance of linking land-use models with other models and data, this report does not profile the full range of models and datasets applied in New Zealand in the areas of biodiversity, water, soil management and climate change impacts. This would be a useful area for future work.

2 Why are models used to understand land use?

A model is a simplified representation of reality that focuses on the key factors and (cause-and-effect) relationships of a phenomenon. Models describe how these factors are related, and the strengths of the different relationships. Constructing a model requires scientists to specify their assumptions explicitly, identify the phenomena they are concerned with and explain their methodology. By capturing the key agents, elements, processes and decisions, models enable complex systems and situations to be understood and complex problems to be solved.

In a way, everyone thinks like a modeller when making a decision in a complex situation. People select certain key details, make assumptions about details they have ignored, and apply intuition and judgement to inform their decisions. Scientists make these models more explicit.

Among scientists, the formal and frequent use of models is so well established that it is accepted without requiring explanation. However, to those outside the scientific community models can seem like black boxes, and the wide variety of available models generally causes confusion among people.

Land-use models provide a structured way to think about land use and a methodology for investigating land-use change and its impact on key environmental/economic/ecological values. These models are used to understand land use because the factors and decisions that determine land use and land-use change are complex and interrelated. This complexity arises from the decision process made by the individual land owners when determining land use, intensity and management practices, and from geographic variability, economic uncertainty and interactions among land owners.

Land owners combine cultural, social, personal, economic, geographic and regulatory information together in ways that are only partially understood. In addition, the values, attitudes and behaviours that guide decisions differ among people. These includes what purpose they have for using the land, what information they consider relevant, what emphasis they place on different types of information, and how they think about the future.

Land-use models aim to deepen understanding of how people decide where and how to use land. Some land-use models consider land use only in aggregate: how much of different types of land use (for example, dairy, forestry, residential) occurs in a given area. Other land-use models consider also the specific locations and configurations of different land uses and land-use intensities, and how they change over time.

There is a variety of land-use models because different models are required to answer different questions, to model different situations and to work at different levels of detail. These models make different assumptions, and use different data and methodologies. As land-use change is too complex for any one model to capture fully, using multiple models in combination can provide a more complete and robust understanding. In addition, cross-model comparisons can be used to help validate the different models. Hence, when used appropriately, the variety of available models should be seen as a strength rather than as a weakness.

Land-use models are often developed to inform government, community and industry stakeholders' decision-making by highlighting probable future outcomes, issues and opportunities. Models also inform the direction of research, provide tools to answer research questions, and express results in a repeatable and robust way that helps promote, but does not guarantee, better understanding of land-use change. While they can be subject to deliberate misuse (generally associated with a lack of understanding of each model's assumptions), they are an important part of doing good science. In general, the quality of a model and the robustness of its conclusions are tested within the scientific community before model results are made available to the wider society (through peer-review process). This helps ensure that modelling, and scientific activity in general, uphold the standards of rigor that are expected by the scientific community.

3 Stocktake: land-use modelling in New Zealand

New Zealand has a range of different models developed to address various land-use-related issues. We are aware that the Ministry for the Environment (MfE) has commissioned a stocktake of ecosystem services models, and while there is some crossover with that work here, we are looking specifically at land-use modelling. This section provides an assessment of the current tools that are available to analyse the impact of land-use policies on the way we use our land, focusing on agricultural/rural use. It contains six parts, as follows:

- an overview of core land-use models used in New Zealand;
- a more in-depth description of the land-use model LURNZ;
- another in-depth description of the land-use model NZ-FARM;
- an overview of some of the agricultural production models used in New Zealand;

- an overview of core datasets used by the modelling community; and
- opportunities to apply international models and datasets to New Zealand.

3.1 Overview of core land-use sector models

This section provides a high-level overview of some of the key models used for investigating land use and land-use change in New Zealand. Table 1 is taken from Anastasiadis et al. (2013) and classifies the land-use models based on the physical area they cover and the central methodology used.

Table 1: Land-use models

	Catchment	**Region**	**National**
Individual agents	ARLUNZ Waikato Multiple Agent Model*	Rural Futures MAS Model	—
Optimisation/best option	NManager*	LUMASS	NZ-FARM
Statistical/ amalgamated preferences	—	WISE*	LURNZ

* Models not currently in use

Source: Anastasiadis et al. (2013)

One class of models uses an individual decision-maker – or agent-based – method. These attempt to model the learning and preferences of individual agents (farmers). In these models, farmers' decisions may differ from those of their otherwise identical neighbours and may not be economically rational. The final outcome arises as a result of many decentralised decisions.

Another class of models uses an optimisation method, based on an assumption that decision-makers are always making an economically rational decision (and that the modeller can mimic that). In these models, profit or revenue is maximised given that the environmental or regulatory targets must be met.

A third class of models uses a statistical or amalgamated-preferences method. These draw on statistical relationships - identified in historical data - among land use, land-use change and geophysical and economic variables. In these models, the statistical relationships capture the combined decisions of many farmers at a regional or national level.

NZ-FARM and LURNZ, the only two models available at the national level, are detailed in the following sections. The remaining models in Table 1 have been described in Anastasiadis et al. (2013), and those descriptions have been included in the Appendix.

In addition to these models, a number of time series and computable general equilibrium (CGE) models exist. In response to scenarios with different economic conditions, these models predict variations in agricultural production and livestock numbers. From these predictions, changes in land use could be inferred. They do not produce spatially-explicit information. These include:

- the Pastoral Supply Response Model (PSRM) (Dake & Manderson, 2010; Gardiner & Su, 2003; Ministry of Agriculture and Forestry, 2008);
- several New Zealand-only CGE models (Lennox & van Nieuwkoop, 2010; NZIER & Infometrics, 2011; Stroombergen, 2010);
- three global models – GTAP, CliMAT-DGE and the model by Saunders and Catagay (Lennox et al., 2012; Rae & Strutt, 2011; Saunders & Cagatay, 2004); and
- the IMPACT model (from the International Food Policy Research Institute), a global partial equilibrium (PE) model focused on agriculture (Robinson et al., 2015), which is used at the New Zealand Institute of Economic Research.

3.2 Case study: LURNZ

Land Use in Rural New Zealand (LURNZ) is an economic model designed to consider the implications of environmental policies on future land use, production and greenhouse gas (GHG) emissions. LURNZ is a national-scale and spatially explicit model, meaning that it considers inputs and produces outputs across pixels of the country.

Broadly, LURNZ can be used to investigate empirically questions such as:

- What will happen if business continues as usual?
- What are the consequences of different policy options?
- What land-use outcomes are possible? Or what would it take to achieve our goals for land use? For example, is it possible to achieve net zero emissions through land-use change? What scale of land-use change would be needed?
- What strategies work consistently over a range of different possible future worlds? What strategies don't work?
- What are the indirect effects of achieving a policy goal? For example, policies focused on reducing GHG emissions in the agricultural and forestry sectors may result in land-use change. How would that land-use change impact biodiversity?

3.2.1 Who owns/operates the model?

LURNZ is an open-source model, developed by Motu Economic and Public Policy Research Trust, and the code is freely available to anyone who wishes to use it.

3.2.2 What is the scope of the model?

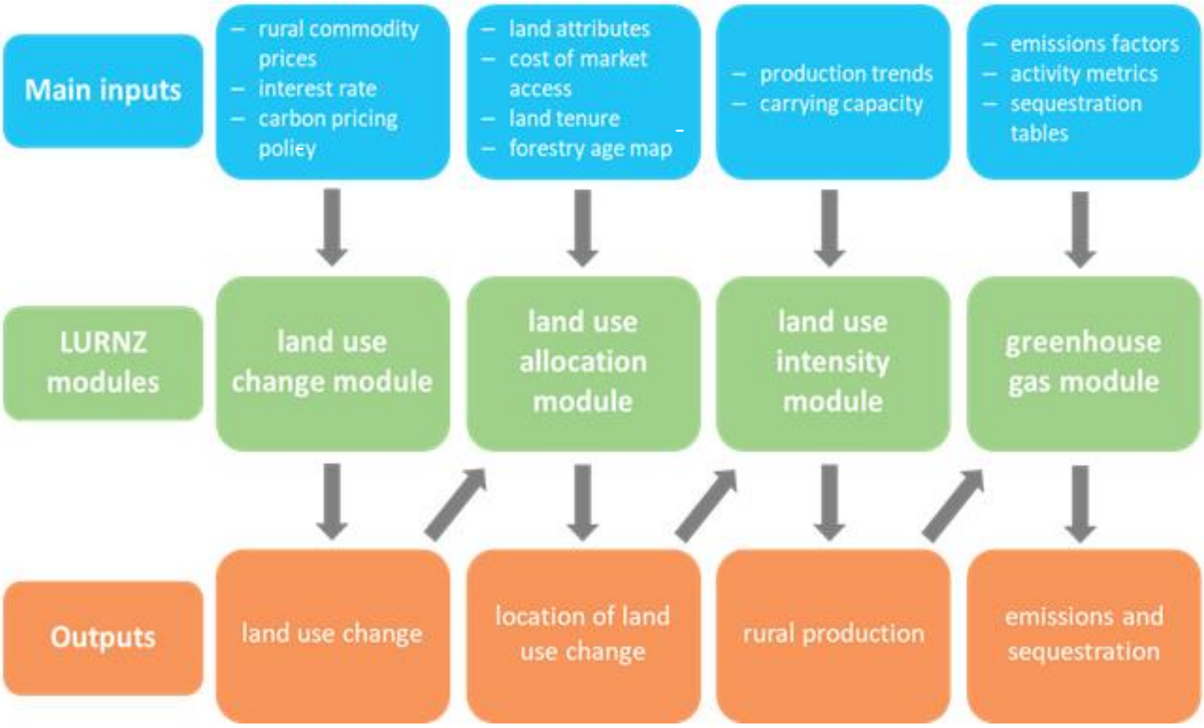
In response to changes in economic incentives, LURNZ can be used to simulate changes in dairy farming, sheep/beef farming, plantation forestry and scrub land uses. In addition, it can spatially map changes in horticultural land.

LURNZ includes all private rural land in New Zealand, and can produce annual maps of land use. The model runs forward from simulations from 2012 with an annual time step. The standard resolution is 25ha (1 grid square = 500 × 500m). A finer 1ha resolution has previously been used (1 grid square = 100 × 100m). The whole country (except Stewart Island/Rakiura and the Chatham Islands) is modelled.

3.2.3 How does the model work?

The foundation of LURNZ is provided by econometrically estimated models that establish the relationship between observed drivers of land use and land-use outcomes. LURNZ results are therefore largely driven by how land use has responded to its main drivers in the past. Simulations in LURNZ are implemented by running its main modules in a pre-determined sequence (see below). The overall amount of land-use change is projected in the land-use change module, while the spatial location of land-use change is simulated in the land-use allocation module. LURNZ also includes functions to simulate rural production[1] and emissions (or sequestration) conditional on the simulated land-use outcomes. These features are outlined in Figure 1.

Figure 1: Schematic representation of the LURNZ model



[1] Animal numbers are not explicitly forecast. For dairy, LURNZ projects milk solid production, and for sheep/beef, LURNZ projects the number of stock units, which are used as a proxy to production.

3.2.4 What datasets are used?

Table 2 contains all the datasets used by LURNZ. It includes data that were used in the estimation of parameters, in the construction of a base land-use map and for simulation purposes.

Table 2: Data used by LURNZ

Dataset	**Source**
Five-year nominal interest rate	Reserve Bank of New Zealand
Agricultural production surveys and censuses	Stats NZ
Average carrying capacity (CCAV)	Manaaki Whenua –Landcare Research
Dairy stocking rates	LIC and DairyNZ
Department of Conservation (DOC) land map	DOC
Emission factors for fertiliser	Reisinger & Clark (2016)[2]
Emission factors for livestock	Reisinger & Clark (2016)
Forest age map	Motu, derived data (see Land Use Change Module and Land Use Allocation Module)
Forest age-class distribution by Territorial Authority (TA)	National Exotic Forest Description (NEFD)
Greenhouse Gas Inventory	MfE
Herd composition	Meat and Wool Economic Service (now Beef + Lamb)
Land Cover Database v4 (LCDB4)	Manaaki Whenua –Landcare Research
Land Use Capability (LUC)	Manaaki Whenua –Landcare Research
Land Use Carbon Analysis System (LUCAS)	MfE
Land Use New Zealand 2011 map (LUNZ)	Manaaki Whenua –Landcare Research
Livestock Improvement Corporation regions	LIC and DairyNZ
Livestock population and slaughter data	Stats NZ
Map of ports in New Zealand	Motu
Map of supermarkets in New Zealand	Motu
Milk-solid prices	LIC and DairyNZ
Milk-solid production trends by region	LIC and DairyNZ
New Zealand Dairy Statistics Reports	LIC and DairyNZ
National Inventory Report yield tables for forestry	MfE
New Zealand Emission Unit prices	CommTrade
Other surveys	Meat and Wool Economic Service (now Beef + Lamb)
Overseas merchandise trade data	Stats NZ
Ownership and land tenure map	Manaaki Whenua –Landcare Research
Sheep/beef region classes	Meat and Wool Economic Service (now Beef + Lamb)
Situation and Outlook for Primary Industries (SOPI) prices	Ministry for Primary Industries
Slope	Manaaki Whenua –Landcare Research
Stock unit conversion factors	Meat and Wool Economic Service (now Beef + Lamb)
Territorial Authority boundaries	Stats NZ

[2] These emission factors incorporate expected efficiency improvements over time.

3.2.5 What are the strengths and limitations of the model?

This section contains two tables, outlining the main strengths and limitations of LURNZ, respectively.

Table 3: Strengths of LURNZ

Spatial	LURNZ can produce maps of land use and how it might change across New Zealand using 25ha pixels (1ha pixels have also been used). It can provide maps of productivity and forest age classes. Total land area is constrained within the model, so the model will not predict more production than is feasible with the land available. If desired, LURNZ can also constrain sub-areas in simulations.
Dynamic	LURNZ steps forward annually, which allows us to model changes in policy direction or economic conditions at different points along a pathway. LURNZ also models adjustment times, taking into account the length of time that it actually takes for land use to change across the country. It captures the fact that some landowners will change faster than others, and that complete adjustment can take a long time.
Interactions among land-use sectors	LURNZ models how changing economic conditions for one land use impact on another. For example, if beef prices go up, then some beef farmers might convert forestry land. If log wood prices rise, the opposite might occur. In a similar way, LURNZ can also model the impacts of different types of government regulations. Different regulations will also change relative economic conditions.
Observed behaviour seen in the past	LURNZ does not model landowner decisions explicitly, but instead is based on empirical estimates of relationships, over time, between aggregate land uses and commodity prices (Kerr & Olssen, 2012); and also relationships, over space, between land-use and land characteristics (Timar, 2011). This is a strength because how landowners make decisions is only partially understood. Basing the modelling on historical responses allows us to capture the different values, attitudes and behaviours that guide current decisions. This is also a limitation if there is a change in behaviour over time – see Table 4 regarding large transformations and new innovations.
Validated	The model's underlying datasets and processes have been validated (Anastasiadis et al., 2014), and its results are consistent with data and trends at the national scale, including New Zealand's Greenhouse Gas Inventory (Timar & Kerr, 2014). [3]

Table 4: Current limitations of LURNZ

Costs and jobs	LURNZ cannot model the total cost of a policy, its impact on employment or its impact on environmental factors. In the past, however, LURNZ studies have been linked to a CGE model to provide this information.
Changing land management practices	LURNZ is limited in regard to changing land management practices and does not endogenously model land management responses to price. This is instead dealt with through exogenous assumptions.
Large transformations and new innovations	LURNZ can consider innovation in only a limited way. This is because it is built on past responses, and so empirical relationships cannot be estimated for new innovative land uses. Similarly, results from LURNZ must be interpreted cautiously when considering large transformations on a scale not seen in the historical data.
Spatial allocation module	This has been estimated from cross-sectional data only. If longitudinal data were available, these would provide a much more robust set of relationships.

[3] There have been a number of significant changes to the inventory since 2014, which could mean that another validation exercise is necessary. However, recent modelling work has shown that current simulated values are close to inventory numbers (New Zealand Productivity Commission, 2018).

Forestry	The harvest age is exogenously determined. There is currently no responsiveness in harvest age to changes in carbon prices. LURNZ also cannot anticipate potential for permanent carbon farming.
Water availability and ecological impacts	LURNZ does not take into account irrigation or model freshwater reforms. Freshwater reforms are currently dealt with as exogenous constraints on expansion of intensive land uses and water constraints are currently dealt with through national-level assumptions.
Horticulture	This is not price responsive and is very aggregated.
Base map	The base map is constructed from land-use maps that are more than five years old. The current base map dates from 2012.

3.2.6 What linkages are there to other modelling work?

LURNZ has been linked with the Catchment Land Use for Environmental Sustainability (CLUES) water-quality model, to investigate how land-use changes might affect future water quality. This work was contracted by the Parliamentary Commissioner for the Environment and was used in the report *Water quality in New Zealand: land use and nutrient pollution* (Parliamentary Commissioner for the Environment, 2013).

In a consortium with Vivid Economics, Concept Consulting and Motu, LURNZ has been linked to a model of the energy and transport sectors. This work was carried out for the Productivity Commission as part of its Low Emissions Economy Inquiry in 2017–18. The work involved modelling to explore what is possible in terms of New Zealand's GHG targets, and to identify opportunities and risks relating to different policy and investment strategies in response to climate change (New Zealand Productivity Commission, 2018).

To support work by the government's Biological Emissions Reference Group, LURNZ has been linked to an economy-wide CGE model run by Infometrics, to estimate the wider economic impacts of land-use change projections, and has been run alongside NZ-FARM for comparison. This work is forthcoming.

3.2.7 What questions have been looked at in the past?

Questions investigated in the past include:

- What are the potential impacts of policies designed to alter land-use decisions – in particular, the New Zealand Emissions Trading Scheme (NZ ETS)?
- How is land use likely to change in New Zealand under different scenarios of price, policy and (potentially) yield?
- Where are these changes likely to occur?
- What would the production and GHG impacts of these changes be?
- How will these changes affect future water quality (linked to CLUES)?
- How might land use, food production, policy costs and GHG emissions be distributed regionally/nationally/by sector/between Māori and freehold land?

3.2.8 What areas are there for future development?

Key priorities for future development include:

- updating the base land-use maps;
- a more detailed forestry model, including harvest-price responsiveness and different composition of species;
- more detailed horticulture modelling, including price responsiveness and disaggregated crops;
- improving the ability of LURNZ to model new innovations and large land-use transformations; and
- improving the empirical basis for modelling land-use transitions spatially.

3.2.9 Bibliography of recent work

See Table 13.

3.3 Case study: NZ-FARM

3.3.1 Who owns/operates the model?

Manaaki Whenua – Landcare Research owns and operates the NZ-FARM model. The initial funding for NZ-FARM was through research funding from the New Zealand Foundation for Research, Science and Technology. Subsequent funding from the Sustainable Land Management and Climate Change Programme (SLMACC) of the Ministry for Primary Industries (MPI) was used to expand and enhance model capability. Manaaki Whenua – Landcare Research has led the development of NZ-FARM, with advice and support also being provided by the United States Department of Agriculture Economic Research Service (USDA-ERS). The NZ-FARM modelling structure is based on the USDA-ERS REAP model. Ongoing support and development of NZ-FARM have been provided through internal funding from Manaaki Whenua – Landcare Research (Strategic Science Investment Fund funding), other Ministry of Business, Innovation and Employment (MBIE) research programmes and commercial funding sources. The commercial and MBIE funding sources have contributed to the model extensions required to analyse specific questions or issues, with these extensions being embedded into the modelling framework. There is ongoing maintenance of the model and, where applicable, some of the data sources that underpin the modelling. This is expected to continue into the future given the commercial use of the model.

3.3.2 How does the model work?

NZ-FARM is a comparative-static, non-linear, partial equilibrium mathematical programming model of New Zealand land use capable of operating at the national, regional, catchment and sub-catchment scale. The model tracks multiple parameters, including changes in land use, land management, agricultural production, nutrient losses, sediment and GHG emissions/carbon sequestration. The model can assess a range of policy options, including, but not limited to, catchment-level cap-and-trade programme, imposition of nutrient-leaching constraints at the enterprise level, allocation options, taxes/subsidies and good management practice requirements. The model is parameterised such that responses to policy are assumed to be a medium- to long-term response where landowners make changes over a 5–10-year period.[4] There are three key components to the model: economic, environment and land management (see Figure 2). These are discussed in more detail below.

Economic component

The core component of the model is economic, with the objective function of maximising rural income while accounting for the environmental impacts of land use and land-use changes. Production activities in each region of NZ-FARM are characterised by fixed and variable input costs, output price and other relevant forms of payments, such as environmental payments. Production and land use are endogenously determined in a nested framework, such that landowners simultaneously decide on the optimal mix of land use for their fixed area, given their land-use classification (LUC; if appropriate) and soil type. This then allows landowners to allocate their land between various enterprises that will yield them the maximum net return for their land use.

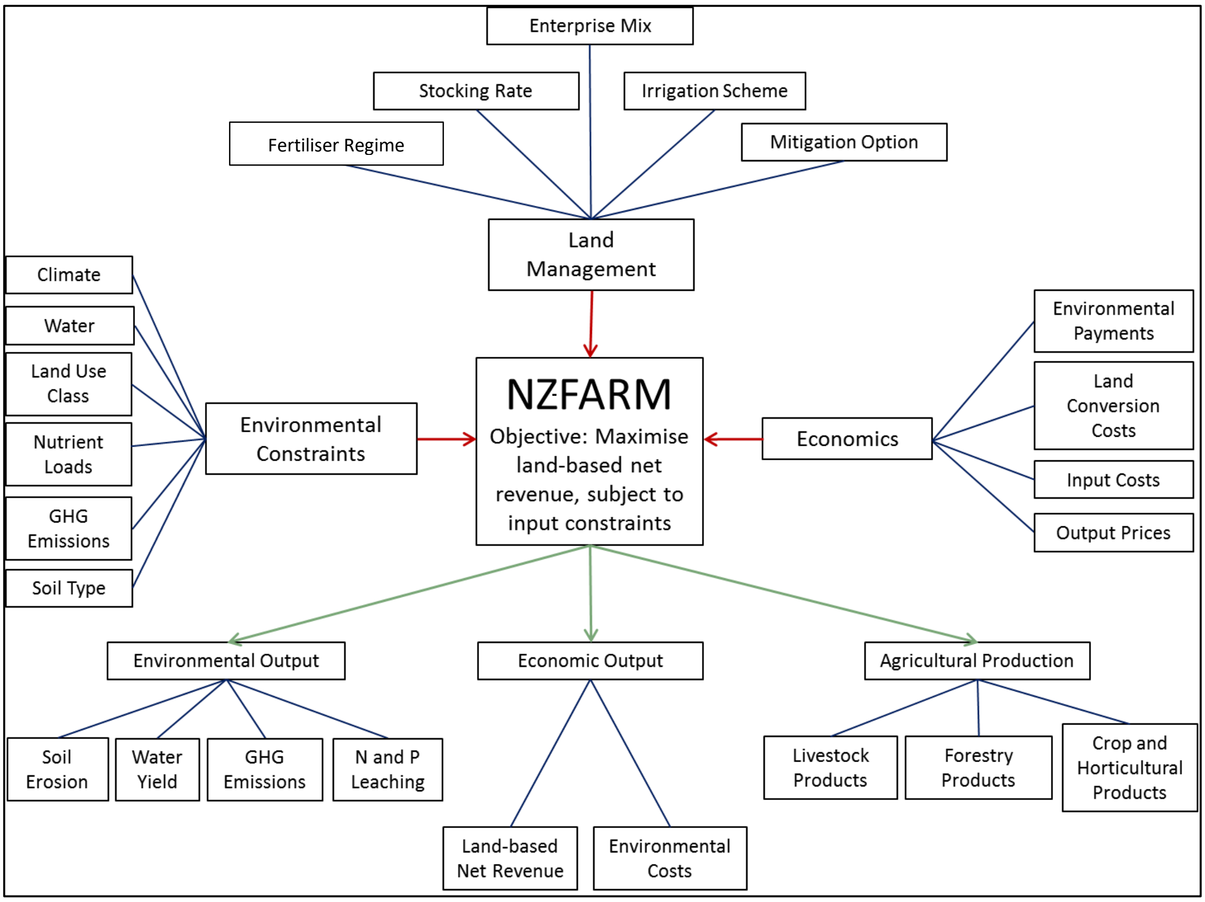
NZ-FARM can account for all types of production activities. To date, the following activities or enterprises have been included in the modelling:

- pastoral uses (sheep, beef, dairy and deer);
- horticultural uses (e.g. kiwi fruit, grapes);
- arable uses (e.g. maize, various arable rotations); and
- forestry.

Other land uses can be included, as long as profitability and environmental impacts are available.

[4] The static analysis compares two different equilibrium states (before and after a change in some underlying exogenous parameter), in which the outcome of these two states is annualised. The annual outcome of the aftershock state is assumed to be in the steady state situation (achieved after 5–10 years). Although the model does not study the motion towards equilibrium (the path of the above-mentioned 5–10-year period), in some cases five-year time steps for model runs have been used for some analysis to simulate a dynamic transition pathway.

Figure 2: NZ-FARM components



Environmental component

In addition to estimating economic output from agricultural and forestry sectors, NZ-FARM has the ability to track environmental outputs. The model has been used to track the following outputs:

- Nitrogen (N) and phosphorus (P) leaching rates for pastoral farming were obtained from the most recent version of Overseer, while N and P leaching rates for all other enterprises were constructed using SPASMO or other literature.
- Forest productivity and carbon sequestration were derived from the CenW model.
- GHG emissions for all other enterprises were derived using the IPCC's Good Practice Guidance (2000) and match the categories in the latest New Zealand Greenhouse Gas Inventory (manure management, agricultural soils, etc.).
- Water yield is based on WATYIELD (Ausseil et al., 2013).
- Sediment losses are based on SedNet and the New Zealand Empirical Erosion Model (NZEEM).
- *Escherichia coli* has also been included for some analyses and based on CLUES/SPARROW modelling.

Land management component

Simulating endogenous land management is an integral part of the model, which can differentiate between "business as usual" farm practices and less typical options that can change levels of agricultural output, nutrient leaching, sediment loss and GHG emissions, among other things. Key land management options include changing fertiliser regimes and stocking rates, adding an irrigation system, or implementing mitigation technologies such as the installation of a dairy feed pad, fencing streams, constructing wetlands or specified packages of management practices. Again, additional management practices can be included, provided it is possible to estimate the environmental impacts and profitability.

3.3.3 What datasets are used?

NZ-FARM has already been parameterised in detail for several New Zealand catchments (e.g. Manawatu, Selwyn, Hinds, Hurunui–Waiau, Whangarei Harbour, Ruamahanga and Kaipara Harbour). In addition, a more aggregated version of the economic land-use model has been parameterised for all of New Zealand using representative farm data. The full range of model variables and typical data sources for NZ-FARM are listed in Table 5; however, the range of variables and data can be modified based on the scope of the work. Note that if data on additional land uses/management practices and/or environmental outputs exist, they can easily be incorporated into the existing model framework. Technically, input data are based on polygons (i.e. farms), which are then converted to XLS format for use in the model.

Table 5: Data sources for NZ-FARM's modelling of a specific catchment

Variable	Data requirement	Availability	Comments
Geographic area	Geographic information system (GIS) data identifying the catchment or other relevant area	Catchment and sub-catchments based on River Environment Classification	Can use alternative boundaries if available/desired
Land-use and enterprise mix	GIS data file(s) of current land use with the catchment Key enterprises (e.g. dairy).	A national land-use map was estimated based on AgriBase and LCDB4 (2012/2013)	Land-use map should be verified by project partners and/or stakeholders
Climate	Temperature and precipitation	Historical data is available. Future climate projections for all of New Zealand is now available	Required for assessing impacts on primary productivity, so need to link with pasture/ livestock, crop and forestry models

Soil type	-	S-map (partial coverage only) and the New Zealand Land Resource Inventory (NZLRI) are available	Used for estimating impacts on nutrient losses
Stocking rates	Based on animal productivity model (e.g. Farmax) estimates or carrying capacity maps	Average land carrying capacity from NZLRI, as well as more detailed "stocking budgets" for various dairy and sheep and beef systems, have been estimated	
Input costs	Stock purchases, electricity and fuel use, fertiliser, labour, supplementary feed, grazing fees, etc.	Obtained using a mix of: pers. comm. with farm consultants and regional experts, MPI farm monitoring report, Lincoln Financial Budget Manual	If appropriate, additional information can be sourced or verified by project partners and/or stakeholders
Product outputs	Milk solids, dairy calves, lambs, mutton, beef, venison, grains, fruits, vegetables, timber, etc.	Yields are available at the farm scale. Data come from farm consultants and regional experts, MPI farm monitoring report, Lincoln Financial Budget Manual	If appropriate, additional information can be sourced or verified by project partners and/or stakeholders
Commodity prices	Same as outputs, but in $/kg or $/m^3	Obtained from MPI and other sources	
Environmental indicators	GHG emissions, forest carbon sequestration, nitrogen and phosphorous loss, water yield, sediment loss, *Escherichia coli*	GHG emissions estimated using the same methodology as MfE's Annual NZ Inventory calculations. Forest sequestration based on CenW. Leaching rates derived using the Overseer and/or SPASMO model. Water yield estimated using WATYIELD (see Ausseil et al., 2013). Sediment loss based on SedNet or NZEEM models. *Escherichia coli* based on CLUES/SPARROW model	Can be updated with farm- or catchment-specific data

3.3.4 What are the coverage and resolution of the model?

NZ-FARM is capable of operating at the national, regional, catchment and sub-catchment scale, and outputs are provided on a per-hectare basis.

3.3.5 What are the strengths and limitations of the model?

NZ-FARM was developed to compare the relative impacts of agri-environmental policies on landowners consistently at the catchment, regional and national scale, with this information forming part of the evidence to evaluate the "best" policy to pursue. It has shown usefulness in illustrating the trade-off between economic and environment impacts of environmentally focused policies. While the model to date has been used only to assess the impact of environmental policy, it can also be used to assess other types of policies, e.g. agricultural policies. NZ-FARM's use of positive mathematical programming and constant elasticity of transformation functions allows the modelled land-use area to closely match the initial GIS-derived land-use areas. In addition, this calibration framework addresses problems of overspecialisation and corner solutions. We find that this method results in only minor differences between observed and modelled baseline land use at the enterprise level (e.g. 3 percent for the Manawatu catchment (Daigneault et al., 2012); two per cent for the Hurunui–Waiau catchments (Daigneault et al. 2012); and less than one per cent for the Hinds catchment (Daigneault et al. 2013)).

It is relatively easy to incorporate new components into the existing model framework, if data on additional land use/land management and/or environmental outputs exist. These new data are integrated as a spatial layer to the NZ-FARM dataset. For instance, *Escherichia coli* data were integrated with NZ-FARM to estimate the cost-effectiveness of sediment and *E. coli* mitigation practices in the Whangarei catchment. Recently, NZ-FARM was successfully linked to an agent-based decision-making framework (ARLUNZ) to estimate the impacts of climate change policy on land use. NZ-FARM has been used to assess the changes in land use, farm management and environmental outputs for several policy scenarios. For instance:

- increase in water storage from capital improvement projects;
- proposed caps on nitrogen and phosphorous loads;
- implementation of NZ ETS on the forest sector;
- implementation of NZ ETS on the agriculture sector;
- regional afforestation schemes;
- implementation of new farm technology and best management practices; and
- increases in farm input costs and/or output prices.

NZ-FARM has some limitations:

- Using NZ-FARM requires a General Algebraic Modelling System licence and access to the model's code, which would require an arrangement with Manaaki Whenua – Landcare Research for the code's usage.
- Only steady-state predictions are provided. However, five-year time steps for model runs have been used for some analysis to simulate a dynamic transition pathway.
- Uncertainty is considered only through a scenario approach rather than a probabilistic one. However, Monte Carlo simulation techniques have been used with NZ-FARM to include bio-economic uncertainty.

3.3.6 What linkages are there to other modelling work?

NZ-FARM is sufficiently flexible to incorporate data from various models and to be used in various contexts. For instance, it has been linked with Overseer and SPASMO, to trace nitrogen and phosphorus leaching rates for pastoral farming and other enterprises; the CenW model, to derive forest productivity and carbon sequestration; the WATYIELD model, to estimate water yield for a range of enterprises; the SedNet and NZEEM models, to derive sediment losses; and CLUES/SPARROW modelling to estimate *Escherichia coli* levels. For more details about model linkages, see section 3.3.2.

3.3.7 What questions are currently being looked at?

Key areas currently being investigated include:

- Analysis of the impacts of land-use management practices to reduce New Zealand's GHG emissions on the incomes, agricultural production, and nitrogen and phosphorous leaching at dairy and sheep and beef farms.
- Estimating the impacts of expected future land-use change under different climate policy scenarios (i.e. GHG emission targets).

3.3.8 What areas are there for future development?

The two key areas for development are the creation of a dynamic version of NZ-FARM and the incorporation of risk and uncertainty in the model. To achieve these developments, uncertainty distribution of key parameters as well as risk profiles of landowners are required. In addition, information on livestock dynamics (e.g. feed, output, age group), forestry growth and crop rotation is needed.

3.3.9 Bibliography of recent work

See Table 13.

3.4 An overview of farm and production-related models

Beyond explicit models of land use, there are a number of models that focus on different aspects of farm production. This section provides an overview of nine of these models: AgInform, Agricultural Production Systems Simulator (APSIM), BiomeBGC, Farmax, Forest Investment Framework (FIF), Forest-oriented Linear Programming Interpreter (FOLPI), Overseer and MitAgator. For each model of the models, the following characteristics are described:

- the main outputs;
- the spatial extent and resolution;
- the methodological approach;
- the main strength and main limitation;
- details around the intellectual property (IP); and
- recent publications that might be of interest.

3.4.1 AgInform®

AgInform® produces two types of output. The first is financial, whereby annual earnings before interest, tax, depreciation and amortisation are calculated and discounted allowing for initial stock purchases and final stock liquidation at the end of the planning horizon. The second output is an optimal farm-system design that maximises the Net Present Value calculated in the financial output. The design shows stock numbers for each of the classes that are in the optimal mix for each fortnightly period over the planning horizon. Animal sale dates are calculated, along with supplementary feed decisions (purchase, sale, make and type of feed), nitrogen fertiliser applications, winter crop planning and feeding, animal purchase decisions, and also urinary and faecal nitrogen production from the animals. The model targets strategic decision-making (not tactical or operational, as this is role of Farmax) over a multi-year planning horizon for pastoral-based animal production. Sheep, beef, bovine dairy and deer (venison) are the current options that can be included in the analysis. It is an optimisation model using linear programming.

Currently, AgInform® operates at the farm level, with the farm being split into any number of land management units (areas of the farm that are, or are nearly, contiguous and so should be managed in the same manner owing to slope, aspect, soil type, pasture type, etc.). A prototype with multiple farms has been run so that AgInform® can operate at least at a catchment level in the near future.

The main strength of AgInform® is that it can identify optimal systems under alternative boundary conditions (e.g. nitrogen leaching limits, GHG limits, pasture or forage types, animal performance, etc.) and paint both financial and farm design pictures, which allows valid comparisons between alternatives. This also identifies any trade-offs that may not be obvious.

A main limitation of the model is that its user interface is still quite crude, with tables being used for input (these can be pasted from Microsoft Excel) and an R script used to summarise output both graphically and numerically.

For recent publications, see Table 13.

3.4.2 Agricultural Production Systems Simulator (APSIM)

APSIM is a suite of models used by researchers to simulate a wide range of complex agricultural systems (Holzworth et al., 2014). It contains interconnected biophysical and management models to simulate systems comprising soil, crop, tree, pasture and livestock processes, and has the flexibility to integrate non-biological farm resources such as water storage and farm machinery.

At its inception in the early 1990s, APSIM was a point-based model with a limited range of soil and crop models that were used primarily for improving land management decisions at a field level (McCown et al., 1995, 1996. Over the intervening years, APSIM has evolved into a framework containing more than 80 models of soil and crop processes that are used together in simulation analyses that go far beyond the original, envisaged problem domain.

APSIM comprises the following: a set of biophysical models that capture the science and management of the system being modelled; a software framework that allows these models to be coupled together to facilitate data exchange; a community of developers and users who work together, to share ideas, data and source code; a data platform to enable this sharing; and a user interface to make it accessible to a broad range of users. (Holzworth et al., 2014).

The main strength of APSIM is its process-based modelling of a vast range of agricultural systems (horticulture, cropping, pastoral, agroforestry), processes (soil sustainability, resource use and efficiency, yield gaps assessments, climate change and adaptation analyses), understanding drivers of production and environmental effects, whole farm system modelling, and continental- and sub-continental-scale analyses.

Limitations include:

- difficulty in achieving operating system independence;
- slow execution time;
- documentation that is out of date; and
- some models that lack formal test and validation simulations.

However, many of these issues are being addressed (Holzworth et al., 2018). The software is free for non-commercial use (available from www.apsim.info).

For recent publications, see Table 14.

3.4.3 BiomeBGC

BiomeBGC is a biophysical model of soil–plant interactions whose main output is pasture biomass. It can produce results from the local to the national level. Model parameters were calibrated using observed pasture growth data and historical climate data, and validated for both dairy and sheep systems (Keller et al., 2014). Climate inputs included minimum air temperature, daily maximum air temperature, precipitation, vapour pressure deficit and solar radiation. BiomeBGC is easy to use and not as data-hungry as APSIM, and can produce maps at a national scale. It is useful for looking at future trends for pastoral systems (dairy/sheep and beef), but is too simplified to understand the impacts of changes in management practices. For instance, irrigation is not simulated, and while it could be simulated by artificially adding precipitation in certain periods of the year, this is not part of a feedback loop on soil moisture deficit. BiomeBCG has open access and is used by GNS Science.

For recent publications see Table 14.

3.4.4 Farmax

Farmax Sheep, Beef & Deer and Farmax Dairy are whole-farm decision-support models that use monthly estimates of pasture growth, farm and herd information to determine the production and economic outcomes of managerial decisions. The models work from production targets and calculate intake required to meet these targets; they don't predict intake from feed availability.

The main outputs of Farmax Sheep, Beef & Deer are animal live weights, pasture production, pasture conversion efficiency and financial profitability. The results are modelled at a property level (single-farm modelling), although it is possible to generate regional information by aggregating farm results.

Farmax is based on the Stockpol model from the 1980s, which combines deterministic intake and pasture models. It is used for both monitoring and evaluating scenarios. The usual process is to calibrate the model by adjusting the growth rate pattern to match known performance. There have been a number of validation projects (e.g. Bryant et al., 2010).

A strength of Farmax is its pasture model, which takes account of pasture quality by calculating the net growth rate and the effects of lost potential and decay. Another advantage is its ability to run in both long-term mode (for policy evaluation) and short-term mode (for feed budgeting and monitoring).

Limitations include:

- Farmax does not optimise outcomes, and instead the user iteratively uses the model to make feasible scenarios based on meeting minimum pasture-cover calculations.
- Farmax does not attempt to define a system and the model does not calculate production. It circumvents this by having the user define the production targets, and the model then defines whether these are feasible.

The user becomes a critical part of the decision-making required to overcome production limitations and system optimisation.

Farmax Dairy was developed by Farmax Ltd, and all IP is owned by the company. Farmax Sheep, Beef & Deer was based on Stockpol (Marshall et al., 1991), which was developed by AgResearch. Ownership of IP pertaining to Stockpol was passed to Farmax in a deed of assignment in February 2018. At heart, both versions of Farmax are based on familiar known algorithms; however, some proprietary elements exist, based on expert adjustments.

For recent publications, see Table 14.

3.4.5 Forest Investment Framework (FIF)

FIF is a spatial economic framework that combines forest productivity, infrastructure networks, planting and harvesting costs, the economic values of ecosystem services such as erosion reduction, log prices, leaching reduction, habitats for native species and other sources of information, and integrates them to calculate outputs for the areas of interest. FIF's spatially explicit outputs include maps and tables of values that can be used to describe the broader benefits of existing or proposed forests or tree blocks.

Among the various outputs that FIF can generate, the current ones are:

- spatially explicit maps and tables of economic values (cost and revenue) of timber (e.g. *Pinus radiata*, eucalyptus, redwood, Douglas fir) of existing and future forests anywhere in New Zealand (supply function);
- spatially explicit maps of economic values of carbon sequestration and avoided erosion provided by planted and native forests (supply function); and
- spatially explicit maps and tables of economic values of habitats for iconic native species (e.g. brown kiwi, New Zealand falcon) provided by current and future forests (on-site and off-site demand function, and use and non-use values).

The following outputs are currently under development:

- spatially explicit maps and tables of economic values of avoided nutrient and water yield (off-site supply functions – environmental values) and recreation (on-site demand function – recreational use value) provided by current and future forests.

Since its development in 2012, FIF has been widely used by scientists, forest companies, iwi and government agencies to identify where best to plant trees for various purposes (e.g. land-use management, afforestation, riparian planting).[5] FIF has been used at the national, regional and sub-catchment levels. FIF's timber (*Pinus radiata*) profitability component has been

[5] More information is available at https://www.scionresearch.com/science/sustainable-forest-and-land-management/valuing-the-forest-ecosystem/forest-investment-framework

validated in forests with areas between 5,000ha and 20,000ha (Yao et al., 2016). The model's current resolution is 25m × 25m.

FIF is essentially a GIS tool that amalgamates various biophysical layers of ecosystem services with their respective values. Among the main ecosystem services included are:

- For the timber viability component, FIF uses comprehensive fine-resolution terrain datasets for New Zealand that have been described in Palmer et al. (2009a,b,c).
    - Datasets used are suitable for the modelling of planted forestry costs and productivities because they are key indicators of impedances, or physical barriers, that impact on forestry processes.
    - Costs are assessed by running the model for known forests and using expert knowledge to adjust impedance values against reasonable real-world costs.
    - The 300 Index is a model used for determining productivity of Pinus radiata in New Zealand (Kimberley et al., 2005). This model has been combined with another model for determining Site Index to generate a series of productivity surfaces across New Zealand.
    - For each forest, the NPV of forestry in perpetuity is determined using discounted cashflow analysis, with the goal to estimate the land expectation value (Bettinger et al., 2008), as described in Barry et al. (2014).
- The level of carbon sequestration is calculated from the same surface used to determine timber productivity (300 Index), combined with the C-change carbon model (Beets et al., 2011, 2012).
- Avoided erosion is measured as the change in sedimentation levels from afforestation and is estimated using NZEEM (Dymond et al., 2010), combined with an economic valuation framework (Barry et al., 2014).

Two of FIF's main strengths are:

- Validation of FIF's timber viability component suggests that the framework provides very good estimates of cost and revenues on existing forests with greater confidence when assessing large planted forest areas (i.e. at least 1,000ha).
- FIF has the ability to provide meaningful results for strategic planning objectives for various forestry regimes (e.g. pruned, unpruned, plant and leave, bio-energy).

Three of FIF's main limitations are:

- FIF is essentially a GIS tool, not an optimisation or simulation model. Hence, FIF can answer "what if" questions using a scenario approach.
- In terms of limitation, FIF currently does not include forest age classes, thereby assuming all trees are planted (and harvested) at one point in time.

- Medium- to large-sized planted forests (>1,000ha) are often planted in a mosaic, where different forest blocks are planted at different points in time to enable year-round forest establishment, silviculture and harvesting for forest companies that usually employ sustainable forestry management practices. However, plans are underway to create new forest spatial functions in FIF (e.g. development of forest age-class distribution using LiDAR).

FIF was developed and is continuously being refined by Scion. Using it requires a geospatial licence and capabilities. More information on FIF's foundation and capabilities can be found in Barry et al. (2014), Yao et al. (2016, 2017) and https://www.scionresearch.com/science/sustainable-forest-and-land-management/valuing-the-forest-ecosystem/forest-investment-framework.

3.4.6 Forest-oriented Linear Programming Interpreter (FOLPI)

FOLPI is an optimisation tool for evaluating forest management and investment strategies. It is essentially a fixed-price forest schedule model that answers the following questions:

- Should new land be bought for afforestation?
- Should more forests be bought and, if so, what will their likely value be?
- What volume of wood should be harvested?
- Should land be replanted after clear-felling?
- What is the current value of my forest estate?

The outputs obtained from FOLPI can be categorised as follows:

- Detail of decision variables (cut/plant/transfer), i.e.
    - how many hectares of which crop type were cut (harvested) in which year at which age;
    - how many hectares of cut forest by age and crop type were replanted into which crop type;
    - how much new land was planted;
    - how much harvested forest by crop type and age was deforested; and
    - how much area at which age(s) was transferred from one crop type to another (e.g. due to optimising silvicultural regime).
- Consequences of decisions:
    - resources (costs, revenues, product volumes, labour, etc.) associated with the area that is cut and planted as above, e.g. annual cashflows for discounted cashflow analysis; and

  - resources associated with the area that is left standing, which in general is an annual description of area by crop type and age class, and associated properties (annual standing volume, carbon stock, nitrogen emissions, etc.).
- Log allocation sub-model decisions:
  - log quantities by species and grade sent from origin to destination mill;
  - product quantities produced at mills; and
  - average delivery costs, etc.

The spatial extent and resolution is user-defined. Management units could be individual stands (polygon within a property) or could be aggregated stands that are dispersed across a region or a mixture. Forest companies typically model properties or regions.

FOLPI is an optimisation model that is structured to comply with a mixed integer linear programming problem.

The model's main strengths are:

- flexibility, in that the user defines what they want the management units to represent, and what resources/inputs/outputs they want to model;
- the system provides standard data-input formats and a simple interface to allow complex models to be defined by relative novices through input forms;
- no coding or mathematical programming skills are required;
- the system keeps track of area by age class through time; and
- it is robust, well tested and used commercially among forest companies.

The model's main weaknesses are:

- current software implementation is obsolete;
- it assumes inputs and outputs can be represented on a unit per hectare basis, i.e. linear relationships (or can force step-wise approximation), so it is not well suited for optimising continuous-cover forestry; and
- it assumes economic optimisation with exogenous prices.

FOLPI was developed by Scion. The formulation is public domain through published papers. The current implementation is owned by Integral, which does not allow open access.

There are no recent publications, as FOLPI was developed in 1984 and in recent years has been used solely for commercial purposes. However, Scion has recently created a partial-equilibrium forest-sector model based on FOLPI principles under the Our Land and Water National Science Challenge. The foundation paper laying out the mathematical structure of this model is currently under review in a scientific journal.

3.4.7 Overseer®

Overseer® Nutrient Budgets (hereafter Overseer) is a software service that provides a large array of farm analysis information. Results include:

- farm- and management-block-level nutrient budgets for nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca), magnesium (Mg) and sodium (Na) (and acidity for pastoral blocks) per source;
- total farm GHG emissions for methane, nitrous oxide and carbon dioxide (per source);
- GHG footprint report per product. This includes the embodied emissions for products brought onto the farm to achieve the production; and
- farm production summary, effluent summary, pasture production, animal dry matter uptake and Diet Metabolised Energy source and location, block-level changes in nitrogen pools, relative yield and maintenance fertiliser nutrient requirements.

Overseer provides a nutrient analysis at the management-block and farm level. The analysis is carried out against a long-term (30-year) climate profile and assumes the farm system (production and management) analysed is in quasi-equilibrium.

The estimates are modelled to the "farm gate", and include below-ground leaching losses from 60cm (pasture) to 1m (crops), total gaseous emissions into the atmosphere and product removal to the farm gate.

Because farm data are stored within the system, Overseer provides the ability to aggregate information at any level up to national level (without identifying farms individually). Overseer has been successfully integrated into catchment models, including modelling of historical and future farms so that the effects of time delays can be incorporated.

There are three main strengths of Overseer:

- Overseer provides a detailed analysis of nutrient flows resulting from farm management and the specific biophysical factors present for that farm, including an estimation of farm-specific emissions. This enables farm management decisions to be based on real impact analysis and to avoid pollution swapping between leaching and GHG emissions.
- Overseer has been constructed to use data farmers have, or provides suitable default values. This enhances its ability to model historical and future farms, and to model farms where information is limited or not available.
- Overseer includes a wide range of farm types and management systems, including the ability to include mitigation options. Farm types include dairy (cow and goat), dry stock (beef, sheep, deer), pig, arable and horticulture, enabling assessment of different types and mixes of land use in one modelling framework.

There are three main limitations

- Like all models, there is a general lack of calibration or validation data. This means that there are gaps in coverage of farm management options used in New Zealand. For example, not all crops grown in New Zealand are included.
- Parts of Overseer can be used at a finer spatial scale, but it is currently set up to relate to the spatial scales of on-farm decision-making, which is frequently at management-block or farm level.
- Overseer currently uses a default 30-year climate data pattern, which is consistent with the model scope. Different climate patterns can be used, but caution is needed in their interpretation.

Overseer is delivered as an online software service and can be used by anyone who registers. Modelling is undertaken at the individual farm level. Overseer enables bulk datasets to be run to compare results. This functionality is new and is being further developed to meet research needs.

The Overseer IP is owned in equal third shares by AgResearch, MPI and the Fertiliser Association of New Zealand. The IP is exclusively licensed to Overseer Limited for all management, including on-licensing.

Overseer is freely available for use in non-commercial research. In 2019, it is expected that Overseer will introduce a farm account charge for commercial use.

Publications are placed on the website (https://www.overseer.org.nz) and are freely available to download.

3.4.8 MitAgator

The MitAgator model is designed to support farm management decisions at a farm scale, providing a spatial understanding of where losses occur across the farm landscape. The main outputs from MitAgator are estimations of relative risk of nitrogen, phosphorus, sediment and *Escherichia coli* loss. In the case of N, P and sediment, losses are estimated and quantified spatially across the landscape, with *E. coli* expressed as a risk-based approach. In addition, the impact of applied mitigation(s) on losses can be investigated/quantified.

The resolution of input data is, in some cases, limited by what is available. MitAgator has the capacity to utilise the best resolution data available (i.e. 1m Digital Elevation Model (slope) vs 15m). Elevation or slope data is an example of variation in the data available. Nationally, a 15m elevation layer is available, but in some areas data at better resolution will be available.

The approach requires the use of an Overseer nutrient budget, combined with spatial datasets of soil and slope, and a farm map in order to generate spatial risk maps indicating where losses occur. Risk maps can then be overlaid with mitigations as required across the farm landscape. The strength of this approach is in understanding where the highest areas of risk are across the farm landscape, which in turn provides the ability to target mitigation strategies to where they will provide the most benefit, both in terms of cost and effectiveness.

MitAgator allows the user to rank mitigations both in terms of cost and effectiveness expressed as dollars spent per kilogram of contaminant retained (i.e. not lost to the environment). Such an approach allows the most effective and cost-effective strategies to be assessed prior to implementation.

As the MitAgator project is funded via the Primary Growth Partnership (PGP) programme, Ballance Agri-Nutrients has exclusive rights to the algorithms that sit behind the model for an agreed time frame as per the terms of the PGP contract.

For recent publications, see Table 14.

3.5 Overview of core land-use sector datasets

Land-use modellers rely on a number of core datasets, both to develop and run their models. This section gives an overview of some of these core datasets, grouped into three tables as follows:

- land-sector production and economic statistics, used to understand and to model the basic relationships;
- GIS maps of both land use and the factors that relate to land productivity and suitability; and
- environmental indicators of impacts associated with land use. Land-use modelling has largely focused on water quality and GHG emissions; these indicators are presented here.

Table 6: Land-sector production and economic statistics

Dataset	Description
Agricultural production surveys and censuses	These contain information on farming in New Zealand, including livestock and arable farming, horticulture and forestry. Farmers and foresters are surveyed annually. Geographic coverage is both national and regional. Source: Stats NZ
Overseas merchandise trade data	These provide statistics on the value of New Zealand's merchandise trade with the rest of the world, including, among other things, exports for various agricultural products and livestock slaughtered for export. These are available monthly at the national level from 1997. Source: Stats NZ
National Exotic Forest Description (NEFD)	The NEFD provides annual data on New Zealand's planted production forest, including detailed descriptions of New Zealand's planted forest area, and forest activity data such as planting and harvesting. Source: MPI
Situation and Outlook for Primary Industries (SOPI) prices	The SOPI spreadsheet shows historical and forecast export volume, prices and revenue for the primary industries. Source: MPI
Annual sheep and beef surveys	These surveys provide sheep and beef farm information on area and livestock numbers, capital structure, expenditure, gross margin of livestock, income and sale prices annually. These data were gathered from Meat and Wool Economic Service (MWES) surveys. The dataset is classified by five regions and by eight classes, which are defined by MWES. Source: Meat and Wool Economic Service (now Beef + Lamb)
New Zealand Monitor Farm Data (NZMFD)	The NZMFD)is a merged dataset of two sources (Henry et al., 2017a). The first source contains information on the financial status of farms.[6] The second source documents information about each farm's production inputs and outputs alongside their environmental outcomes.[7] The aggregated NZMFD has 407 observations, which cover farms from most regions of the country. These farms are categorised into dairy farms (223 farms), sheep and beef farms (165), and deer farms (19). This dataset fills an important gap in New Zealand agricultural economics at a practical level. It generates different fields for researchers to use in interrogating agricultural production, nutrient and GHG emissions, and financial outcomes across farms.
New Zealand Dairy Statistics Reports	The purpose of New Zealand Dairy Statistics is to provide statistical information related to the New Zealand dairy industry. Funding is provided by the Livestock Improvement Corporation (LIC) and DairyNZ Incorporated (dairy farmer levy). Contributors include New Zealand Animal Evaluation Limited. Data are sourced from the LIC Herd Improvement Database, New Zealand dairy companies, Animal Evaluation Database, TB Free New Zealand, Real Estate Institute of New Zealand and Stats NZ. Source: LIC and DairyNZ

[6] These data were collected by the Ministry of Agriculture and Forestry (MAF) under the Farm Monitoring Programme, which was designed to provide an annual aggregated overview of a range of farm types throughout New Zealand (Ministry of Agriculture and Forestry, 2010).

[7] Most of the inputs and outputs information were collected by MAF, while the environmental outcomes were calculated using version 6.2.1 of Overseer (see section 3.4.7).

Table 7: GIS maps

Data	Description	Comments
Land-use and enterprise maps	A national land-use map was estimated based on AgriBase and LCD4 (2012/2013).	These data and their workflow have been developed by Manaaki Whenua – Landcare Research and have recently been updated with Agribase 2018. The issue is around restrictions for sharing, as Agribase is a proprietary dataset.
Maps of land capability/ suitability	The New Zealand Land Resource Inventory (NZLRI) is a national database of physical land resource information. Land Use Capability (LUC) classifies each polygon on its ability to sustain agricultural production, based on an assessment of the inventory factors above, climate, the effects of past land use and the potential for erosion.	The NZLRI is an old dataset with varying resolution across the country. It should be updated to increase its spatial resolution. Our Land and Water is looking at improving information on land-use capability with the concept of land-use suitability.
Maps of water availability and irrigation	Information is usually available through regional councils via their water plan. Information requires a combination of both surface water and groundwater availability, which is currently established at case-study level across regions. Several sources of information are based on national-scale modelling under limited assumptions (e.g. IrriCalc, the national hydrological model). MfE has recently published a layer of irrigation for 2017 as part of the land domain report (available at: https://data.mfe.govt.nz/layer/90838-irrigated-land-area-2017)	Not a uniform, harmonised source of information at national scale. There is a need for information taking into account irrigation scheme resource and distribution systems. The irrigation layer was produced by Aqualinc and has various level of accuracy across the country
Maps of soil	S-map (partial coverage only) and the NZ Land Resource Inventory (NZLRI) are available Soil maps (Fundamental Soil Layer) used to divide area into dominant soil types	S-Map is patchy
Maps of stocking rates	Average land carrying capacity from NZLRI is available.	More detailed ‘stocking budgets’ for various dairy and sheep and beef systems have also been estimated from other sources including regional or district level statistics and Agribase (Ausseil et al, 2013). Note that Agribase has information on stock numbers per farm.

Table 8: Environmental indicators

Indicators	Examples of data available	Comments
GHG emissions	Greenhouse Gas Inventory. This provides emissions estimates back to 1990. It reports at a national level, although regional dairy emissions are calculated. Biological emissions and emissions from fuel use on farms are reported separately, although Stats NZ is looking to aggregate emissions based on industry (e.g. all biological and energy emissions from the dairy sector). For more information, see https://www.stats.govt.nz/reports/environmental-economic-accounts-2018	
Forest carbon	National Inventory Report yield tables for forestry.	
Nitrogen and phosphorus loss	Leaching rates can be derived from Overseer and SPASMO, as well as the CLUES/SPARROW model (see Anastasiadis et al. (2013) for descriptions of these models).	Also refer to leaching maps from stocking rates (see Dymond et al., 2013), used in the MfE freshwater domain reporting and MfE & StatsNZ (2015) (see https://data.mfe.govt.nz/layer/52850-nitrogen-leaching-2011). These layers are being updated for MfE for 2017.
Water yield	Water yield can be estimated using WATYIELD (see Ausseil et al., 2013; Dymond et al., 2012).	Available on the Land Resource Information Systems (LRIS) portal (https://lris.scinfo.org.nz/layer/95385-water-yield).
Sediment loss	Sediment loss can be estimated using SedNet, NZEEM (Dymond et al., 2010) and MitAgator models.	Available on the LRIS portal (https://lris.scinfo.org.nz/layer/48178-nzeem-erosion-rates-north-island and https://lris.scinfo.org.nz/layer/48176-nzeem-erosion-rates-south-island).
Escherichia coli	Can be calculated based on the CLUES/SPARROW and MitAgator models.	

3.6 Opportunities to apply international models and datasets to New Zealand

There was discussion during the workshop on the needs and opportunities to increase international collaboration on modelling. These include adapting international models to New Zealand's models, linking international models to New Zealand's models, and enabling international modelling experts to help improve and validate models in New Zealand. The land-use models available in the global community are varied in terms of structure, methodology, the temporal and spatial scale of their analysis, the driving forces behind them and their level of integration (Gutman et al., 2004; Veldkamp & Lambin, 2001; Verburg et al., 2004). Most land-use models in New Zealand assume that the land sector is unaffected internationally. In reality, this is not the case, and it would improve the standard of models in New Zealand if they were to incorporate global environmental and economic changes. There would be value in making it easier to use the complexities and abilities of models from elsewhere to improve the modelling capacity in New Zealand.

There is potential value in using international statistical tools along with domestic statistical tools to help feed the inputs and inform the outputs of land-use models in New Zealand. Two examples of this are statistical emulators of maize, rice, soybean and wheat yields from global gridded crop models (GGCMs), and the water resources model; these are described below.

New Zealand could strive toward greater integration into the international modelling community to benefit from model improvements, comparisons, data exchange and joint projects.

Examples of these international modelling networks include:

- The Global Trade Analysis Project (GTAP)[8] is a global network of researchers and stakeholders working on quantitative analysis of international policy issues. In addition to trade policy issues, GTAP also focuses on topics related to energy, labour migration, poverty, land use and land cover. The objective of the GTAP network is to enhance the exchange of ideas among the modelling community, as well as improve collaboration and joint projects. GTAP has also developed its own global CGE model.
- The Agricultural Model Inter-comparison and Improvement Project (AgMIP)[9] connects a worldwide community of experts and policy-makers working on improving the state of the science through model comparisons, validation exercises, regional integrated assessments and global-scale analysis to evaluate climate effects and other impacts on food security and socioeconomic factors in future decades.
- The Consultative Group for International Agricultural Research (CGIAR)[10] is a global network of 15 research institutes focusing on rural poverty, food security, human health and nutrition, and sustainability.

Three examples of international tools and models presented here are: statistical emulators of maize, rice, soybean and wheat yields from global gridded crop models; the water resources model; and the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT).

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8 https://www.gtap.agecon.purdue.edu
9 http://www.agmip.org
10 https://www.cgiar.org

3.6.1 Statistical emulators of maize, rice, soybean and wheat yields from global gridded crop models

The vulnerability of crops to weather is well known, and numerous studies have attempted to estimate the impact of climate change on yields (Challinor et al., 2014). These studies generally rely on either process-based crop models (e.g. Deryng, et al., 2014; Parry et al., 1999; Rosenzweig & Parry, 1994) or statistical techniques (e.g. Blanc, 2012; Blanc & Strobl, 2013; Lobell & Field, 2007; Schlenker & Roberts, 2009). While process-based models can capture the effect of weather and other environmental conditions, they are computationally demanding and sometimes proprietary, which limits their accessibility. On the other hand, statistical models are more easily applicable, but they depend on the availability of observations to estimate the impact of average weather conditions on crop yields while controlling for other factors. To benefit from the capabilities of processed-based models while preserving the application simplicity of statistical models, Blanc (2017a) and Blanc & Sultan (2015) provide an ensemble of statistical tools emulating crops yields from GGCMs at the grid-cell level using a simple set of weather variables.

These emulators are based on GGCM simulations from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) Fast Track experiment (Rosenzweig et al., 2013; Warszawski et al., 2014), driven by climate change projections from the Coupled Model Intercomparison Project, phase 5 (CMIP5) archive (Hempel et al., 2013; Taylor et al., 2011). To estimate the determinants of crop yields statistically, Blanc (2017a) and Blanc & Sultan (2015) consider a parsimonious specification that includes only monthly precipitation, temperature and annual carbon dioxide concentrations. Among various representations of weather effects on crop growth, this set of variables was found to provide the best compromise in terms of predictive ability and simplicity. Additionally, as the weather effect on crops is expected to differ across soil types, the preferred estimation strategy estimates separate weather response functions for each soil order.

Validation exercises show that, in general, the emulator reproduces relatively accurately the temporal and spatial patterns of climate change impacts on crop yields projected by GGCMs. Areas of disagreement regarding the sign of climate change impact on yields are limited and generally observed in areas where the projected yield impact is close to zero.

These emulators provide an accessible tool to estimate the impact of climate change on rain-fed maize, rice, soybean and wheat yields, while accounting for crop modelling uncertainty by allowing users to emulate yields projections from five different GGCMs. To enhance the accessibility of this tool further, Blanc (2017b) offers a companion code to estimate crop yields at the regional level under user-defined climate change scenarios. Crop yield estimates for various regional delineations can them simply be used as input into a variety of numerical equilibrium models and other analyses. The scope of the statistical emulator is expended to irrigated crop yields and associated irrigation water demand (Blanc, 2018).

3.6.2 Water resources model

To evaluate the impacts of climate change on water resources and crop production using a large ensemble of climate change scenarios, this model uses the Water Resource System for the United States (WRS-US) model version 2.0 (Blanc, 2015; Blanc et al., 2014) within the Massachusetts Institute of Technology's Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) modelling framework (Monier et al., 2013).

In the IGSM-WRS-US framework (Blanc et al., 2014), the interaction of water resources and anthropogenic water requirements are analysed using an integrated set of economic and Earth system models. Within the IGSM integrated assessment framework (Sokolov et al., 2005), the global economy is represented by the Emissions Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005). This general equilibrium model projects the level of GHG emissions associated with global economic activity in five-year time steps. Global GHG concentrations are then used as inputs to the Earth system component, which encompasses climate, land surface and crop models. In this study, precipitation, temperature, evaporation and run-off are estimated using the IGSM-CAM.

Within this modelling framework, WRS-US simulates water resources and requirements for 99 river basins. The water resources considered in WRS-US are composed of run-off (estimated using IGSM-CAM) and groundwater resources. Water requirements are composed of anthropogenic and environmental requirements. Anthropogenic water requirements are estimated for five sectors: irrigation, thermoelectric cooling, public supply, self-supply and the mining sector. Water requirements for irrigation in the current version of the WRS-US model are estimated using a biophysical crop model. In this project, they propose to expend the statistical emulator (Blanc, 2017b; Blanc & Sultan, 2015) to irrigation requirements estimated by GGCMs and then use these water requirements as input into the WRS-US model. Monthly accumulated precipitation and average temperature (estimated using IGSM-CAM) are used to drive the statistical emulators of crop yields, which simulate crop yields and water requirements for each plant.

The estimated resources and requirements are inputs to a Water System Management (WSM) module. For each basin, the model allocates available water among users each month while minimising annual water deficits (i.e. water requirements that are not met) and smooths deficit across months. Irrigation is a residuals user and water is allocated to this sector once the requirements of all the other sectors have been met. Stress to the irrigation sector in particular is calculated monthly as the ratio of water supplied for irrigation over water required by this sector. This stress indicator is then used to calculate irrigated yield reductions due to lack of irrigation water shortages. To this end, Blanc et al. (2017) extends the WRS-US model to include a crop yield reduction module that estimates the effect of irrigation water shortage on crop yields. These actual irrigated crop yields under water stress are used to estimate actual food production.

3.6.3 The IMPACT model

IMPACT was developed by the International Food Policy Research Institute (IFPRI) at the beginning of the 1990s. It is a flexible tool that can assess and compare the potential effects of changes in biophysical systems, socioeconomic trends, technologies and policies. Researchers and policy-makers can use the model to help determine what policies are needed to meet future food needs.

The IMPACT model is a multi-market agricultural partial-equilibrium model. It simulates the operation of commodity markets and the behaviour of economic "agents" (e.g. producers and consumers) that determine supply and demand for agricultural commodities in those markets across the globe. It provides a detailed specification of production technology and shocks affecting productivity (e.g. water shortages and changes in temperature). IMPACT is an integrated modelling system that links information from climate models (earth system models), crop simulation models (Decision Support System for Agrotechnology Transfer, DSSAT), water models (hydrology, water basin management and water stress models), crop simulation models (DSSAT), value chain models (sugar, oil, livestock) and land-use models (pixel-level land use, cropping patterns by regions) linked to a core global partial-equilibrium multi-market model focused on the agriculture sector (Robinson et al., 2015).

The core model incorporates detailed information on agricultural products, markets, trade, production technologies, environment, land use, and policy shocks or interventions. The IMPACT model and many of its linked modules are written in General Algebraic Modelling System (GAMS).[11]

IMPACT has been used in several ways:

- The IMPACT model is designed for scenario analysis rather than forecasting. The objective is not to predict the most likely outcome (usually extrapolating from historical data), but to generate logically consistent future pathways that include trends and non-linear interactions that may deviate from past experience.
- IMPACT has been used to evaluate linkages between agricultural production and food security at the national and regional levels.
- The model has also been used for analysing the effects of changes in socioeconomic trends, the environment and technology.
- It is also designed to consider scenarios of changes in public investment patterns and trade policy. IMPACT specifically allows for the analysis of alternative scenarios about

[11] https://www.gams.com

how population, income, climate and technologies may change over time. Borrowing from the scenario analysis literature, we can group these traditional scenarios into four categories: socioeconomic, environmental, political and technological.

- IMPACT is also used to evaluate the impact of extreme weather events (e.g. floods and droughts) at national and regional levels, as well as various adaptation strategies. For example, IMPACT can simulate the introduction of new crop varieties (e.g. heat- or drought-resistant crops) through simulating increases in the yield of a specific crop and country with a specific schedule. IMPACT can also simulate an increase in irrigation efficiency or a conversion of a rain-fed area into an irrigated area.
- The model can be used for long-run scenario analyses of the effect of climate change on the agricultural sectors and macroeconomic indicators.

Table 9 gives a non-exhaustive overview of studies that have used the IMPACT model. Table 10 and Table 11 present IMPACT's main input data and parameters.

Strengths of IMPACT include:

- IMPACT has a modular structure that makes it more flexible for future additions and improvements, while allowing for transparency and accessibility to a broader community of users.
- IMPACT's modular structure also allows linkages with CGE models or land-use models. As an example, IMPACT was linked with the OECD's in-house model, ENV-Linkages (OECD, 2017b).
- The latest version of the IMPACT model (IMPACT 3) has an Excel interface that allows users to design and run scenarios without having to learn how to use GAMS, the system in which the model is written.

Table 9: Examples of policy analysis conducted with IMPACT

Themes	References	Summary
Impacts of socioeconomic trends and climate change on agriculture	Nelson et al., (2010)	Investigated the effects of population and gross domestic product (GDP) growth, as well as climate change, on future agricultural productivity, crop area expansion, trade and human well-being. Three population and GDP growth scenarios were used in combination with three climate scenarios, at global and regional scales.
	Waithaka et al. (2013)	Assessed linkages between agricultural production and food security, at national and regional levels.
	Hachigonta et al. (2013)	
	Sulser et al. (2011)	
Adaptation to climate change in agriculture	Ignaciuk et al. (2014)	Analysed technology adoption in the context of adaptation to climate change in Organisation for Economic Co-operation and Development (OECD) countries, where IMPACT was used to compare the effects on yields, prices and food security of research and development and changes in irrigation technology as adaptation strategies.
Adoption of new technologies	Rosegrant et al. (2016)	IMPACT has been used to evaluate the effects of large-scale adoption of agricultural technologies. It also assessed global and regional effects on agricultural productivity, commodity prices and food security indicators under climate change conditions.
Investment policy comparisons	Rosegrant et al. (2016)	IMPACT has been used to assess and compare investment policies, where cost-benefit analysis was carried out to compare the value of investments in decreasing post-harvest loss versus the value of increased investment in agricultural research and development.
Consumer preferences and diet changes	Rosegrant et al. (1999)	The authors used IMPACT to evaluate the effects of possible changes in consumer preferences and diets, as well as changes in productivity and socioeconomic indicators.
	Delgado et al. (1999)	
	Rosegrant et al. (2013)	
Agricultural and food security outlook for Southeast Asia	OECD (2017a)	IMPACT has been linked with the OECD ENV-Linkages model to assess the potential long-run effects of climate change on agricultural production and economic activity. The model has also been used in this report to consider various adaptation strategies.
Water risk hotspots for agriculture	OECD (2017b)	IMPACT has been used to evaluate the impacts of future water-risk hotspots on agricultural production, trade and food security.

Source: Robinson et al. (2015)

Table 10: IMPACT data requirements for the baseline

IMPACT parameter	Data source	Geographic scope	Commodity requirement	Unit
World prices	OECD Agricultural Market Access Database	Global	All commodities	US$/mt
GDP	OECD	National	N/A	Billion USD
Population	IIASA	National	N/A	Million
Total supply	FAOSTAT commodity balances	National	All commodities Crops and livestock	’000 mt
Animal numbers and area	FAOSTAT commodity balances	National	Crops and livestock	’000 producing animals mt/ha
Yield	FAOSTAT commodity balances	National	Crops and livestock	’000 mt
Total demand (food, feed, intermediate)	FAOSTAT commodity balances	National	All commodities	’000 mt
Stock change	FAOSTAT commodity balances	National	All commodities	’000 mt
Net trade	FAOSTAT commodity balances	National	All commodities	’000 mt
Total irrigated area Irrigated crop area	FAO AquaStat, OECD	National	Crops only	’000 ha
Harvest area Yield Production	IFPRI SPAM	FPU (aggregated from pixels)	Crops only	’000ha mt/ha ’000 ha
Calorie availability	FAOSTAT food supply	National	Food commodities	kcal/capita/day
Food supply quantity	FAOSTAT food supply	National	Food commodities	kg/capita/year
Food supply	FAOSTAT food supply	National	Food commodities	kcal/comm/capita/day

Baseline: year 2005

Source: Robinson et al. (2015)

Table 11: IMPACT key parameters

Parameter/ assumption	**Data source**	**Explanation**
Demand elasticities (price and income)	USDA and expert opinion	Determined demand responses to changes in prices and income. Adjusted over time to reflect changing preferences for high-value goods over staples due to economic growth. Calibrated to be consistent with Engel's law (food expenditure falls as a share of total expenditure with economic growth).
Supply elasticities	Expert opinion	Determined production responses to changes in commodity prices.
Marketing margins	OECD and expert opinion	Assessed the cost of transporting commodities from the point of production to national and international markets.
Producer and consumer support estimates	OECD and expert opinion	Analysed subsidies and other national policies that create price wedge between national and international markets.
Export taxes and import tariffs	GTAP 7 database	Showed how national trade policies contribute to the price wedge between national and international markets.
Exogenous yield growth rates (IPRs)	Expert opinion	Presented assumptions about how crop and livestock productivity will change over time due to advances in technology. Methodology used to estimate IPRs is based on Evenson & Rosegrant (1995) and Evenson et al. (1999). Adjusted over time through consultation with experts and economic model comparison projects.
Pop and GDP growth rates	SSP database	IMPACT is calibrated to the IIASA SSP 2 population scenario and to the OECD SSP2 GDP scenario.

Source: Robinson et al. (2015)

Areas for future development:

- IMPACT is a global multi-market model and hence is not quite tailored for New Zealand. New Zealand is not yet disaggregated at the regional level in the model, which means that projections and results of simulations are at the national level only. A collaboration with New Zealand research organisations, the private sector and government bodies could work to tailor the IMPACT model to New Zealand.
- IMPACT is a partial-equilibrium model in that it deals only with agricultural commodities and so covers only part of the overall economic activity. Linking IMPACT with New Zealand land-use models or CGE models would allow the advantages of the different models to be utilised.

4 Setting the agenda for future land-use modelling

During the workshop, it was widely acknowledged that land-use modelling in New Zealand tends to be reactive to policy needs, with demand for services ebbing and flowing depending on the particular priorities of the moment. As a modelling community, we need to approach land-use modelling in a more strategic way. Such an approach would involve being proactive around the kinds of questions that need to be modelled. It would also mean finding ways to maintain a sustained effort with a focus on retaining and enhancing capacity and expertise. With this in mind, this section lays out the ideas and issues raised in the workshop relating to:

- priority policy questions where modelling is needed;
- specific data and modelling development needs; and
- improving the process of modelling in New Zealand.

4.1 Priority policy challenges where modelling is needed

Workshop participants were informed that land-use-related issues are high in the Government's list of priorities. Areas of immediate focus include:

- setting up an independent Climate Change Commission to undertake emission budgeting;
- setting a 2050 target for New Zealand's GHG emissions;
- achieving what is being termed a "just transition" to a low-emissions economy; and
- improving freshwater management.

There is also potential for the development of a national policy statement on soils and another on biodiversity.

Table 9 lists some of the questions that have been the focus of recent land-use modelling efforts. These were obtained through a survey of workshop participants and have been grouped in the following categories, representing the kinds of questions that can be usefully explored by land-use models: projections; simulation of policies; feasibility of targets; and robustness of decisions.

Table 12: Recent areas of modelling effort

	Projections	**Simulation of policies**	**Feasibility of targets**	**Robustness of decisions**
GHG mitigation	Inventory projections for agriculture and forestry	Prices, learning, deliberate horticultural expansion, comparing policy options	How do on-farm mitigation potentials add up? What is the potential mitigation from land-use change? What is the future	Robust paths under uncertainty

			potential biofuel supply?	
Climate change impacts	Agricultural production and risk		Land suitability	
Water quantity	Water demand	Limits, pricing	Regional or sub-regional case study (e.g., Ruamāhanga Whaitua process)	
Water quality	N, P, *Escherichia coli*, sediment	Markets, groundwater	Impact of best practice	
Biodiversity	Habitat			
Biosecurity/pest control	Myrtle rust response (SCION, MWLR)			
Soil	Erosion modelling (MWLR research programme)			
Rural outcomes	Employment, incomes, wealth	What are the distributional impacts of different policies?		

Workshop participants noted that much of the current modelling work is focused on projections, while there is much less focus on the other kinds of questions that could be interrogated through modelling.

Discussion also highlighted the lack of work investigating the sensitivities around decisions and the robustness of different options. The lack of this type of analysis is apparent across all of the land-related environmental issues. There tends to be a focus on how model choice affects error in decision-making. Projections involve making large assumptions about future climate, future technologies and/or future prices. Rather than relying on deterministic projections alone, modelling could and should be used to explore uncertain futures, using the uncertainty in a way that can inform us and help us make better decisions.

In addition to putting uncertainty bounds around projections, we could be using modelling to understand what happens if we take the wrong actions. What happens if we make a particular decision based on an assumption that does not eventuate? How much does it matter? Which actions would be more robust to a range of possible future eventualities? Which actions would be the most sensitive?

In discussion on modelling the impact of a changing climate, a point was made that important insights may be missed if we model purely deterministically. Globally, climate models are good at predicting temperature, but there is large uncertainty when it comes to predicting changes in precipitation, and in addition to this New Zealand has huge climate variability extending over 30-year periods. It is important not to base our decisions solely on an understanding of averages; we need to understand the potential extremes and potential changes in operating regimes.

Table 9 shows that there is relatively little modelling looking at questions around water quantity, biodiversity, biosecurity/pest control, soil and rural outcomes. For each of these issues, there is a clear need to look at the implications of both changing land use and a changing climate. Questions discussed at the workshop included:

- What are the biosecurity risks associated with large-scale land-use change to forestry and horticulture?
- What are the implications for our biodiversity and soil?
- How do we get good outcomes for our rural communities?

The point was also made that work to assess how rural communities respond to policies has tended to be reactive. We could be more proactive, with a regional development focus, exploring proactive options and working on alternative rural futures. An example raised was the Southland study on options for horticulture. It was also pointed out that we need a different modelling approach for blue-sky thinking, so these new ideas can be interrogated.

Other ideas raised included:

- interrogating the differences between local- versus national-level decisions to get insight into impacts of blanket rules at a regional level;
- modelling disruptive futures that are outside the box (e.g. synthetic milk and meat);
- looking at the benefits of having fewer farms that are more efficient;
- looking at issues of forest definition and how they affect small farmers and native forests; and
- interrogating the influence of changes in international markets and terms of trade (resulting from policy within or outside New Zealand) on land use and land-use change within New Zealand.

4.2 Specific data and modelling development needs

This section contains points raised in discussion relating to development needs. These can largely by grouped in four areas: data needs; primary research needs; the integration needed to understand a wider range of environmental issues; and general investment in model maintenance.

4.2.1 Data needs

It was acknowledged that New Zealand is "data poor" compared to other countries and that this is a limiting factor on the quality of our modelling results. The following data needs were raised in discussion:

- We need regularly updated digital maps of land use that are available to all. The most current land-use map that is available for use dates from 2012.
- We need to get much better farm-level data that can be used to analyse economic performance of farms. Options for developing better data might be:
  - randomised controlled trials to estimate key parameters;
  - working with Landcorp to conduct experiments;
  - use of Integrated Data Infrastructure data; and
  - on-farm data that is randomised, systematic, detailed and longitudinal.
- Better farm-level data on environmental outcomes (e.g. nitrogen leaching, GHG emissions) and ecosystem services (e.g. soil, water retention, biodiversity), linked to farm profits and production, that can be used as input to land-optimisation models.[12]

4.2.2 Primary research needs

Also raised were a number of primary research needs, to allow us to understand better the underlying processes so we can increase the capability of models to address relevant policy questions. These included:

- More work is needed on understanding and modelling innovation, including understanding how learning and adoption of new practices occur and how the process of change works.
- A greater understanding is needed about the potential for horticulture, including how quickly horticulture can scale up. Maps of what crops/species can grow where would be a starting point. This is being developed as part of the SLMACC projects on future horticultural use and low-emission futures led by Plant and Food Research. The Deep South National Science Challenge is also collaborating to create maps of future crop potentials with climate change projections. It is important to build capability around alternative crops, so that if we want to scale it up fast, we can.
- Better modelling of forestry and responsiveness to emission price is needed, especially in relation to understanding forest carbon farming and the creation of a better forest suitability/profitability map.
- More granular land-use analysis is needed, including more detailed categories within dairy and sheep/beef.

[12] Data linking farm environmental and financial outcomes exist nowadays, but are either small in terms of sample size (Henry et al., 2017a) or are not publicly available (DairyNZ confidential farm data).

4.2.3 Integrated land-use modelling

To date, integrated land-use modelling has been largely focused on water quality and GHG emissions. The need to understand the impact on a wider range of issues was discussed. For example:

- Co-benefits should be further investigated. We have reasonably good information on water. What about tourism? What about social benefits?
- There should be more linkages with the data available on water availability. For example:
    - IrriCalc is a soil-water balance and irrigation system model (Bright, 2009). The soil-water balance updates the calculated soil-water content on a daily basis given daily measurements or estimates of rainfall, irrigation, drainage and actual evapotranspiration (Bright, 2009). The irrigation system model enables key irrigation system design and irrigation management parameters or constraints to be specified (Bright, 2009). These are the depth and spatial uniformity of irrigation applications, the return period, the soil-water level at which irrigation is triggered, the beginning and the end of the irrigation season, and the maximum irrigation water use (Bright, 2009).
    - Land, Air, Water Aotearoa (LAWA) will present metered data and raw discharge information, and regional councils will have a handle on water availability and how to access this information.
    - The National Institute of Water and Atmospheric Research (NIWA) has national-scale hydrological simulations providing time series for discharge in rivers (as well as catchment-scale soil moisture) that can be used to establish the reliability of supply time series.
    - NIWA has developed two tools. The Environmental Flows Strategic Allocation Platform (EFSAP) tool is based on analysis of flow-duration curves and can be used to assess regional-scale planning questions associated with reliability of supply and impact on ecological functions. The Cumulative Hydrological Effects Simulator (CHES) tool has been developed to perform the same type of analysis at catchment scale, looking at the impact of water management (storage) on downstream water availability.
    - MfE reporting on pressure, state and impact is another source of information that is led by NIWA. This project is looking at real-take impact on downstream users and a number of additional characteristics.
    - The NIWA National Hydrological Project is currently conceptualising a way to simulate water take (surface water and groundwater) using real-time water-take information as a guide to how much water is taken.

- Linkages with biosecurity models and data need to be built. There is a lot of expertise in on-farm biosecurity in the science community, but this is yet to be linked to land-use modelling.
- Linkages with biodiversity models and data need to be built. There need to be stronger links with the biodiversity modelling community. Participants mentioned the availability of DOC Tier 1 monitoring, and maps of status and change in native bird distribution (Walker & Monks, 2017; Walker et al., 2017). There is potential for biodiversity data to be linked with the models, possibly as constraints or outputs. Some of the approximately 70 types of naturally uncommon ecosystems on land have been mapped nationally, and some additional information would exist in regions or districts. The current data available include:
    - the Land Cover Database, which maps broad vegetation classes;
    - Land Environments of New Zealand, an environmental classification which groups together areas of similar physical character;
    - the Threatened Environment Classification, which categorises land environments according to the degree of indigenous cover loss and extent of current legal protection; and
    - mapping by Auckland Council of indigenous vegetation classes, which provides more of a descriptor of the current plant community rather than the ecological system.

4.2.4 General model development

There was also discussion about general model development, including investing in our models so that they are high quality and fit for purpose. This highlighted the following areas:

- There is a need for more validation of models, stress testing and sensitivity analysis. This includes models developed within government as well as within research institutions.
- There is a need for more linkages between models, including partial and general equilibrium models, and international trade and domestic land-use models. Most land-use models take commodity prices and terms of trade as exogenous inputs. While it is defensible and necessary given the design of those models, it limits their ability to simulate likely impacts of policy decisions on the rural sector where those policies could affect terms of trade. The same applies where models are used for projections, but actions by countries other than New Zealand could significantly alter the trade and commodity price assumptions of the models.
- There is a need for the development of models so that they capture uncertainty. This is not actively included in work programmes. We also need to work on interfaces with other models to do this.
- There is a need for improvement of land-sector representation in CGE models.

4.3 Improving the process of modelling in New Zealand

Workshop participants considered the more general question of how we could improve the process of land-use modelling in New Zealand, and develop a more strategic approach as a modelling community. The following ideas and areas for improvement were raised in discussions.

4.3.1 Applying Consistent data, and common assumptions, and increasing transparency

We need to improve consistency and comparability of underlying data, assumptions and projections of key variables as well as modelling outputs. As much as possible, we need to coordinate and share data and underlying parameters, so we all work from a consistent base. Differences in our results need to be meaningful rather than being driven by arbitrary and opaque inconsistencies in data and assumptions. Ideally, we would create a repository, where the key data, parameters and base assumptions are held (e.g. a national harmonised geodatabase of nationally important datasets). One suggestion was that this could potentially be housed at Stats NZ. To do this we would need to identify the key datasets that need to be enhanced and consistently advocate for these.

4.3.2 Strengthening underlying knowledge

We need more social science that produces quantified relationships (e.g. barriers to land-use change) and we need to work more with industry experts. Data confidentiality is an issue and it can be hard to get data from industry as a result. Some social science and behavioural data are available from the Survey of Rural Decision Makers (https://www.landcareresearch.co.nz/science/portfolios/enhancing-policyeffectiveness/srdm/srdm2017). We need to fund data collection across New Zealand so that it is transparent and accessible.

4.3.3 Ensuring research relevance to decision-makers

We need to develop integrated modelling across all land-use-related impacts. One issue raised was the need to focus our modelling on the decision issue and not on what we can model easily. The example given was that resource management decision-makers need to know about impacts on minimum flow and fisheries, rather than achieve a general understanding of climate and water. We also need to anticipate modelling needs so each project is not a crisis. One suggestion was the development of a process that allows policy-makers and researchers to collaborate more with stakeholders up front to refine the questions and identify data sources.

4.3.4 Enabling greater collaboration among researchers, policy-makers and other end

users

It was suggested that the relationship between researchers and end users needs to change from a client basis to long-term partnerships, with a closer connection between the research world and the policy world. Secondments might help with that, but the loss of institutional memory when analysts move on is an issue. Also, the point was made that we need to allow policy-makers better access to models, and the challenge is to design something that is flexible enough to be used by policy-makers but that is also of sufficient quality. We need more workshops to facilitate networking and data exchange. We need better collaboration between the international community and local researchers.

4.3.5 Improving communication of modelling results

We need to do a better job of explaining model limitations to others. This involves building in time to write a coherent narrative around the insights that can be drawn from the modelling, as well as those that should not be drawn from it, rather than a narrow focus on the numerical outputs. We need more coherent and accessible ways to communicate what the uncertainty means for decision-making, especially in the face of end users, who often want a single number.

4.3.6 Investing in maintaining a suite of high-quality models

Having multiple models is a strength; different models focus on different aspects of land use and comparison between models produces insights. We need improved processes for validation and peer review of models. We need to update, repeat and undertake model comparisons consistently. New Zealand should also continue to explore opportunities for international collaboration to adapt international models for use in New Zealand, and engage international modelling experts in building New Zealand's modelling capacity and peer reviewing its models.

We also need more linkages between different kinds of models (e.g. partial and general equilibrium models) to reduce the extent to which fixed assumptions or an inability to model processes within one model constrain the utility of its output for policy decisions. For example, a CGE model could provide estimates of the emission price and changes in product prices under a climate policy as inputs for a land-use model. In turn, the land-use model could provide a CGE model with estimates of land use, land productivity and changes in land-use GHG emissions.

4.3.7 Considering the impact of domestic policies in a global context

As other countries are also formulating policies to reduce emissions, New Zealand-focused models need to consider how domestic polices will affect the competitiveness of New Zealand's exports, and also how polices in other countries will impact New Zealand. This can be accomplished by either estimating how policies in other countries will impact international prices and/or developing global models that represent New Zealand and its key trading partners and competitors. As most global models focus on emissions-abatement options in energy production (and not agriculture), creating global models may require bespoke developments.

5 Conclusion: what are our main priorities for the future?

New Zealand's land sector is an immensely valuable resource, and managing it wisely under competing pressures and a changing climate will require some fundamental improvements in New Zealand's modelling capability. Based on a high-level review of New Zealand's current land-use models and datasets, and discussions among expert researchers who participated in Motu's workshop, it is clear that the following improvements would be beneficial as a matter of priority.

We need to focus more on modelling uncertainty and undertaking sensitivity tests. In addition, we need to use modelling in a way that helps us make better decisions and ensures we do not miss the most important insights.

We need to broaden and integrate the modelling of diverse environmental issues. Much of the modelling effort to date has been focused on water quality and climate change mitigation. We should also be looking at implications of changing land use and changing climate on water quantity, biodiversity, biosecurity, soil and rural outcomes. We need to build stronger linkages across the modelling communities for land use, climate change, water, biosecurity and biodiversity.

We need to improve the supply and quality of land-use datasets in New Zealand. New Zealand is data poor in comparison to other countries. We need regularly updated GIS maps of land use and better data relating to the performance of farms. Primary research is also needed to better understand innovation, learning and adoption of new practices. Two specific priorities are gaining greater understanding of how horticulture might scale up and how forestry might respond to high emission prices.

Many of the suggested improvements could be realised by creating an integrated framework for climate change mitigation modelling in New Zealand. This framework would regularly bring together a suite of models and a network of researchers to assess climate change mitigation policies. Core elements of the framework would include a central repository of data, common input assumptions and scenarios, and a "dashboard" that synthesises results from different models, allowing decision-makers to understand and apply the insights from the models more easily.

The framework would also have several other benefits. First, it could be used to improve linkages among models and ultimately allow each model to capitalise on the strength of other models in the framework. Second, enabling modellers to access high-quality datasets and apply consistent assumptions and scenarios would improve transparency and facilitate comparison of model outputs. Third, the framework would provide a centralised, formal channel for international collaboration.

Overall, sustained investment in a strategic modelling framework will create a stronger and more functional "ecosystem" for climate change mitigation modelling in New Zealand. In addition, it would help to ensure that New Zealand's models are fit for purpose and ready to deploy when the policy demand becomes urgent.

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Appendix

The following descriptions of land-use models are taken from Anastasiadis et al., (2013). For the list of references, see Table 15.

ARLUNZ (Agent-based Rural Land Use New Zealand model) is a catchment-scale spatial model for considering the response of landowners to different agricultural policies. It extends the modelling of NZ-FARM to allow for the individual decisions made by farmers who differ in their attributes, preferences, behaviour and response to policies over time. ARLUNZ considers the following land uses: arable, dairy, sheep/beef, indigenous vegetation, plantation forest and scrub. It produces estimates of changes in catchment profitability, GHG emissions, nutrient loss, management practices and land use over time. The model inputs include data on initial land use, land quality, commodity prices and commodity demand by land use and land management, in addition to definitions of farmers' characteristics and social networks.

ARLUNZ has been developed by Manaaki Whenua – Landcare Research. Using Landcare capability funds it has been used to investigate how the Hurunui–Waiau catchment would respond to various carbon prices under the NZ ETS. The intention of ARLUNZ was to expand the ability of NZ-FARM to consider other drivers of farmer decision-making beyond just profit-seeking behaviour. Its primary purpose is to access how the impact of agricultural policies, resource constraints and other external pressures might differ across farms (Daigneault & Morgan, 2012).

ARLUNZ addresses questions such as:

- How might individual farmers respond to changes in commodity prices, carbon prices and resource constraints?
- How do these individual responses and the overall response vary over time?

The **Land Allocation Simulator** is a modelling framework for assessing the possible impacts of agricultural and environmental policy. A feature of this framework is that it provides a robust means of calibration. The model inputs can include data on farm systems, hydrology, forestry and urban land, and Overseer results. The model can both investigate long-run outcomes as well as dynamic interactions.

The Land Allocation Simulator has been used to analyse alternative allocation systems, different load-reduction targets and alternative irrigation futures in the Selwyn–Te Waihora catchment in Canterbury, and also to guide policy formulation in the Lake Taupo catchment. In response to the National Objectives Framework, the model is currently being used to identify the implications of policy and dairy conversions on future water quality in the Upper Waikato catchment. The model has also been applied throughout Australia (Doole & Paragahawewa, 2012; Doole et al., 2013; Howard et al., 2013).

The Land Allocation Simulator addresses questions such as:

- How do the long-run outcomes for a catchment differ under a range of policies?

LUMASS (Land-use Management Support System) is a geospatial modelling and optimisation framework. It supports the development and application of spatial-system dynamic models for land-use impact assessments and spatial land-use optimisation scenarios for spatial planning and policy development support. The spatial optimisation framework of LUMASS optimises the allocation of arbitrary land uses and management practices across a landscape subject to multiple and possibly conflicting objectives and constraints. The optimisation is based on quantitative performance-indicator maps, such as the potential nutrient loss, erosion, water regulation and provision, and production by land-use type. They can be derived from maps of initial land use, soil type, land quality and property boundaries using the LUMASS spatial modelling framework.

Optimisation outcomes can be constrained in terms of the land-use type, locality and performance. This enables the control of where potential changes can occur and what performance levels are required (e.g. expected revenue) or tolerable (e.g. environmental limits). Different optimisation scenarios can be used to represent different stakeholder preferences and different planning scenarios. These objectives could include maintaining or improving catchment-level nutrient leaching, erosion, production (milk, meat, wood and wood) or revenue. LUMASS generates an optimal land-use configuration (map), "before" and "after" performance statistics, and a land-use change matrix for each individual optimisation scenario.

LUMASS is free and open software, and has been developed by Manaaki Whenua – Landcare Research to support spatial planning and policy development by regional councils. It helps explore environmental and economic limits of a landscape (such as a catchment), assess the resource-use efficiency of land use and identify future development potential. LUMASS has been used in a number of case studies in Germany (Herzig, 2008), Ireland (Hochstrasser & Herzig, 2018), Korea (Herzig et al., 2018) and New Zealand (Ausseil et al., 2012; Herzig et al., 2013a,b, 2016).

LUMASS addresses questions such as:

- What is the impact of land use on the ecosystem?
- How efficiently does the land use in a given area use the available natural resources?
- How much headroom is available for a given land-use system to improve its resource-use efficiency in a given area?

- What distribution of land uses would reduce nutrient loss while maintaining current levels of production or revenue?
- Where should regional councils encourage land-use change to occur in order to meet their social and environmental objectives?

NManager is a catchment-scale model for considering the effectiveness of different designs of nitrogen regulation. The land uses it considers are dairy, sheep/beef and plantation forestry. NManager models land-use change as a result of farmers' nitrogen-mitigation decisions and gives non-spatial results, including the share of land in each land use along with costs of mitigation. The model inputs include land use, nitrogen transport and the design of regulation.

NManager has been developed by Motu Economic and Public Policy Research to assess the possible gains from regulation that account for the hydrological complexity of the Lake Rotorua catchment. It has been used to inform both local (Bay of Plenty Regional Council) and national (Ministry for Primary Industries) government on issues, including relative costs of different lake-quality targets (stringency and timing), allocation of costs, likely land-use change and interactions with GHG regulation. (Anastasiadis et al., 2011; Cox et al., 2011; Daigneault & McDonald, 2012; Yeo et al., 2012).

NManager addresses questions such as:

- How do different nitrogen-leaching policies affect land use and land-use intensity?
- How does the cost of obtaining a nitrogen-leaching target vary with the complexity of nitrogen-trading regulation?

The **Rural Futures MAS Model** is a regional-scale spatial simulation model for considering the implications of farmers' demographics and decision preferences, agricultural policies, and trends and shocks in prices and technologies on rural communities. The Rural Futures MAS Model allows for individual decision-making by farmers who differ in their avoidance of risk, objectives and peer networks. The land uses it considers are different intensities of dairy, sheep/beef and forestry. The Rural Futures MAS Model calculates the share of land in each land-use category on an annual time step, and estimates probable strategic decisions by farmers in response to changes in their operating environment. Given these responses, it also calculates regional wealth creation, and social and environmental outcomes. The model inputs include maps of land use and parcel boundaries, and data on farm inputs, outputs, prices, overhead costs and externalities.

The Rural Futures MAS Model has been developed by AgResearch and the New Zealand Institute of Economic Research as part of the Rural Futures Innovation Platform. It was designed to engage rural stakeholders with the issues affecting their communities (including irrigation and nutrient leaching) and possible approaches to addressing these (including regulatory responses). The model is intended to be customised for each region where it is used in order to focus on the issues of interest. The Rural Futures MAS Model has been used in Hawke's Bay, Taupo and Southland. (New Zealand Institute of Economic Research, 2013; Schilling et al., 2012).

The Rural Futures MAS Model addresses questions such as:

- How might individual farmers respond to nutrient-leaching and irrigation issues affecting their communities?
- How do these responses vary between individuals and over time?

The **Waikato Multiple Agent Model** is a regional model for considering the impact of policy design on the dairy industry. It considers only dairy farms, but allows the farms to vary according to their own unique characteristics. The model inputs include farm area, milk production, stocking rate, distance from waterways and soil types. Model outputs include grazing rotation across the year, feed allocation and sources (pasture, silages, concentrates and crops), herd size and structure, fertiliser use and abatement practices.

The Waikato Multiple Agent Model was developed solely to inform the design of nitrate policy. It has been applied to investigate the use of uniform reductions and the trading of entitlements for restrictions levied at stocking rates, use of nitrogen fertiliser and nitrogen leaching. The model has been used exclusively in the Waipa, Otorohanga and South Waikato areas (Doole, 2010; Doole et al., 2011; Doole, 2012; Doole & Pannell, 2012; Doole et al., 2012).

The Waikato Multiple Agent Model addresses questions such as:

- How do different regulations designed to reduce nitrogen loss impact land use and land-use intensity?
- How might dairy farms change management practices in response to different regulations?

WISE (Waikato Integrated Scenario Explorer) is an integrated model that links land use, demography, economics, climate, hydrology, water quality and biodiversity. We focus on its land-use sub-model. The WISE land-use sub-model considers changes among 25 different categories of land use, including dairy, dry stock, forestry, indigenous vegetation, horticulture, commercial, manufacturing and three types of residential use. Land-use change is determined based on transition potentials calculated from four factors: the suitability of the land; land uses on neighbouring land; ease of access; and zoning restrictions.

WISE determines land-use change by allocating land to the locations with the highest transition potential according to an externally provided demand. In WISE, the external demand for land is provided by the economic sub-model.

WISE produces annual maps of land use, along with indicators of the potential for each piece of land to change use. The sub-model inputs include maps of current land use, accessibility, zoning and other land-use restrictions, and the suitability of land for different uses in addition to industry and residential demands for land.

WISE was developed to support and facilitate long-run integrated planning by the Waikato Regional Council. The land-use sub-model is based on a model originally developed by White and Engelen (1997) and implemented by the Research Institute for Knowledge Systems in the Netherlands. WISE has been used exclusively in the Waikato region for which it was designed. Similar land-use models are currently under development for use in the Auckland and Wellington regions (Rutledge et al., 2011).

WISE addresses questions such as:

- How might land use in the Waikato region evolve under different climate, policy, price and demographic scenarios?
- How could the Waikato Regional Council respond to potential changes in land use and water quality?

Table 13: A bibliography of recent work from New Zealand's core land-use sector models

Model	Bibliography of recent work
LURNZ	Ausseil, A.G.E., Bodmin, K., Daigneault, A., Teixeira, E., Keller, E. D., Baisden, T., Kirschbaum, M.U.F., Timar, L., Dunningham, A., Zammit, C., Stephens, S., Bell, R., Cameron, M., Blackett, P., Harmsworth, G., Frame, B., Reisinger, A., Tait, A. & Rutledge, D. (2017). *Climate change impacts and implications for New Zealand to 2100: synthesis report RA2 lowland case study. Synthesis Report LC2714. Climate change impacts and implications for New Zealand to 2100*. Wellington: MBIE contract C01X1225. Daigneault, A., Elliot, S., Greenhalgh, S., Kerr, S., Lou, E., Murphy, L. & Timar, L. (2017). *Modelling the potential impact of New Zealand's freshwater reforms on land-based greenhouse gas emissions*. Motu Working Paper 17-10. Wellington: Motu Economic and Public Policy Research. Fleming, D., Dorer, Z., Stroombergen, A., Kerr, S. & Cortés-Acosta, A. (Forthcoming). *Land-use change as a mitigation for climate change: report 1, LURNZ and NZFARM model runs results*. Motu Working Paper. Wellington: Motu Economic and Public Policy Research. New Zealand Productivity Commission. (2018). *Low-emissions economy: Draft report*. Wellington: New Zealand Productivity Commission. https://www.productivity.govt.nz/inquiry-content/low-emissions-draft-report Rutledge, D. T., Ausseil, A. G. E., Baisden, T., Bodeker, G., Booker, D., Cameron, M. P., Collins, D.B.G., Daigneault, A., Fernandez, M., Frame, B., Keller, E., Kremser, S., Kirschbaum, M.U.F., Lewis, J., Mullan, B., Reisinger, A., Sood, A., Stuart, S., Tait, A., Teixeira, E., Timar, L. & Zammit, C. (2017). *Identifying feedbacks, understanding cumulative impacts and recognising limits: a national integrated assessment. Synthesis report RA3. Climate change impacts and implications (CCII) for New Zealand to 2100*. Wellington: MBIE contract C01X1225. Rutledge, D. T., Baisden, T., Cradock-Henry, N., Keller, E., Mason, N. Mullen, B., Overton, J.McC., Sood, A., Stuart, S., Tait, A., Timar, L., Vetrova, V. & Zammit, C. (2017). *Upper Waitaki catchment. Synthesis report RA2, uplands case study. Climate change impacts and implications (CCII) for New Zealand to 2100*. Wellington: MBIE contract C01X1225. Timar, L. (2016). *Does money grow on trees? Mitigation under climate policy in a heterogeneous sheep–beef sector*. Motu Working Paper 16-09. Wellington: Motu Economic and Public Policy Research.
NZ-FARM	Daigneault, A., McDonald, H., Elliott, S., Howard-Williams, C., Greenhalgh, S., Guysev, M., Kerr, S., Lennox, J., Lilburne, L., Morgenstern, U., Norton, N., Quinn, J., Rutherford, K., Snelder, T. & Wilcock, B. (2012). *Evaluation of the impact of different policy options for managing to water quality limits. Final report – main report and appendices*. MPI Technical Paper 2012/46. Wellington: MPI. Daigneault, A., Samarasinghe, O. & Lilburne, L. (2013). *Modelling economic impacts of nutrient allocation policies in Canterbury: Hinds catchment. Final report*. Landcare Research Contract Report LC1490 for Ministry for the Environment. Wellington: Ministry for the Environment. Daigneault, A., Greenhalgh, S. & Samarasinghe, O. (2014). A response to methodological limitations in the evaluation of policies to reduce nitrate leaching from New Zealand agriculture. *Australian Journal of Agricultural and Resource Economics*, *58*(2), 281–290. Daigneault, A. J., Greenhalgh, S. & Samarasinghe, O. (2017). Economic impacts of multiple agro-environmental policies on New Zealand land use. *Environmental*

	and Resource Economics, *69*(4), 763–785. https://doi.org/10.1007/s10640-016-0103-6 Djanibekov, U., Soliman, T., Stroombergen, A., Flood, S. & Greenhalgh S. (2018). Assessing the nationwide economic impacts of farm level biological GHG emission mitigation options. First draft. Report prepared for Ministry for Primary Industries. Dorner, Z., Djanibekov, U., Soliman, T., Stroombergen, A., Kerr, S., Fleming, D. A., Cortes-Acosta, S. & Greenhalgh, S. (2018). Land-use change as a mitigation option for climate change. Report to the Biological Emissions Reference Group (Project No. 18398). Walsh, P., Soliman, T., Greenhalgh, S., Mason, N. & Palmer, D. (2017). *Valuing the benefits of forests*. MPI Technical Paper 2017/68. Wellington: Ministry for Primary Industries.

Table 14: Recent publications using farm- and production-related models

Model	Recent Publications
AgInform®	Rendel, J. M., Mackay, A. D. & Smale, P. N. (2015). Valuing on-farm investments. *Journal of New Zealand Grasslands*, *77*, 83–88. Rendel, J. M., Mackay, A. D., Smale, P. N. & Vogeler, I. (2016). Moving from exploring on-farm opportunities with a single to a multi-year focus: implications for decision making. *Journal of New Zealand Grasslands*, *78*, 57–66. Rendel, J. M., Mackay, A. D. & Smale, P. N. (2017). The value of legumes to a Whanganui hill country farm. *Journal of New Zealand Grasslands*, *79*, 27–34.
APSIM	Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., G., Chenu, K., van Oosterom, E.J., Snow, V., Murphy, C., Moore, A.D., Brown, H., Whish, J.P.M., Verrall, S., Fainges, J., Bell, L.W., Peake, A.S., Poulton, P.L., Hochman, Z., Thorburn, P.J., Gaydon, D.S., Dalgliesh, N.P., Rodriguez, D., Cox, H., Chapman, S., Doherty, A., Teixeira, E., Sharp, J., Cichota, R., Vogeler, I., Li, F.Y., Wang, E., Hammer, G.L., Robertson, M.J., Dimes, J.P., Whitbread, A.M., Hunt, J., van Rees, H., McClelland, T., Carberry, P.S., Hargreaves, J.N.G., MacLeod, N., McDonald, C., Harsdorf, J., Wedgwood, S. & Keating, B. A. (2014). APSIM – evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software*, *62*, 327–350. Holzworth, D. P., Huth, N. I., Fainges, J., Brown, H., Zurcher, E. J., Cichota, R., Verrall, S., Herrmann, N.I., Zheng, B. & Snow, V. (2018). APSIM next generation: overcoming challenges in modernising a farming systems model. *Environmental Modelling and Software*, *103*, 43–51.
BiomeBGC	Keller, E. D., Baisden, W. T., Timar, L., Mullan, B. & Clark, A. (2014). Grassland production under global change scenarios for New Zealand pastoral agriculture. *Geoscientific Model Development*, *7*, 2359–2391. Rutledge, D. T., Ausseil, A. G. E., Baisden, T., Bodeker, G., Booker, D., Cameron, M. P., Collins, D.B.G., Daigneault, A., Fernandez, M., Frame, B. Keller, E., Kirschbaum, M.U.F., Lewis, J., Mullan, B., Reisinger, A., Sood A., Stuart, S., Tait, A., Texeria, E., Timar, L. & Zammit, C. (2017). *Identifying feedbacks, understanding cumulative impacts and recognising limits: a national integrated assessment. Synthesis report RA3. Climate change impacts and implications (CCII) for New Zealand to 2100*. Wellington: MBIE contract C01X1225. Thornton, P. E., Running, S. W. & Hunt, E. R. (2005). *Biome-BGC: Terrestrial Ecosystem Process Model, Version 4.1.1*. Oak Ridge, TN: ORNL DAAC. https://doi.org/10.3334/ORNLDAAC/805

Farmax	Bryant, J. R., Ogle, G., Marshall, P. R., Glassey, C. B., Lancaster, J. A. S., Garcéa, S. C. & Holmes, C. W. (2010). Description and evaluation of the Farmax Dairy Pro decision support model. *New Zealand Journal of Agricultural Research*, *53*, 13–28. Frater, P., Howarth, S. & McEwen, G. J. (2015). Livestock feed intake assumptions in decision support tools; a stocktake of the current science and assumptions used by livestock models. *Journal of New Zealand Grasslands*, *77*, 19–22. Litherland, A., Snow, V. & Dynes, R. (n.d.). *Decision support software and computer models to assist in feed allocation and utilisation in the New Zealand pastoral sheep and beef industries*. Hamilton: AgResearch. White, T. A., Snow, V. O. & King, W. McG. (2010). Intensification of New Zealand beef farming systems. *Agricultural Systems*, 103, 21–35.
MitAgator	McDowell, R. W., Lucci, G. M., Peyroux, G., Yoswara, H., Cox, N., Brown, M., Wheeler, D., Watkins, N., Smith, C., Monaghan, R., Muirhead, R., Catto, W. & Risk, J. (2014). MitAgatorTM: a farm scale tool to estimate and mitigate the loss of contaminants from land to water. In *21st Century Watershed Technology Conference and Workshop Improving Water Quality and the Environment Conference Proceedings, 3–6 November 2016, University of Waikato, New Zealand*. St Joseph, MI: American Society of Agricultural and Biological Engineers. https://doi.org/10.13031/wtcw.2014-024 Risk, J. T., Old, A. B., Peyroux, G. R., Brown, M., Yoswara, H., Wheeler, D. M., Lucci, G.M. & McDowell, R. W. (n.d.). *MitAgator™-in action solutions for managing nitrogen, phosphorus, sediment and e. coli loss*. Hamilton: Massey University.

Table 15: Recent non-core land-use model references

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LUMASS	Ausseil, A.-G. E., Herzig, A. & Dymond, J. R. (2012). Optimising land use for multiple ecosystem service objectives: a case study in the Waitaki catchment, New Zealand. In Seppelt, R., Voinov, A. A., Lange, S. & Bankamp, D. (eds), *Proceedings: 6th International Congress on Environmental Modelling and Software (iEMSs 2012), Leipzig, Germany, 1–5 July 2012*. Leipzig: International Modelling and Software Society. Herzig, A. (2008). A GIS-based module for the multi-objective optimisation of areal resource allocation. In Bernard, L., Friis-Christensen, A., Pundt, H. & Compte, I. (eds), *Proceedings: 11th AGILE International Conference on Geographic Information Science, Girona*. Herzig, A., Ausseil, A.-G. E. & Dymond, J. R. (2013). Spatial optimisation of ecosystem services. In Dymond, J. R. (ed.), *Ecosystem services in New Zealand – conditions and trends*. Lincoln: Manaaki Whenua Press. Herzig, A., Ausseil, A.-G. E. & Dymond, J. R. (2013). Sensitivity of land-use pattern optimisation to variation in input data and constraints. In Piantadosi, J., Anderssen, R. S. & Boland, J. (eds), *MODSIM2013, 20th International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2013*. Modelling and Simulation Society of Australia and New Zealand. Adelaide, Australia. http://www.mssanz.org.au/modsim2013/H12/herzig.pdf Herzig, A., Dymond, J. R. & Ausseil, A.-G. E. (2016). Exploring limits and trade-offs of irrigation and agricultural intensification in the Ruamahanga catchment, New Zealand. *New Zealand Journal of Agricultural Research*, *59*, 216–234. Herzig, A., Nguyen, T. T., Ausseil, A.-G. E., Maharjan, G. R., Dymond, J. R., Arnhold, S., Koellner, T., Rutledge, D. & Tenhunen, J. (2018). Assessing resource-use efficiency of land use. *Environmental Modelling and Software*, 107, 34–49. https://doi.org/10.1016/j.envsoft.2018.05.005 Hochstasser, T. & Herzig, A. (2018). Research needs for climate change mitigation through land use change. Contract report prepared for the Environmental Protection Agency (EPA) Ireland (unpublished).
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Rural Futures MAS Model	New Zealand Institute of Economic Research. (2013). Rural Futures. Presentation. Schilling, C., Kaye-Blake, W., Post, E. & Rains, S. (2012). The importance of farmer behaviour: an application of Desktop MAS, a multi-agent system mode for rural New Zealand communities. Paper presented at the 2012 NZARES Conference, 30–31 August, Nelson, New Zealand. New Zealand Agricultural and Resource Economics Society.
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