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Development of a Systems Model for Assessing Pathways to Resilient, Sustainable, and Profitable Agriculture in New Zealand

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Abstract: There is a clear research gap in understanding how future pathways and disruptions to the New Zealand (NZ) agricultural system will have an impact on the environment and productivity. Agriculture is in a period of significant change due to market disruptions, climate change, increasingly stringent environmental regulations, and emerging technologies. In NZ, agriculture is a key sector of the economy, therefore government and industry need to develop policies and strategies to respond to the risks and opportunities associated with these disruptors. To address this gap, there is a need to develop an assessment tool to explore pathways and interventions for increasing agricultural profitability, resilience, and sustainability over the next 5–30 years. A decision support tool was developed through Stella Architect, bringing together production, market values, land use, water use, energy, fertiliser consumption, and emissions from agricultural sectors (dairy, beef, sheep, cereals, horticulture, and forests). The parameters are customisable by the user for scenario building. Two future trend scenarios (Business as usual, Optimisation and technology) and two breakaway scenarios (Carbon farming, Reduction in dairy demand) were simulated and all met carbon emissions goals, but profitability differed. Future environmental regulations can be met by adjusting levers associated with technology, carbon offsets, and land use. The model supports the development and assessment of pathways to achieve NZ's national agriculture goals and has the potential to be scaled globally.

Keywords: agricultural technology; reduction in carbon emissions; environmental targets; future scenarios; decision support tool

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1. Introduction

Global food and agricultural systems are under pressure from a variety of disruptive forces such as climate change [1], emerging diseases or pandemics [2,3], socioeconomic factors (i.e., war, conflict), trade restrictions/barriers or agreements [4], new food consumption trends [5,6], disruptive technologies such as cow less milk [7] and policy decisions such as the Carbon Zero initiative for 2050 [8,9]. These disruptions are critical for countries such as New Zealand (NZ) where agriculture is a major production and export industry. For example, over the past years, challenges arising from the Covid-19 pandemic, such as supply chain and food service disruption and tight labour markets together with abnormal climate (a warm and dry summer, low soil moisture levels, and a severe hail event) have caused significant damage to horticulture production and export in NZ [10]. Although this has resulted in significant short-term issues, these types of disruptive factors highlight weaknesses in the NZ agricultural system and the urgent need to address long-term resilience [11,12]. This type of challenge has also been observed at every scale of the agricultural system all around the world.

Moreover, the future of agricultural systems depends on the system's responses to the global challenges and international goals arising from carbon emission reduction, water availability, water quality and biodiversity restoration, and ecosystem services provision. Since the 2000′s, the international community, through multilateral agreements and Non-Governmental Organisations (NGOs), have advocated for countries to restore or limit their impact on the environment. At the international scale, the Intergovernmental Panel on Climate Change (IPCC) and United Nations (UN), have guided recommendations and incentives on climate, biodiversity, and ecosystem services challenges, such as the Paris Agreement [13], the Sustainable Development Goals (SDGs) [14,15], the Millennium Ecosystem Assessment [16], and the Aichi Biodiversity Targets [17]. Policy, technology, and science have a key role to play in addressing these challenges at a national scale and gain in systems resilience, sustainability, and profitability [18–20]. Indeed, recent technological advances can be seen as positive factors helping achieve policy goals and adapt to disruptions. For example, precision agriculture can be used to optimise yields and minimise nutrient losses [21,22], biotechnology, through the use of seaweed in cow feed, can reduce methane emissions [23,24], and water use efficiency improvements can be achieved through irrigation optimisation [25].

To evaluate the future performance of agriculture in New Zealand or elsewhere, resilience, sustainability, and profitability need to be quantified. More specifically, the resilience of the agricultural system, the sustainability of the agricultural production, practices, and resources used, and the economic profitability of the agricultural system. Resilience is defined as the ability of an agricultural system to cope–withstand and/or adapt-from multiple challenges [26–28]. In our context, the resilience concept means maintaining an agricultural production of sufficient measurable quantities (such as volume of production, calories) despite disruptive perturbations. The resilience of the agricultural system at a national scale is linked with sustainability and profitability concepts and is understood to ensure a certain level of agricultural production a year is achieved, regardless of disruptions. Resilience is gained if the amount of production, sustainability, and profitability objectives are exceeded. The concept of "sustainability" represents the integrity and health of the biosphere/ecosystem and the future wellbeing of its population and the capacity to preserve this integrity in the mid to long-term [28,29]. "Sustainability" is understood here as sustainable agricultural production under a goal-oriented framework [30], focusing on water use (i.e., irrigation) and the sustainability of agricultural practices in regards to greenhouse gas (GHG) emissions. Finally, profitability in NZ agriculture follows the goals set out by the NZ Ministry of Primary Industries (MPI) strategy, by producing high-value food and primary production to build prosperity for all New Zealanders. The yearly MPI profitability objectives are currently quantified as adding $44 billion in export earnings in total over the next decade from 2020 to 2030 [31].

There is an urgent need for prospective modelling and scenarios to define pathways for a resilient, sustainable, and profitable agricultural system. Models are critical to making informed agricultural policy decisions [32], however, few countries have appropriate agricultural systems models or decision-support tools to inform policy development under disruptive changes. One notable exception is the EU which uses the Common Agricultural Policy Regionalised Impact (CAPRI) model to evaluate the impacts of the Common Agricultural Policy and trade on production, income, markets, and the environment from global to regional scales [33]. Although there are a number of models available for agricultural systems modelling, none are intended to be used for modelling major national or regional disruptions to agriculture, or their usability outside inbuilt geographic boundaries is low [34]. Modelling approaches and available agricultural systems' models at the regional to national scale were reviewed in previous work to define the best options for the New Zealand policy development [33]. Available agricultural models were developed from science knowledge for policy development and focus on agricultural sustainability and resilience [32,33,35–37]. Some of the available models group a wide range of indicators, such as the integrated Sustainable Development Goals model (iSDG, [36]), which is customisable for all countries, or the Integrated Valuation of Ecosystem Services and Tradeoffs (InVest), a multi-ecosystem-services modelling platform [38]. Other models only focus on one part of the system, such as crop models, water models, energy models, GHG emission calculators, or climate models. Additionally, several other quantitative national-based DST were reviewed, with or without spatially explicit components. For example, the American Trade-Off Analysis–Multidimensional impact assessment model (TOA-MD) simulates the economic, environmental, and social impacts of agricultural systems [35]. The Australian Multi-Criteria Analysis Shell (MCAS-S) for Spatial Decision Support allows stakeholders to see the effects of land use change decisions [39]. The American Agricultural Conservation Planning Framework (ACPF) identifies site-specific opportunities to install conservation practices across small watersheds [40–42]. The Reflexive Interactive Design (RIO) conceptual approach works as an expert consultation guideline [43,44]. However, none of those models consider all the sectors of the NZ agricultural system, were adaptable at the national scale or were easily transferable to NZ without significant re-development of the model. Furthermore, the complexity of the NZ agricultural system and its economic, social, and environmental implications, requires integrative approaches, particularly at the national scale for policy and decision-making. Modelling options are being considered by the New Zealand government and requested by the industry and sectoral organisations to gain in national understanding of the future of NZ agriculture and help define efficient policies over the next 5–30 years. Developing an assessment tool to explore different pathways and interventions for increasing the profitability, resilience, and sustainability of agriculture in *Aotearoa* in the long-term is also seen to be of great importance to *Māori*, both in terms of *Māori* economic interests and with respect to *Te Taiao (the environment that contains and surrounds us)*.

The main aim of this paper is to present the development of a systems model that provides a better understanding of the key factors that drive NZ's agricultural system and helps to identify pathways for a sustainable, resilient, and profitable future under disruptive changes. The development of this tool addresses key gaps in national and global agricultural modelling. Through future scenario simulations, research questions of how different pathways and interventions can achieve national environmental and economic goals, are investigated. The specific objectives of this paper are to (1) develop a numerical model that quantifies agricultural outputs such as carbon emissions, water quality, and irrigation quantity used, as influenced by land use, technology, and other factors; (2) to explore pathways to ensure high export value production while reaching New Zealand's carbon neutrality target by 2050.

2. The New Zealand Agricultural System

2.1. Agricultural Land in New Zealand

Agriculture is present in 53% of the total NZ land area. The dairy sector represents 12% of the agricultural land, forestry 11%, and meat and wool sectors (sheep, beef, deer production) represent 75% of the agricultural land. Horticulture and arable sectors cover 1% of each of the agricultural land (Figure 1). Most of the Dairy sector is located in the North Island (Waikato, Taranaki, and Northland regions), and irrigated lands of the Canterbury plains are home to a large part of the arable sector. Horticulture is mainly located in the Marlborough and Tasman-Nelson regions for the South Island, and in the Bay of Plenty on the North Island. Finally, the meat and wool sectors are located throughout the country, mainly on hill lands.

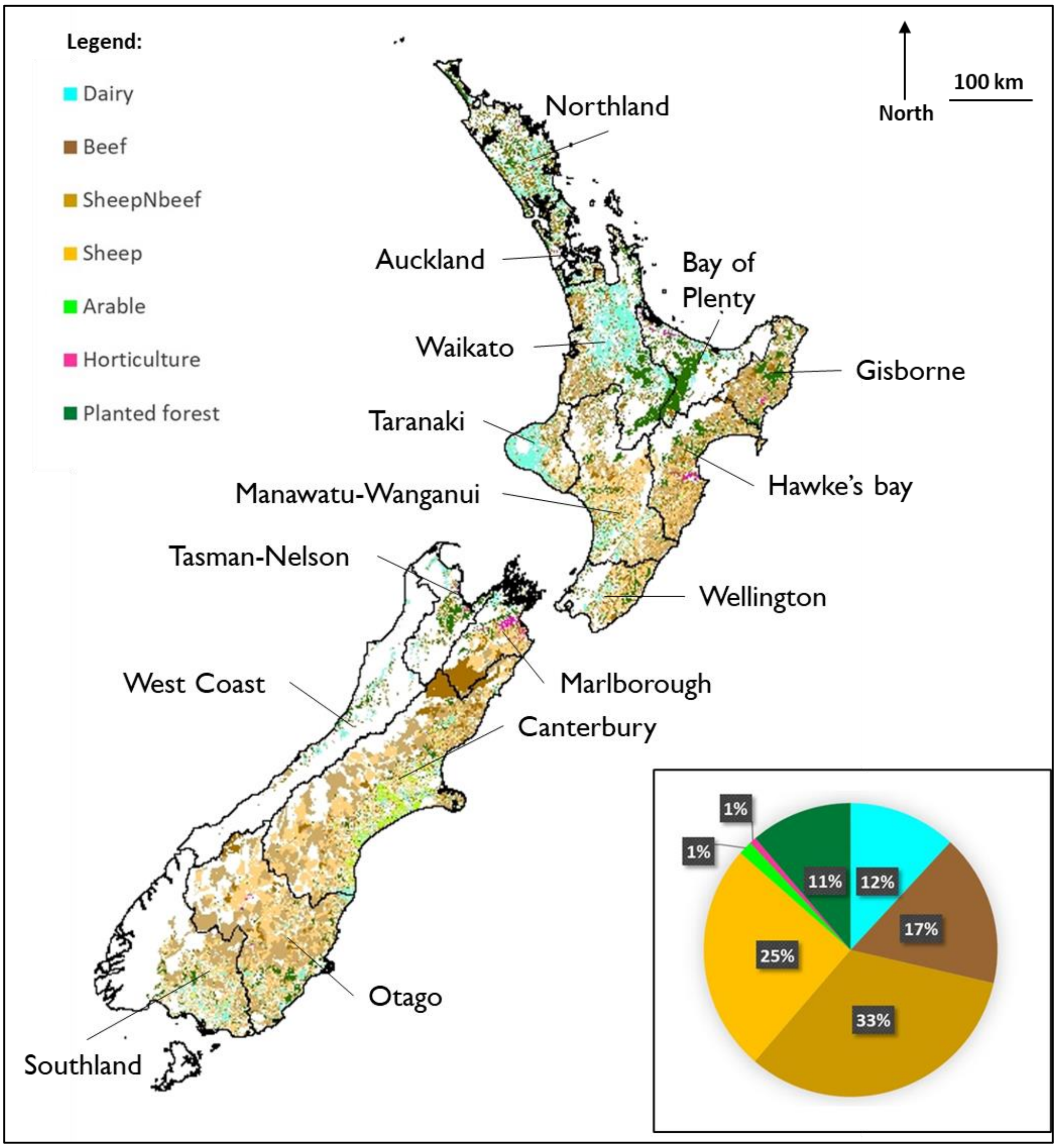


Figure 1. The agricultural land use in New Zealand. (Data sources: LUCAS NZ Land Use Map 1990 2008 2012 2016 v006, Ministry for the Environment; Land Use Capability, Manaaki Whenua Landcare Research; AgriBase, Asure Quality Kaitiaki Kai.).

2.2. An Agricultural System Geared towards Global Exports

The New Zealand agricultural production system encompasses six main sectors: dairy, meat and wool, forestry, horticulture, seafood, and arable. According to the Ministry for Primary Industries (2021), the food and fibre export revenue represented 47.5 billion NZ$ in 2021 mainly from dairy (40%), meat and wool (22%), horticulture (14%), and forestry (13%). Agricultural production is exported to China (35%), the USA (9%), Australia (9%), Europe (6%), Japan (6%), and smaller amounts to other countries. Over the past 10 years, except for the year 2021, total export revenues from food and fibre were growing from 2% to more than 10% each year. The New Zealand Ministry of Primary Industries is now forecasting an increase of about 2.5 to 3.5% each year for the next five years. This should push export revenue from food and fibre to 53.1 billion NZ$ by 2025. Agricultural sector exports are detailed in Appendix A and the impact of climate change on the agricultural system is in Appendix B.

2.3. Agricultural Technology

New Zealand is at the forefront of technological advances both in pastoral and horticultural sectors, due to its need to increase productivity and tackle environmental impacts. Pastoral technological advances focus on soil nutrient management driven by sensor technology and innovation in precision low-rate fertiliser spreading, virtual fencing to shift herd remotely and monitor herd's health, livestock intelligence for animal identification and monitoring, use of genomics for breeding, variable rate irrigation systems coupled with soil moisture sensors, and innovative effluent treatment to reduce environmental impacts. Horticulture technologies focus on resource optimisation for production increase, such as the use of 24/7 robotic harvesters, unmanned aerial vehicles (UAVs), map-based software to predict yields, robotics for packing and stacking, and automated cold storage and storage temperature sensors.

A recent study estimates one in every 10 protein products sold in 2035 will come from alternative protein sources [45]. Biotechnologies driving the development of animal-free food products, such as plant-based 'meat', cultured meat, and synthetic cow's milk, have the potential to overcome various environmental, health, and ethical challenges [7]. This is already impacting New Zealand, and its optimal response to these developments will depend on the scale, breadth, and timing of innovation as well as the ability of alternative proteins to deliver to core consumer needs [46]. A diverse range of new processed vegetable products is already available on the NZ market, especially plant-based 'meat' [10]. While there will be strategic risks to the food and agriculture sector, alternative proteins also offer potential opportunities to diversify on-farm production and build new income streams.

2.4. Environmental Consequences and Government Response

Nearly half of New Zealand's GHG emissions come from agriculture [47]. The main source of agricultural emissions is methane from livestock digestive systems and manure management which makes up around three-quarters of agriculture emissions. The next largest source is nitrous oxide from nitrogen added to soils. Nitrogen is used as fertiliser, but not all nitrogen can be used by plants and microorganisms, so some nitrogen may leach from the soil into groundwater or runoff into waterways. Leaching also comes from urine or dung from livestock. According to Stats NZ, of the estimated nitrate leached from livestock, 65% was from dairy and 15% from sheep in 2017. Consequently, 70% of river lengths have been modelled to have nitrogen concentrations above the expected range for natural conditions between 2013 and 2017.

As a result of climate change and the Paris Agreement ratification, and the need to improve degraded water bodies (wetlands, streams, and groundwater), the New Zealand Government has actioned the following policy statements:

- The Zero Carbon Amendment Act (2019);
- The National Policy Statement for Freshwater management (2020).

The Zero Carbon Act (2019) provides a framework to implement climate change policies that contribute to achieving the Paris Agreement (limit the increase of global average temperature to 1.5 °C above pre-industrial levels) and allow the country to prepare and adapt to the effects of climate change. This requires the Government to develop and implement policies for climate change adaptation and mitigation. The agricultural sector requires farmers to reduce on-farm agricultural GHG emissions and adapt to climate change. The Government's Zero Carbon Amendment Act has the following quantitative targets to reduce all GHG:

- Carbon dioxide and nitrous oxide have to be reduced to net zero by 2050.
- Methane has to be reduced by 10% below 2017 levels by 2030 and 24–47% by 2050.

The Climate Change Commission will monitor progress towards these goals, establish a system of emissions budgets for the agricultural sector, and review targets by 2022.

The National Policy Statement for Freshwater [48] provides local authorities with direction on how they should manage freshwater under the Resource Management Act 1991. Among the seven standards designed, four are directly related to agricultural activities:

- set minimum requirements for feedlots and other stockholding areas;
- improve poor practice intensive winter grazing of forage crops;
- restrict further agricultural intensification until the end of 2024;
- limit the discharge of synthetic nitrogen fertiliser to land, and require reporting of fertiliser use.

With a highly productive agricultural sector, specifically designed for international export, New Zealand needs to balance production with climatic challenges and environmental consequences and respond to disruptions. In this context, there is a need for exploring pathways to maintain high production and export levels to sustain growth in profitability while ensuring environmental sustainability and resilience of the agricultural system.

3. Materials and Methods

3.1. Model Design

3.1.1. Aim and Originality of the Model

A linear statistical model, the first of its kind, has been developed to represent the whole agricultural system of New Zealand at the national scale. The model brings together all the different sectors production, market values, land and water use, energy and fertiliser consumptions, and emissions. The model quantifies agricultural outputs relative to resilience, sustainability, and profitability, i.e., carbon emissions and offset consequences, irrigation water use, and water quality as influenced by land use, technology, agricultural production value, and other factors. The model runs with current data, is validated using historical data, and is designed to integrate user assumptions and compute output indicators for 2050. Ultimately, the model aims to be used for building disruptive scenarios and exploring pathways to reach government objectives of ensuring high export value production and carbon neutrality by 2050.

3.1.2. Model General Organisation

The model has three main parts (Figure 2): the inputs (land, productivity, and value in terms of $ per unit of production), the technology (irrigation, fertilisers, energy), the outputs (water used–quality and quantity-, food and fibre energy produced, GHG emissions, and export value of goods). The input and technology parameters are set with current data and customisable by the user for projections. The five main production sectors are explicitly represented in the model (dairy, meat, and wool, horticulture and viticulture, arable and forestry production), whereas seafood and processed food are only implicitly represented in the production export value because they are not land-based direct production.

The model assumes that the land sustains most of the agricultural production. Land use is represented by dairy, beef, sheep, cereals, horticulture, and forestry. Production is represented in the model by the agricultural yields and the number of animals per hectare (dairy cattle, beef, sheep). Agricultural production is then multiplied by a mean market value to calculate an export value per sector. The technologies selected contribute to productivity and sustainability outcomes. The model accounts for the average use of irrigation, nitrogen fertilisers, and energy, and estimates GHG emissions of carbon dioxide and its equivalent from nitrogen and methane emissions. The model also allows the user to input an efficiency improvement percentage to estimate the impact of a technological improvement. For example, a particular irrigation efficiency improvement due to a new technological adoption will reduce a 10% amount of water used for the same area irrigated. These technological or biotechnological assumptions or inputs allow the user to determine how much and what type of technology is needed (along with other factors, i.e., land use change) to reach environmental objectives.

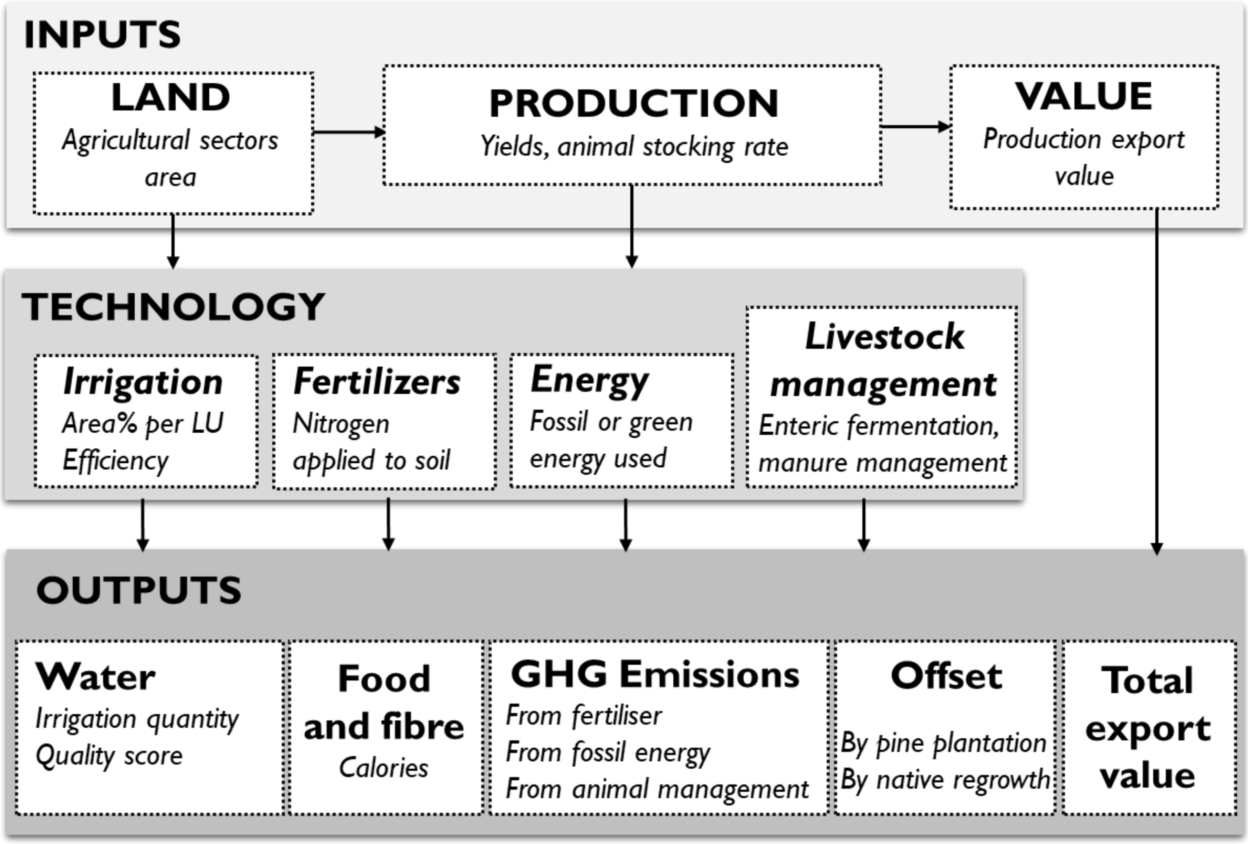


Figure 2. Model flowchart consisting of inputs, technology parameters, and computed outputs.

A large range of outputs are computed by the model: the amount of water used by irrigation for agricultural production; a water quality (improvement) score; overall food and fibre energy production; GHG emissions from fertilisation, livestock, and fossil energy; the emissions' offsets by vegetation and land use changes; and the overall export value (Figure 2).

3.1.3. Key Model Assumptions

The model is designed for disruptive scenario exploration with the objective to reach NZ's environmental and profitability goals. To achieve this, land use change, production optimisation, high-value products, and technology efficiency gains are the main parameters that can be adjusted. Table 1 describes the model process and responses for selected disruption examples.

Adjusting land use change and production optimisation means making broad assumptions about changes in agricultural practices, and changes in production systems, but also gains in technology efficiency, new technologies, or biotechnologies. Those upcoming technological and biotechnological gains are highlighted in the discussion section.

Irrigation changes can be used as an example of applying the model to simulate technological disruptions. Irrigation is widely used for cereals and horticulture production but is it also largely used for the dairy sector [49] because NZ dairy relies on grass-fed cows. However, irrigation efficiency varies according to the type of technology installed. The irrigation technology efficiency can thus be adjusted to simulate the wide adoption of a new irrigation technology by 2050.

Table 1. Model processes and responses according to disruption examples.

Main Disruption Examples		Element Adjusted in Model Input/Tech	Process	Output Consequence
Environment	• Climate change	• Yields • Irrigation	• Low increase or decrease in yields • Increase need for irrigation	• Decrease in food calories produced • Decrease in export value • Increase in irrigation water used
	• Extreme events (drought, flooding)	• Yields • Irrigation	• Decrease of yields • Increase need for irrigation	
	• Pandemics, diseases	• Production values • Sectoral land area	• Lower demand, lower market value • Land abandonment, native vegetation regrowth	• Decrease in export value • Food calories adjustment • Increase in carbon stock • Emission offsets
Technology	• Water and nutrient use efficiency	• Irrigation efficiency • Fertilisers	• increase in irrigation efficiency • Decrease in nitrogen input	• Decrease in irrigation water used • Improved water quality • Decrease in N_2O emissions
	• High-tech data access • Precision agriculture generalisation • High tech material	• Irrigation efficiency • Fertiliser use efficiency • Green energy use	• Better irrigation efficiency • Lower fertiliser use • More green/Less fossil fuel energy used	• Decrease in irrigation water used • Improved water quality • Decrease in N_2O emissions • Decrease in CO_2 emission from energy
	• Biotechnology	• Enteric fermentation • Manure management improvement	• Lower enteric fermentation emitted • Lower Manure or lower emission from manure	• Decrease in CH_4 emissions
Socio-economic	• Food consumption trends	• Sectoral land area • NZD Value	• Increase cereal/horticulture area • Decrease meat production land use and animal numbers • Increase the value of niche market (high-value crops)	• Increase export value • Decrease emissions from CH_4 • Increase in irrigation water used • Food calories adjustment

Table 1. *Cont.*

Main Disruption Examples	Element Adjusted in Model Input/Tech	Process	Output Consequence
• Trade restrictions/barriers, trade agreements	• NZD Values • Sectoral land area	• Lower/higher demand, lower/higher market value • Land abandonment, native vegetation regrowth • Or agricultural land extension	• Increase/decrease in export value • Food calories adjustment • Increase/decrease of carbon stock and emission offset

An example of simulating the implications of modifying agricultural practices can be shown with managing fertilisers. Nitrogen fertilisers are extensively used in the NZ agri-system, especially in the dairy sector along with the irrigation of pastures. Strategies to reduce Nitrogen fertiliser use are widely promoted by the Ministry of Primary Industries in order to meet the water quality requirements and reduce GHG emissions. The model allows the simulation of better management of Nitrogen fertiliser or the adoption of green fertilisers, and their consequences on the water quality.

Livestock emissions, i.e., enteric fermentation and manure management, play a key role in GHG estimates. Standard values can be applied, but the model allows users to modify these values and simulate improvements in management by assuming efficiencies from new biotechnologies (e.g., alternative forage, inhibitor pills, vaccine–see discussion section).

Energy used on farms from fossil fuels (e.g., building, irrigation, machinery, tractors) also plays a large role in GHG emissions. Electricity from renewable energy is set to be more generalised and the effects of this can also be simulated. The model allows for more green energy use, e.g., solar panels or wind turbine fields, to reduce the GHG emissions from energy used.

3.2. Model Data and Parameters

Data used for the model development (2019) and the validation (2010) all come from a freely available database or online data source (Table 2), i.e., Stats New Zealand [50], Ministry for Primary Industries [51], Food and Agriculture Statistics (FAOSTAT) [52], Beef + Lamb New Zealand [53], Dairy NZ [54], and Irrigation NZ [49].

Parameters not provided directly by the databases were computed following a proxy-based or phenomenological statistical modelling method (Table 2).

Proxy-based is a relatively simple statistical approach based on well-known causal relationships between variables and computed by way of calibrated empirical relationships. For example, the horticultural yield is assumed to be a simple ratio between production amount and area of production. The horticultural yield parameter is based on the production amount per item and the area of production per item. The horticultural mean yield is computed by a weighted ratio between the amount of production per item divided by the area of production per item.

Phenomenological models are simplified models to describe the empirical relationship of phenomena to each other. Phenomenological parameters in this model are based on quantitative relationships between land use or animal and a biophysical, biological, or technological process. In contrast to simple proxy models, at least part of the parameters and relationships are transferred from in-depth process-based studies or *meta*-analyses of observations [55]. These models represent a functional relationship between landscape/animal attributes and environmental outcomes. For example, the methane emissions are based on the known biological process of enteric fermentation per animal, depending on the animal type and function, and by the known biophysical process of manure management depending on the farm type.

Table 2. Model development (2019) and validation (2010) data: parameters, determination methods, data sources, and values.

	Parameters	Method	Data Sources	Value 2010	Value 2019
Inputs	Land area (ha)	Data provided	Stats New Zealand		
	- Dairy			2,200,000	2,221,459
	- Beef			2,800,000	2,718,917
	- Sheep			5,200,000	4,101,801
	- Horticulture			129,000	132,717
	- Cereals			135,547	124,292
	- Forest			1650,000	1,597,957
	- Total			12,114,547	10,897,143
	Yields	proxy	Stats New Zealand FAOSTAT Beef + Lamb NZ Dairy NZ		
	- Milk solids (kg/animal/year)			307	380
	- Meat from beef (kg/an)			167	155
	- Meat from sheep (kg/an)			18.6	20.2
	- Horticulture (t/ha)			17.1	19.6
	- Cereals (t/ha)			7.4	8.2
	Animal stocking rate (animal/ha)	proxy	Stats New Zealand FAOSTAT		
	- Dairy cattle			2.68	2.81
	- Beef			1.41	1.43
	- Sheep			6.26	6.65
	Value	proxy	Ministry for Primary Industries Beef + Lamb NZ Dairy NZ		
	- Milk solid (NZD/kg)			6.1	9.6
	- Beef (NZD/kg)			3.3	4.9
	- Sheep (NZD/kg)			4.7	6.3
	- Horticulture (NZD/tonne)			1697	2342.4
	- Cereals (NZD/tonne)			159	231.8
	- Forest (NZD/ha)			2341.2	4307.3
Technology	Irrigation (%)	Phenomenological	Irrigation NZ Stats New Zealand FAOSTAT		
	- Dairy irrigation			18.6	19.14
	- Livestock irrigation			1.6	2
	- Cereals irrigation			62	62
	- Horticulture irrigation			73.8	86.8
	Total nitrogen fertiliser applied (nitrogen tonnes)	Phenomenological	Stats New Zealand FAOSTAT	249,366.5	332,593.4
	- Dairy (kg/ha/year)			96.5	100.6
	- Meat prod (kg/ha/year)			8.6	12.3
	- Horticulture (kg/ha/year)			52.1	46.8
	- Cereals (kg/ha/year)			98.6	154.1
	Energy used (tj/year)	Phenomenological	FAOSTAT		
	- From electricity			7675.2	8338.3
	- From gas/diesel			14835	13923.4
	- From other gas			3598	2471

Table 2. *Cont.*

	Parameters	Method	Data Sources	Value 2010	Value 2019
	Enteric fermentation (kg CH_4/head) - Dairy cattle/Beef/Sheep Manure based CH_4 production (kg CH_4/Head) - Dairy cattle/Beef/Sheep	Phenomenological	FAOSTAT	90/60/8 23.35/1/0.19	90/60/8 23.35/1/0.19
Outputs	Irrigation water used (km^3/year)	proxy	FAOSTAT	2.72	2.8
	Food energy production (million kcal/ton/year) - Dairy - Meat - Horticulture - Cereals	Phenomenological	FAOSTAT	0.03 0.3 0.65 0.05	0.037 0.25 0.85 0.113
	Emissions (Gg CO_2 eq) - From nitrogen - From carbon dioxide - From methane	Phenomenological	FAOSTAT (IPCC Guidelines for National GHG Inventories)	13,900 1854.3 23,381.5	14,700 1824.8 23,150
	Total export value (NZD million)	proxy	Ministry of Primary Industries	28,398	46,329

3.2.1. Model INPUTS

Land Use Areas

Agricultural and horticultural land uses are expressed in surface area (hectares) for the following categories: dairy, beef, sheep, horticulture, cereal, and forestry area.

Production

Agricultural production is expressed by yield per agricultural sector and livestock parameters. Yield per agricultural sector is expressed as follows: milk solids in kg/animal/year, meat from beef production in kg/animal, meat from sheep production in kg/animal, horticulture production in tonne/hectare, and cereal production in tonne/hectare. Livestock parameters are the number of animals/hectare, per animal type, which represent the animal pressure on the land and the intensity of the agricultural system.

Value

The value of products is expressed in New Zealand Dollars (NZD). The value of milk solids and meat from beef and sheep are expressed in NZD/kg, whereas horticulture and cereals are expressed in NZD/tonne and forestry value in NZD/ha.

3.2.2. Technology and Emission Mitigation Options

Irrigation

Irrigation represents the percentage of area irrigated or land equipped by an irrigation system per sector (i.e., dairy, livestock, cereals, horticulture).

The irrigation efficiency improvement represents the use of an improved irrigation system that could save a percentage of water use. For example, the user can test a scenario with 40% water saved by micro-drip irrigation (comparted to 2019) for the horticultural sector.

Fertiliser

Fertiliser represents the amount of nitrogen fertiliser used in kg/ha/year per agricultural sector (i.e., dairy, livestock, cereals, horticulture).

The efficiency improvement percentage allows the simulation of a reduction in nitrogen fertiliser use (by better management practices or other green fertiliser use). In addition, this option can be used to quantify the reduction in use needed to reach environmental objectives.

Energy

Energy represents the fossil energy and electricity used. On a farm, energy is mainly used by buildings, irrigation systems, machinery, and tractors. Electricity used is expressed in terajoule/tonne/year, gas diesel oil, or other gas are expressed in terajoule/ha/year.

The green energy used indicator is a percentage of green energy that can be added on-farm to reduce the use of fossil energy.

Livestock and Emissions

Livestock manure and enteric fermentation are computed per animal type (dairy cattle, beef, sheep), in methane kg/animal/year.

Efficiency improvements represent a percentage of methane reduction assumed by the user if new technology or biotechnology is implemented (e.g., enteric fermentation inhibitors, alternative forage generalisation, vaccine, see discussion section).

3.2.3. Computation of Model Outputs

Output indicators are computed from input data and technological parameters (Figure 3).

Irrigation Water Use

The total amount of water used by irrigation is represented in km^3/year units. This indicator is computed for each irrigated land use type, accounting for irrigation efficiency improvements, as follows:

$$\mathrm{IWU} = \sum_k \left(L_k \times \left(W_k \times \left(1 - \left(\frac{Ef}{100} \right) \right) \right) \right) \tag{1}$$

where

IWU is the irrigation water use, L_k is the land type area where k is the land use type, W_k is the average water used per ha per land use type k, and Ef is the percent efficiency improvement from the baseline in 2019.

Water Quality Improvement Score

The water quality improvement score represents the consequences of better or worse practices for water quality improvement from the 2019 baseline. At a national scale, and using only quantitative data (non-spatial data), representing the concept of water quality is difficult [56]. However, some basic trends in water quality improvement can be used to establish a water quality (improvement) score:

- decreasing the average amount of water used by irrigation (especially on pastures) reduces nitrogen loss and soil leaching [57].
- decreasing or improving the application of fertilisers reduces nitrogen loss [58]
- developing riparian protection, and nutrient and effluent management reduces losses [58].
- favouring the planting of native vegetation over exotic vegetation appears more favourable in the long term to the improvement and restoration of water quality and biodiversity as a whole [59,60].

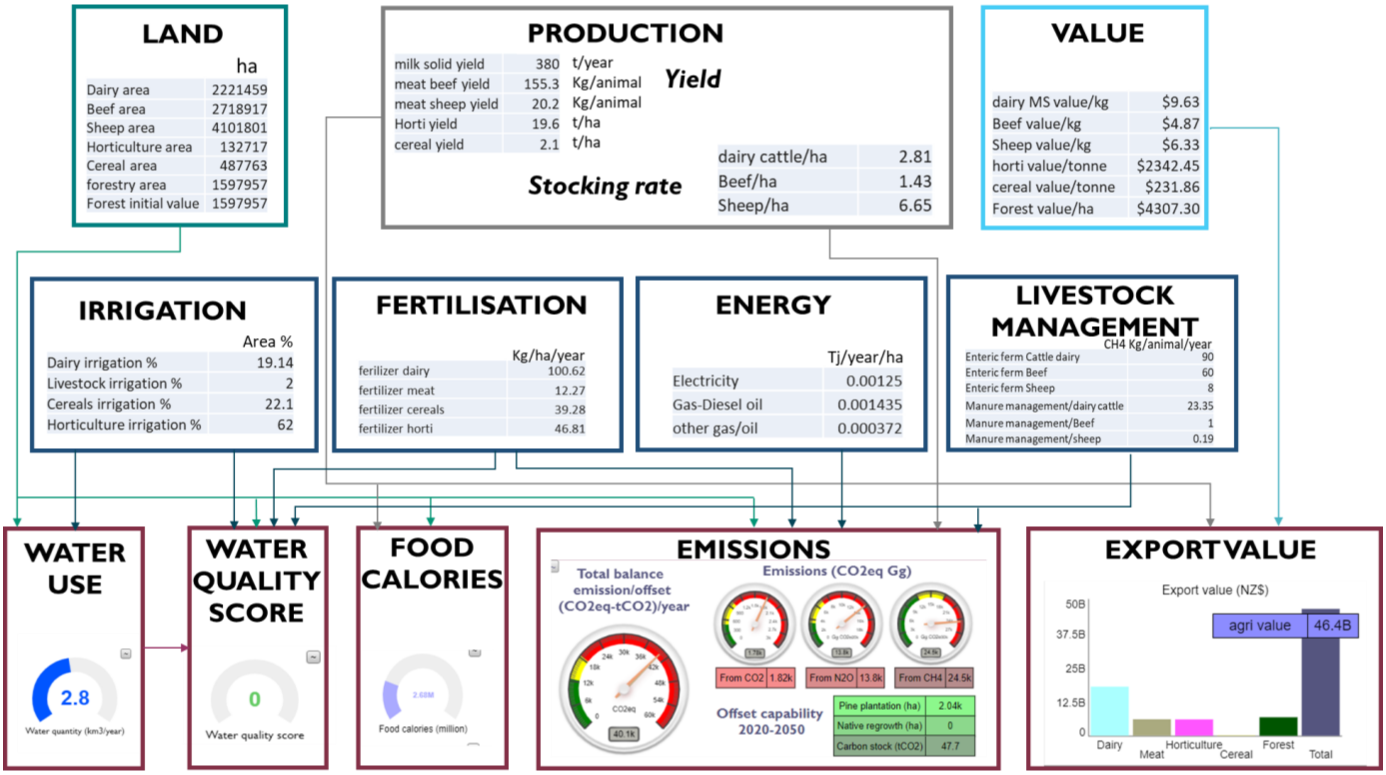


Figure 3. Model process description: relationships between input parameters, technological parameters, and output indicators. Values are for 2019.

The water quality improvement score ranges from 0 to 6. The value of 6 represents the best practice to improve water quality. The value is computed by a score of 0 or 1 for each of the following parameters: the irrigation water used per year (A), the irrigation percentage of pastures (B), the amount of fertiliser used (C), the quantity of manure managed (D), the area of planted forest (E) and native regrowth (F). A score of 0 is given to a parameter if its value is identical or worse than the 2019 value, and a score of 1 is given to a parameter that improves its value over time (Equation (2)).

$$\mathrm{WQS} = \sum_i P_i \tag{2}$$

where WQS is the water quality improvement score (ranging from 0–6) and P_i is the best practice value to improve water quality (0 being false and 1 being true) for the range of i parameters from A to F (as indicated above).

Food Calories

Food energy production is expressed as calories produced each year. The amount of production (tonnes per agricultural product) is multiplied by the mean energy per weight (Equation (3)).

$$\mathrm{Fe} = \sum_s (P_s \times E_s) \tag{3}$$

where Fe is the food energy in calories, P is the production (tonnes) for each sector s, and E is the mean energy for products in each sector s (i.e., 0.1135 kcal/tonne of cereals; 0.000037 kcal/tonne of milk solid; 0.00025 kcal/tonne of meat; 0.85 kcal/tonne of fruits and vegetables).

GHG Emissions

GHG emission indicators are expressed in carbon dioxide equivalent (CO_2eq in Gigagrams), from nitrogen, carbon dioxide, and methane emissions (Equation (4)).

$$\mathrm{GHG} = \mathrm{CO_2eqE} + \mathrm{CO_2eqN2O} + \mathrm{CO_2eqCH4} \tag{4}$$

where GHG is total greenhouse gas emissions (Gigagrams/year), CO_2eqE is carbon dioxide equivalent for energy, CO_2eqN_2O is carbon dioxide equivalent for nitrogen, and CO_2eqCH_4 is carbon dioxide equivalent for methane.

Emissions from carbon dioxide are computed from the fossil energy used, the total agricultural area and production, and a carbon dioxide conversion factor (Equation (5)).

$$CO_2\mathrm{eq\ E} = ((Ptot * Elt) + (L * Gha)) \times \left(1 - \frac{Gr}{100}\right) \tag{5}$$

where CO_2eq E is carbon dioxide emissions equivalent from energy used (terajoule/year), $Ptot$ is total agricultural production (tonne), Elt is electricity used (terajoule/tonne/year), L = agricultural land (ha), Gha is fossil energy used (terajoule/ha/year), and Gr is green energy (%). Green energy use is deduced from total energy.

Emissions from nitrogen are computed from nitrogen fertiliser used per agricultural sector (kg/ha/year), the amount of land use associated per sector, and a carbon dioxide conversion factor. An efficiency improvement percentage is also considered in the calculation (Equation (6)).

$$\mathrm{CO_2eq\ N_2O} = \left((N_2OM + \sum_k N_2OSk) \times c\right) \times \left(1 - \frac{Ef}{100}\right) \tag{6}$$

where CO_2eq N_2O is carbon dioxide emissions equivalent from nitrogen (tonnes), $N_2O\ M$ is nitrogen emission from manure (tonnes) (which can be derived from emissions factors and the number of cows times the mean tonne of manure per cow per year), $N_2O\ Sk$ is nitrogen emission from fertiliser (tonnes) per sector, k is the sector, c is a conversion factor where 1 tonne of N_2O emitted equals 265 tonnes of CO_2, and Ef is efficiency improvement (%).

Emissions from methane are computed from the enteric fermentation and manure management per animal type (kg/CH_4/animal/year) and a carbon dioxide conversion factor. An efficiency improvement indicator for methane emissions is also considered (Equations (7)–(9)).

$$\mathrm{CO_2eq\ CH_4} = (c \times (CH_4\ M + CH_4\ Ent)) \times (1 - \frac{Ef}{100}) \tag{7}$$

$$\mathrm{CH_4\ M} = \sum_i A_i \times Mt_i \tag{8}$$

$$\mathrm{CH_4\ Ent} = \sum_i A_i \times Entf_i \tag{9}$$

where CO_2eq CH_4 is carbon dioxide emissions equivalent from methane (tonnes), CH_4 M is methane emission from manure (tonnes), CH_4 Ent is methane emission from enteric fermentation (tonnes), c is a conversion factor where 1 tonne of CH_4 = 28 tonnes of CO_2, Ef is the efficiency improvement (%), A is animal where i is the type of animal (dairy cow, beef, sheep), Mt is the average manure production (kg) managed per animal type (i.e., dairy cow = 23.3, beef = 1, sheep = 0.19), and $Entf$ is the average enteric fermentation factor (kg) per animal type (i.e., dairy cow = 90, beef = 60, sheep = 8).

Offset

Offsets are computed from new plantation areas of exotic-pine or native vegetation from the 2019 baseline multiplied by carbon storage per hectare (700 t CO_2/ha after

30 years for exotic-pine and 250 t CO_2/ha for native vegetation plantations after 30 years, New Zealand and Ministry for Primary Industries, 2017).

$$\mathrm{CO_2eq\ O} = (\mathrm{RN} * \mathrm{cn}) + (\mathrm{P} * \mathrm{cp}) \tag{10}$$

where CO_2eq O is the carbon dioxide Offsetting (tonnes), RN is the regrowth area of native vegetation (ha), P is the pine plantation area (ha), cn is the offset conversion factor for native vegetation (i.e., 250 t CO_2/ha in 30 years), cp is the offset conversion factor for pine plantation (i.e., 700 t CO_2/ha in 30 years).

The emission balance in the model is displayed in three gauges indicating the national targets. The total offset value (in CO_2eq) is subtracted from the total emissions (fossil energy used, nitrogen, and methane emissions) (Equations (11)–(13)).

$$\mathrm{GHG\ B\ E} = (\mathrm{CO_2eq\ E} - \mathrm{CO_2eq\ O}) \tag{11}$$

$$\mathrm{GHG\ B\ N_2O} = \mathrm{CO_2eq\ N_2O} - (\mathrm{CO_2eq\ E} - \mathrm{CO_2eq\ O}) \tag{12}$$

$$\mathrm{GHG\ B\ CH_4} = \mathrm{CO_2eq\ CH_4} - (\mathrm{CO_2eq\ N_2O} - (\mathrm{CO_2eq\ E} - \mathrm{CO_2eq\ O})) \tag{13}$$

where GHG B E is greenhouse gas emissions from energy used to balance (Gigagrams), GHG B N_2O is greenhouse gas emissions from nitrogen balance (Gigagrams), GHG B CH_4 is greenhouse gas emissions from methane balance (Gigagrams), and CO_2eq O is carbon dioxide Offsetting (Gigagrams).

Export Value of Agricultural Products

The total export value of agricultural products is expressed in NZDs (millions) and consists of the production times and the mean value for each product (Equation (14)).

$$\mathrm{Ev} = \sum_{s} (\mathrm{Ap}_s \times \mathrm{Mv}_s) \tag{14}$$

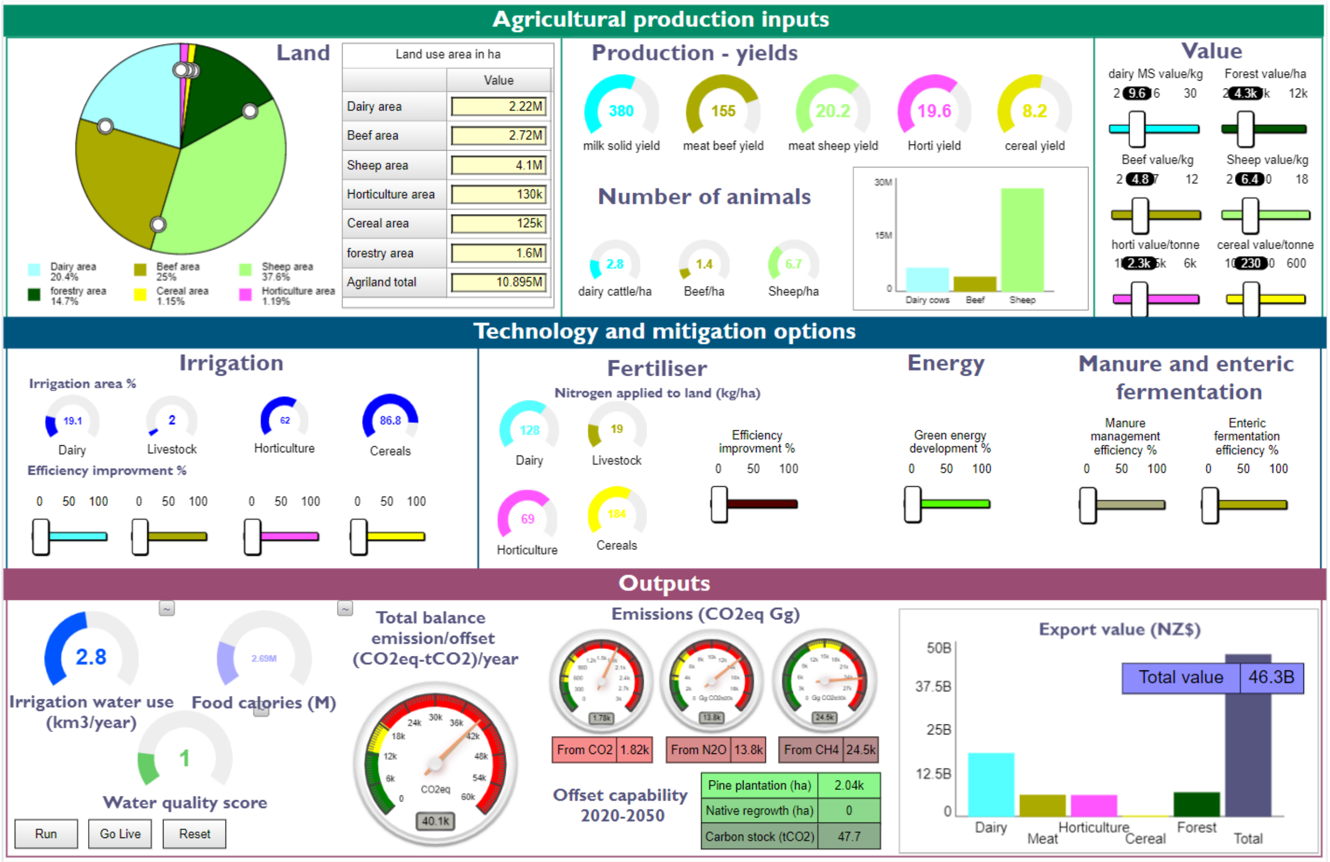
where Ev is the export value (million NZDs), Ap is the agricultural production (tonnes), Mv is the mean value ($NZD), and s is the agricultural sector.

3.3. Model Interface

The model was developed with Stella Architect®, a modelling platform developed by Integration, Software & Electronics Engineering (ISEE) systems designed for Systems Dynamics model implementation. A version of the model is available online [61].

The model interface displays three components (Figure 4). In the top part of the interface, the user sets the inputs related to the land, the production, and the yields. In the middle part of the interface, the user sets the technological and mitigation parameters related to irrigation water use, fertilisation applied on soils, energy used, and livestock emissions. The bottom part of the interface displays on live the outputs. The model interface uses default input data from 2019 (Table 2), which can be modified by the user to allow simulations of future scenarios. It also allows disruption testing on the current agricultural system. For example, by doubling the forest areas at the expense of sheep production, or the dairy industry, the model simulates the environmental and economic consequences of that scenario.

Minimum and maximum threshold values have been set to avoid unrealistic model outputs (Table 3).



Land use area in ha

	Value
Dairy area	2.22M
Beef area	2.72M
Sheep area	4.1M
Horticulture area	130k
Cereal area	125k
forestry area	1.6M
Agriland total	10.895M

From CO2	1.82k
From N2O	13.8k
From CH4	24.5k

Pine plantation (ha)	2.04k
Native regrowth (ha)	0
Carbon stock (tCO2)	47.7

Figure 4. Model interface with agricultural production input values, selected technology, mitigation options, and outputs representing water use (km^3/year), food calories, water quality improvement score, emissions, offsets, and export value for each sector.

Table 3. Model input parameters thresholds.

Model Input Parameter	Min Value	Max Value	Note
Agricultural land (ha)	–	17,000,000	Based on the highest observed area used for agriculture in the 80′s
Production yields:			
Milk solid (kg/cow/year)	-	650	maximum observed yields in other agricultural systems in the world (EU, Switzerland, Canada, USA)
Meat from beef (kg/head)		200	
Meat from sheep (kg/head)		30	
Cereals (tonne/ha)		15	
Horticulture (tonne/ha)		30	
Animals per hectare:			
Dairy (cow/ha)	-	15	Agricultural system change to a less grass-fed animal could be implemented.
Meat from beef (animal/ha)		15	
Meat from sheep (animal/ha)		20	
Export value:			
Dairy (milk solid NZD/kg)	2	30	Thresholds allow tripling the current values
Beef (NZD/kg)	2	12	
Sheep (NZD/kg)	2	18	
Cereals (NZD/tonne)	100	600	
Horticulture (NZD/tonne)	1000	6000	
Forest (NZD/ha)	2000	12,000	

3.4. Development and Validation Process

The model was developed using 2019 data values (Table 2), where ‘inputs’ and ‘technology’ were matched to ‘output’ values given by national datasets. The baseline for efficiencies in water use, fertilizers, and technology was set to zero in 2019 and all increases in efficiency for future simulations were thus a reflection of an increase in efficiency from the 2019 baseline. Model validation was carried out using the 2010 dataset (Table 2), where 'inputs' and 'technology' parameters were used to compare observed against model computed 'outputs'. Most input values used in the model did not require any calibration process as they were directly obtained from the national datasets. However, factors such as water use per hectare per sector were derived from the baseline 2019 values and used for other simulations with the understanding that changes in this value could be made by changing the percent efficiency. Similarly, fertilizer use per hectare per sector was derived from the 2019 data set and used in other simulations, where deviations from these baseline values could be accounted for by the fertilizer efficiency.

3.5. Scenario Building

To illustrate the capabilities of the model and its ability to identify possible policy pathways to achieve national environmental and economic goals, four example disruption scenarios were simulated. These scenarios were intended to illustrate a wide range of possibilities, but in no way to provide fixed and quantified answers to a prospective exercise that must be carried out in partnership with all local stakeholders at all levels of decision-making. The four example scenarios are:

- Business As Usual (BAU),
- Agricultural practices optimisation by extensive use of technology,
- Carbon farming and building a strong forestry sector,
- Reduction in dairy demand.

The BAU scenario is based on the observed trends between 2010 and 2019, projected until 2050. It is a linear statistical projection, and thus has clear limitations, but is useful to illustrate the model. The other three scenarios are designed to meet the 2050 environmental and economic objectives (Table 4): (i) wide use of technology and optimisation of best management practices, (ii) a shift to carbon farming and the revitalisation of the forestry sector due to a high carbon value, (iii) a major economic disruption represented by a reduction in dairy demand and new opportunities in high-value crop diversification. These scenarios have a quantitative translation in their land use allocation, yields, animal numbers, and production values in the international market.

Table 4. Quantitative objectives and expected results for a sustainable, resilient, and profitable system.

Objectives	Expected Results by 2050
Carbon 0 by 2050 (from nitrogen and energy)	=0
CH_4 −24% to −50% by 2050	<18.62 k
Amount of water used is not unlimited	<2.8 km^3/year
Freshwater quality improvement	water score > 0
Food calories may rise by 20–34%	3200–4000 MCal
Agricultural export value continues to rise +2 to +5%/year	85,600–210,234 NZ$ million

The model platform allows testing a wide range of scenarios, and the interactive nature of the online model allows for alterations to be discussed with stakeholders in real-time. The four scenarios selected for presenting and discussing in this paper were chosen to illustrate the versatility of the model, but the model has been tested widely to help define thresholds and simulate numerous future projections.

4. Results

4.1. Model Validation

The validation for 2010 data suggests a low error threshold between the 2010 national dataset and modelled output data for the following indicators: irrigation water use, food energy production, GHG emissions, and total export value (Table 5). The percentage difference between the 2010 national dataset and the model outputs ranges between −2.16% to 5.64%. Those percentages highlight an underestimation in the model computation to estimate the irrigation water use and emissions from nitrogen and an overestimation of the model computation to estimate the emission from carbon dioxide, methane, and the total export value. A large part of this percentage error could be explained by the assumption that efficiencies in 2010 were not the same as in 2019 (i.e model efficiencies were not increased or reduced). For example, water use efficiency in 2019 may be better than in 2010, thus the model indicating a lower irrigation water use than the observed one in 2010. Furthermore, the management of nitrogen applied on soils and nitrogen emissions may have also improved. Other factors related to the quality of data in 2010 may also influence results, particularly related to factors affecting emissions such as the number/type of cows, land use areas, and others.

Table 5. Validation results using the 2010 dataset.

	Irrigation Water Use (km^3/year)	**Food Energy Production (million kcal/ton/year)**	**Emissions from Nitrogen (Gg CO_2 eq)**	**Emissions from Carbon Dioxide (Gg CO_2 eq)**	**Emissions from Methane (Gg CO_2 eq)**	**Total Export Value (NZD million)**
Data source	FAOSTAT	FAOSTAT	FAOSTAT	FAOSTAT	FAOSTAT	Ministry for Primary Industries
Dataset 2010	2.72	235	13,900	1854	23,382	28.4
Output model results from 2010	2.67	235	13,600	1900	24,700	29.3
Difference (in %) between the 2010 dataset and the 2010 model result	−1.80	0	−2.16	2.46	5.64	3.17

4.2. Scenario Narratives

4.2.1. Business as Usual (BAU)

In this scenario, observed trends from the past 10 years were linearly projected to 2050. Over the past 10 years, we have seen an overall decrease in the agricultural area, and especially a large decrease in beef, sheep, and lamb land use. Extending this trend to 2050 resulted in almost a third (3.4 M ha) of land abandonment, but it is also giving the opportunity for a large regrowth of native bush and forestry increase to occur. In parallel, over the last 10 years, the dairy industry has become more efficient in milk solid production per cow. Extending this trend resulted in 630 kg/animal/year, which is a 165% increase from 2019 (which although seems large for pasture-based production, is comparable to current European productivity). Beef and lamb meat production over the last 10 years fell due to a lower demand internationally, partially explained by diet changes leading to crop-based and cellular-based meat. Extending this trend to 2050 resulted in a loss of 31% of beef and 54% of sheep animal numbers. In 2050, the horticultural sector production almost doubled thanks to climate change opportunities allowing new places to grow fruits and vegetables with the help of new technologies such as the precision agriculture and irrigation systems that boost yields. In this scenario, product export values will continue to rise due to the high-quality products and the clean green image of New Zealand products with grass-fed cows, beefs, and lambs and the development of high-value crops, fruits, and luxury products (i.e., wine, kiwi fruits, honey, hops, hemp food supplement, super food crops, etc.).

The BAU simulations show that emission levels by 2050 remained the same as in 2019. However, the regrowth of native vegetation on abandoned land allows the offset of agricultural emissions to meet the Zero Carbon goal and the establishment of native vegetation would also be a large win for biodiversity. Overall export revenues are high; however, the amount of water used for agriculture becomes a major point of concern and raises the potential for land conflicts and crises. Droughts by 2050, as a result of climate change, would begin earlier during the cropping season with peaks being more intense, and duration lengthening.

The BAU scenario for 2050 meets most of the quantitative objectives. Land abandonment allows for very high offset levels for emissions and thus CO_2 *equivalent emission targets can be achieved, and profitability is high, but this scenario is not sustainable nor resilient for water quality and quantity used.*

4.2.2. Optimisation and Technology

In this scenario, the best options, practices, and technology currently available or in development are widely implemented. All the animal production yields are maximised and the number of animals is reduced. Pastures are only grazed twice to three times a year, complemented with grain feed and an increase in arable production, and this requires less nitrogen to grow grass all year round. Freeing up some land allows crops and horticulture diversification for high-value production. With more high-value production, a better spatial optimisation, more on-farm diversification, and the use of technology such as solar panel systems and electric tractors, precision low-rate fertilisers, innovative effluent treatment systems, and livestock intelligence, all the goals are reached in 2050. Emissions from energy or nitrogen fertiliser used have fallen with the help of better practices and technology, simulated through increases in efficiency. Offsetting helps reduce the remaining emissions. The amount of water used has fallen below current levels with a higher overall production by efficient use of water and optimisation of yields. Water quality improvement is high and total export value is high.

In this scenario, all the goals are reached thanks to the wide adoption of optimal practices in mainstream farming and the use of the best technology possible. The sector is profitable. An increase in native plant regrowth may also result in increases in biodiversity (i.e., native birds) and protection of riparian areas leading to water quality improvements. The main assumption is that technology will be readily available and widely implemented to achieve these goals.

4.2.3. Carbon Farming and a Strong Forestry Sector

In this scenario, agricultural practices and animal production are the same as in 2019 and rely only on offsetting to meet the carbon neutrality goal. A carbon budgeting system implemented by the New Zealand government in 2022 allows farmers to financially value their tree plantations as carbon storage (i.e., carbon farming). In 2050, enhancing and maximising the benefits of the carbon and forest sector could become mainstream in farm diversification. High carbon stock pine forests, largely planted and sometimes exploited, will help farmers to gain in profitability and reach carbon neutral objective. By 2050, forest areas in this scenario increase by 1/3 from the 2019 area and represent more than 20% of the overall agricultural area. Carbon farming has become a high-value diversification option. This growth comes at the expense of beef and sheep pasture area only where the land is the least suitable for other diversification options. However, the number of animals is stable with a slightly increase in land use efficiency (i.e., a higher number of animals/ha), as seen in the past decades. With yields remaining stable and an increase of product values, this offsetting scenario meets most of the quantitative goals. Overall export value is high and the agricultural sector is profitable, emission levels meet the goals thanks to the forest offset, and the amount of water used remains stable as well as the food production.

In this scenario, we show the maximum exploitation of a short-term solution, the plantation of trees to offset carbon emissions, without modifying the current agricultural system. Through this scenario, NZ can quickly reach carbon neutrality objectives and increase profitability to farmers, but it is not sustainable nor resilient for ecosystems in the long term.

4.2.4. Reduction of Dairy Demand

In this extreme scenario, demand for dairy products has plummeted. This sudden change has created a huge disruption in the agricultural system where farmers are obligated to adapt quickly. New opportunities have been explored, and the free lands have been shifted into (i) high-value production in horticulture and crops (irrigated), (ii) and new forest areas to offset carbon emissions. Horticultural and crop areas have expanded by

1 million hectares thanks to the new irrigated and suitable lands for diversification. The less suitable dairy abandoned lands have been converted to carbon farming by growing pine forests. Thanks to the balance between diversification, high-value crops, and carbon farming, this scenario also meets all the quantitative objectives. Dairy production has been reduced by 40%, water quality improves, and irrigation water used is stable thanks to a more efficient irrigation technology used for horticulture and crop growing. CO_2 equivalent emissions are low thanks to the use of more precision agriculture technology and more green energy. The pine forest plantations at the expense of the dairy help offset the remaining emissions. The overall export revenue is high and profitable.

In this scenario, we explore how a major system disruption can create new opportunities to sustain the agricultural sector. The disruption of the dairy industry is not necessarily a straightforward solution to environmental problems. Technology improvement and offsetting are still needed to reduce emissions to target levels. Profitability relies on the development of high-value products.

4.3. Quantitative Outputs

Quantitative differences in outputs can be significant between scenarios (Figure 5 and Table A1 Appendix C). Of the four scenarios tested, only the *optimisation and technology scenario* meets all the quantitative objectives (Figure 5):

- Irrigation water used is lower than the current 2019 value (2.6 km^3 vs. 2.8 km^3),
- water quality improvement score is maximised to 4 out of 6 (with a large reduction of fertiliser used, manure and irrigation reduction, and allowing a large native regrowth),
- food and fibre calorie production is sustainable to feed the New Zealanders and continue large exportation of agricultural products, by meeting the international objectives to defeat hunger and feed more population by 2050,
- the GHG emissions are reduced to 17 k t CO_2equivalent offset by large native vegetation regrowth (997 k ha) and carbon farming (300 k ha),
- the total export value is 85.6 k million NZD by 2050, representing a +2% each year of export value.

The relative success of this scenario is due to the high level of technology used, the optimisation of yields and shared pastoral land, a slight decrease of the agricultural area allowing a large native bush regrowth, and a reasonable amount of carbon farming for offsetting the remaining emissions.

The “business as usual” and “Reduction of dairy demand” scenarios meet almost all quantitative goals (Figure 5). The business-as-usual scenario meets the food and fibre calorie production (3920 m Kcal) and the total export value (133 k million NZD). However, even if GHG emissions are reaching the objectives, it is only due to the effect of offsetting. Agricultural emissions have increased (+2000 t CO_2eq compared to current values), and the large agricultural land abandonment of almost one million hectares (out of 10.9 m ha) is offsetting the GHG emissions. Finally, the irrigation water used has risen to 3.4 km^3/ha (+0.6 km^3 from current consumption) and the water quality improvement score is only slightly improving due to the native vegetation regrowth.

The “reduction of dairy demand” scenario meets all the quantitative objectives except the export value (Figure 5). Milk production has fallen by 40% and the high value of this production has not been compensated enough by new high-value products. Even with a new large amount of horticulture and crop areas (1 million hectares in total) with values 20 to 25% higher than current prices, the total export value of agricultural products reaches only 74.7 k million NZD, which is less than a 2% yearly increase. However, the other environmental quantitative values are met. With the gain in efficiency from technology, the amount of water used is stable (2.8 $km^3/year$), and the water quality improvement score is slightly improved by the irrigation and fertilisers efficiency gains. The food and fibre calorie production is very high (11,500 m kcal) allowing to feed the New Zealanders and continue a large agricultural product export, meeting the international objectives to defeat hunger and feed more people by 2050.

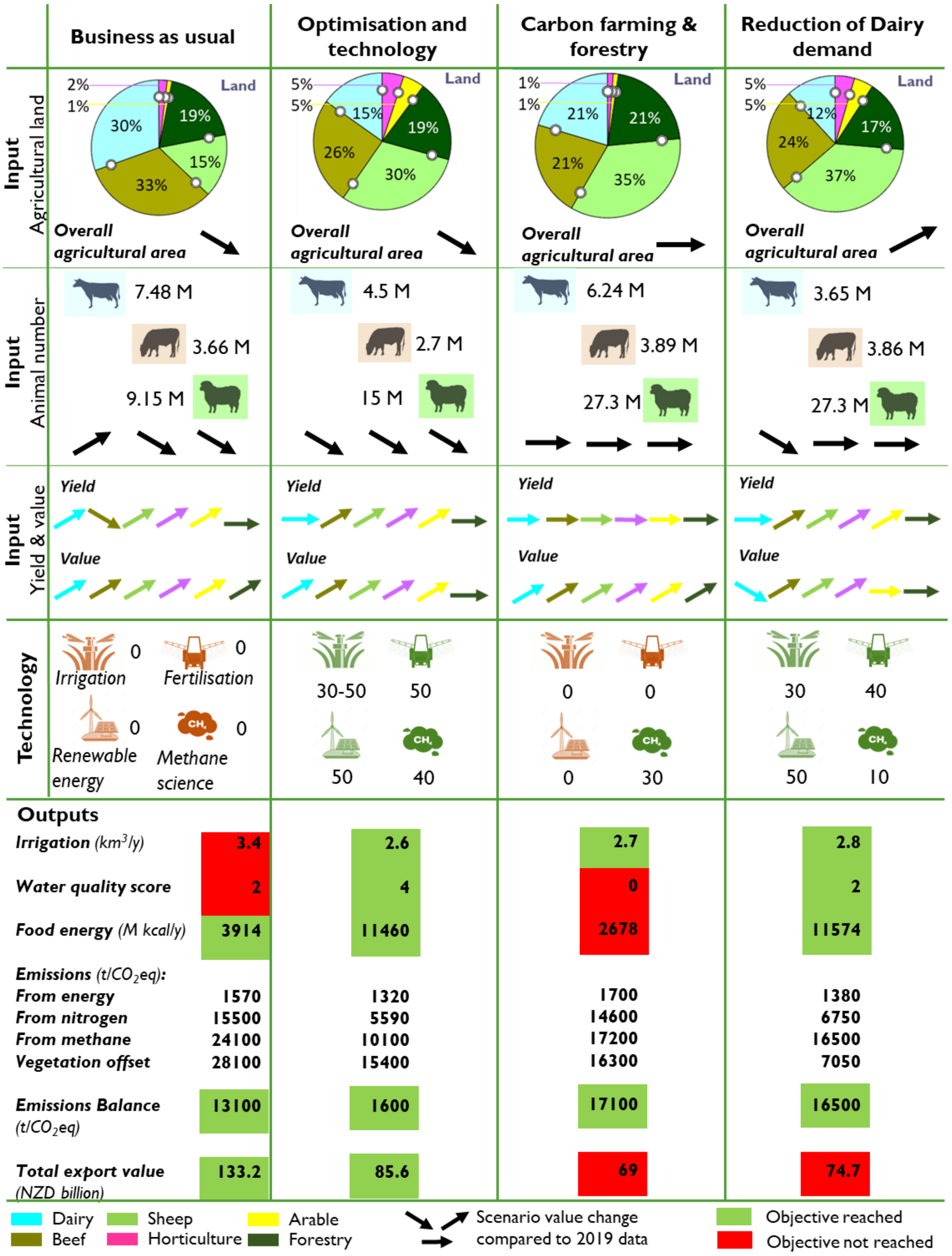


Figure 5. Results of example simulations as described in the scenarios.

The "carbon farming and forestry" scenario performs the worst (Figure 5). Even if GHG emissions reach the quantitative goals, it is only due to the effect of offsetting (emissions = 33.5 k t CO_2eq/year). The offsetting option of this scenario relies on pine forest plantations that do not meet any ecosystem sustainability or resilience recommendations. The total export value is low (69 k million NZD) despite higher product values (+20 to 50% increase from 2019) to sustain agricultural profitability. The food and fibre calorie production has not increased enough to be nationally or internationally sustainable. The water quality improvement score is equal to zero meaning the water quality will not improve. Irrigation water use, however, has decreased (to 2.7 km^3/year) due to the decrease of pasture irrigated areas.

Despite the mixed results, all scenarios can achieve the zero-carbon act objective, although some scenarios are more complex to implement or less beneficial for the economy and the ecosystems.

5. Discussion

5.1. Model Mechanisms behind the Scenario Results

There are two major levers in the model to meet emission goals. The first one is the offsetting action by carbon farming (forestry), and the second is the agricultural land abandonment at the expense of natural vegetation regrowth (allowing 1/3 of Carbon storage compared with pine forest plantations).

Carbon offsetting is one of the tools developed after the 2015 Paris Agreement, together with carbon pricing, trade, and taxes, which help countries reduce their carbon footprint [62]. Other environmental incentives will be implemented at a farm scale [63], set in line with the NZ Emissions Trading Scheme [64], and used to encourage agricultural innovation, mitigation, and forest planting.

As outlined by Funk et al. [65], carbon farming could change New Zealand's landscapes. For example, there is a potential incentive to convert pasture to forest; however, no carbon price for the agricultural sector is currently set to model precisely the landscape consequences. It is, however, already known that the carbon price in the NZ Emission Trading Scheme values exotic forest planting more than native forests by twice the price [66,67].

The carbon farming incentive should be coupled with incentives for good ecosystem management, especially on pasture land/forest lands to achieve win-win outcomes [68] alongside verification systems as already implemented in the EU with the Payment for Environmental Services [69,70]. For example, agroforestry generates large amounts of biomass and is particularly suitable for replenishing soil organic carbon [71]. Opportunities such as the One Billion Trees [72] can achieve several Ecosystem Services goals by building resilient and multifunctional agricultural landscapes, instead of focusing only on GHG emission offsetting. However, carbon farming could result in a significant loss of jobs in the agricultural sector, loss of GDP, and land competition with forestry [73]. These negative outcomes could be particularly true in the northeast of the North Island where the major afforestation is modelled. When looking at afforestation scenario projections [74], permanent forests would be planted in already heavily forested landscapes (with Land Use Capacity classes between 5 to 8) and not in intensive agricultural landscapes where nitrogen loads exceed limits and agricultural pressure on land should be lightened [75].

The second major lever is agricultural land abandonment. The past 10 years have seen a decrease of 1.2 million ha of agricultural area, particularly from sheep pastoral areas. In the modelled scenarios we assume native vegetation regrowth from land abandonment. The native vegetation regrowth assumption comes from satellite observations on the northern hemisphere, where land abandonment has been seen as a major initiator of vegetation change with a strong increase of semi-natural vegetation types across Europe, for example [76]. Under suitable conditions, these regenerating forests conserve biodiversity and provide a wide range of ecosystem services. Moreover, international and national policies, land-use planning, and spatial prioritization approaches can help ensure native vegetation regrowth and persistence [77]. National programmes to promote native tree planting with local commercial values or ecological values as landowner's incentives can help develop and assist in the good management of tree planting and native vegetation regrowth in a way it does not compromise food or fibre production and maximise environmental benefits [77]. Future interventions need a spatial assessment using national-scale maps of natural vegetation and natural regeneration capacity in assessments of national-level restoration opportunities. Natural regeneration capacity should be associated spatially with productive land (such as sheep and beef farms) that can play a role in the conservation of ecosystems and native vegetation [74,77,78].

Both levers should be considered nationally or regionally as quantitative indicators (e.g., as the number of trees planted, area reforested, carbon stocked by ha, and the land area abandoned). The spatial organisation of the landscape and historical landscape context should drive future planning and management intervention to make the best of these simple, but very efficient levers.

5.2. Model Limitations

This model is intended to be applied at the national scale representing all agricultural sectors and thus detailed data had to be aggregated. High-level approaches and parameter options are inherent, and all the regional agricultural practices' specificities are lost in the model design itself. The model uses broad levers to reach environmental objectives, without specific spatial and temporal details. Consequently, the main levers to reach environmental objectives (especially Carbon 0 and the reduction of methane emissions) relies on forest planting for offsetting, agricultural land abandonment, or a drastic reduction of livestock. Technological parameters are built on the assumption of a wide adoption of new technologies or a wide adoption of new/changes in agricultural practices. Here again, regional specificities or specific technological developments cannot be considered due to the national scale chosen for this study. However, the model can simulate the impact of a wide adoption of new technology through increases in efficiency, such as new irrigation systems allowing for more water saving.

The second main limitation relies on the lack of spatial parameters to constraint model choices. Even for basic levers such as forest planting or agricultural land abandonment, a spatial analysis makes sense in the decision-making process. Spatial modelling could also have been even beneficial for water quality score computing.

5.3. Role of Technology, and New Zealand Development Potentials

In the simulations, the role of technology is modelled as a percentage improvement from today's practices. A wide range of technological improvements are being developed and this model allows to focus on the quantitative way technology should be able to improve environmental outcomes instead of focusing on individual technology improvements. However, the way we quantified these parameters reflect current research and implementation capacity as well as any other disruption in the system.

5.3.1. Irrigation

Drip irrigation is only used at small scales in New Zealand, although it could reduce the amount of water used by 20 to 60% and improve yields by 15 to 30% using low-pressure and solar energy systems [25,79,80]. Today more than 85% of the irrigation technology in New Zealand is sprinkler irrigation systems, and only 7% is localised low-pressure irrigation systems (Source FAO Aquastats). The adoption of the drip-irrigation technology for all crops and horticulture could save 7 to 22% of the total amount of water used for irrigation in New Zealand (i.e., 0.2 to 0.5 km^3/year), but this has a direct capital investment cost which needs to be balanced against profits and environmental impacts. Moreover, irrigation of pasture is a well-established practice in the Dairy farm system when rainfall alone is not sufficient. It represents 20% of the dairy area and almost half of the total amount of water used by irrigation. When not applied correctly, it leads to a denitrification increase and an increase in nitrogen emissions [57,58].

5.3.2. Nitrogen Emissions

Recent research argues that 16 to 23% of nitrogen and phosphorus loss is evitable if mitigation options are implemented across dairy and sheep/beef farms [81]. Nitrogen emission reductions rely more on management strategies than on technology development, except for precision agriculture technology that helps farmers significantly reduce the use of synthetic fertilisers [82]. Other options promoted under conventional farming systems are adaptations of current practices (e.g., increasing round length, not applying in

January/February, skipping a few paddocks). Under regenerative or organic agricultural systems, only organic fertilisers are used, such as seaweed-based ones and their efficiency relies on a change of management mode [83]. Moreover, in New Zealand, 75 to 80% of the nitrogen emissions come from manure left on pastures that consist of direct and indirect emissions by grazing livestock. Optimisation of the diet, moving to a silvopastoral or agroforestry style system, and better soil cover all year round by using nitrogen-fixing plants have the potential to reduce emissions of methane or nitrogen from manure up to 50% and increase soil carbon storage [84]. This could provide a balance between the conventional and regenerative agricultural system.

5.3.3. Methane Emissions

New Zealand research and technology developments to reduce methane emissions from livestock is also promising. A breeding program to identify genetic markers in low-methane-emitting dairy cattle cows and bulls is underway. Previous studies on sheep methane emissions have shown a consistent difference of 8 to 44% between the high-emitted group and the low-emitted group depending on their diet [85]. Other Australian studies on Angus beef cattle have shown a difference of 19 to 40% in methane emissions correlated with the genetics of tested animals [86]. Feeding alternatives, such as alternative forages, are also investigated. A 100% forage rape diet as winter forage reduces methane emissions by 30% in experiments conducted on sheep and cattle [87]. Fodder beet for more than 70% of the dairy cows diet reduces methane emissions by 20% [88]. Furthermore, the introduction of a proportion of plantain in the diet or other non-pasture feed is currently investigated to reduce nitrogen emissions from livestock excretions [89,90]. Biotechnologies such as methane inhibitors or vaccines are also being investigated. A reduction of 22 to 35% can already be achieved using the commercial compound Bovaer®, but it is not well adapted to pasture-based systems [91]. Furthermore, an anti-methanogen vaccine is under development to reduce at least 20% of methane emissions from rumen [92,93]. Aquaculture and the seaweed industry are developing biotechnological solutions such as methane inhibitors and livestock productivity improvement [94,95] as well as sustainable fertilisers to reduce the use of synthetic fertilisers [24].

5.3.4. Renewable Energy

Finally, 100% renewable energy seems achievable with generalisation of solar and wind farming [96,97], electric tractors, large spraying drones, or energy farms implementing different sustainable energies designed in northern Europe [98–100]. In New Zealand, much of the electricity already comes from hydropower, and large solar and wind farm projects are already operating, and more are on their way [101,102].

5.4. Statistical Modelling of Agricultural System under Climate Change Disruption: Where Are the Limits?

The main limitation of this model lies in the indirect consideration of climate change scenarios and spatial variations. Working with a national quantitative model has not allowed us to directly take into account the great spatial disparity of input parameters. The model, however, allows implementing a range of yields per sector, irrigation and fertiliser need to simulate the effect of climate change on the primary production per sector.

During the scenario-building phase, we worked on the climate change assumptions following scientific research and reports [103–105]:

- Climate change and yields are linked and future projections do not allow a great improvement in yields because of more extreme events such as droughts and less water availability for irrigation;
- Climate change can have a positive impact on growing crops or horticulture, and yields have been adapted consequently;

- Climate change and water availability are difficult to predict because of the varying spatial allocation of predictions. The model objectives are to reduce the total quantity of water used by irrigation.

6. Conclusions

In this paper, we have developed a numerical model, the first of its kind, representing the whole agricultural system of New Zealand at the national scale. This model has allowed to quantify agricultural outputs such as carbon emissions, water quality, and irrigation quantity used, as influenced by land use type, technology, and other factors, informing on resilience, sustainability, and profitability of the agricultural sector.

Using this numerical model, we have explored pathways through four different scenarios intended to illustrate a wide range of possibilities: two future trend scenarios (Business as usual, Optimisation, and technology) and two breakaway scenarios (Carbon farming, Reduction in dairy demand) were simulated. These scenario applications show that future environmental regulations can be met by adjusting levers associated with technology, carbon offsets, and land use.

Technological improvements are implemented in this model allowing to quantify the way technology should be able to improve environmental outcomes. Moreover, two additional major levers in the model allowed to meet environmental goals, the offsetting action by carbon farming or the development of the forestry sector, and the agricultural land abandonment at the expense of natural vegetation regrowth. In the near future, both levers should be considered regionally as quantitative indicators (e.g., number of trees planted, area reforested, carbon stocked by ha, land area abandoned). Moreover, the spatial organisation of the current and historical landscape should be considered in future scenario development.

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Appendix A. Agricultural Sector Exports

Agricultural sectors and exports are organised as follows [10]:

- The dairy sector produces and exports whole milk powder, butter, anhydrous milk fat (AMF) and cream, skim milk, casein and protein products, cheese, and infant formula. Dairy is the top sector for export revenue, reaching more than NZ$20 billion in 2021, and exporting mainly to China (39%), Australia (9%), the USA, Japan, and Indonesia (~4% each).
- The meat and wool sector produces and exports beef, veal, lamb, mutton, wool, and venison. The sector achieved more than 10 billion NZ$ in export revenues in 2021 and exports mainly to China (38%), the USA (20%), and UE (9%).
- The forestry sector produces logs, sawn timber, sleepers, pulp, paper, and panels, for a total of more than 6 billion NZ$ in 2021, and exports mainly to China (55%), Australia (9%), South Korea and Japan (6% each).
- The horticulture sector produces and exports mainly kiwifruit, wine, apples, and pears. This sector achieved more than 6.5 billion NZ$ in export revenues in 2021 and exports mainly to the EU (17%), Australia (14%), Japan and USA (13% each), and China (12%).

- The seafood sector represents wild captures and aquaculture, for 1.8 billion NZD$ exported to China (37%), Australia and USA (13% each), EU (11%).
- The arable sector produces vegetable and ryegrass seeds, other seeds, and grains. It exported 270 million NZ$ in 2021 mainly to the EU (47%) and Australia (13%).
- Processed food such as honey, sugar, or cereal products, as well as innovative processed foods, had an export revenue of more than 3 billion NZ$ in 2021 from exports to Australia (38%) and China (20%).

Appendix B. A Sector under Climate Change Pressure

Changes in seasonal weather patterns, linked with water availability are a big issue for most of the food and fibre sectors [10]. Recent analysis shows that the probability of extremely warm days has already increased due to climate change and the probability of extremely cold days has decreased (New Zealand and Ministry for the Environment, 2020). There is also clear evidence of a decreasing number of frosts, increasing numbers of very warm days, and an increase in the frequency and severity of extremes [103]. Extreme climate events are likely to cause flooding, nitrogen leaching, drought, soil erosion, and pests affecting stock management, productivity, and profitability. These changes have significant negative impacts on the primary sector through water availability during droughts, increased soil erosion due to heavy rainfall events, heat stress for crops and animals, and increased likelihood of pests and disease [106]. On the other hand, climate change can have positive impacts on crops, where higher temperatures allow earlier sowing of crops that reach maturity faster, and where coupling with fertilisation results in yield increases for wheat and barley [104]. Viticulture, one of NZ's fastest growing sectors, is extremely sensitive to climate change due to grape phenology, and the long lead times required to establish vines and build market share. Adaptation to climate change involves increasing diversity within crops and planting of new grape varieties [107,108].

Appendix C.

Table A1. Scenario inputs and indicators results. Scenario output values are highlighted in green when the targets (Table 4) are met and in red when the target is not met.

Indicator	**2019 (Current)**	**BAU 2050**	**Optimisation and Technology**	**Carbon Farming & Forestry**	**Reduction of Dairy Demand**
			Inputs		
Land area (ha)					
- Dairy	2,221,459	2,295,373	1,500,000	2,221,459	130,0000
- Beef	2,718,917	2,439,631	2,500,000	2,318,917	270,0000
- Sheep	4,101,801	1,142,863	3,000,000	3,801,801	410,0000
- Horticulture	132,717	145,520	500,000	132,717	500,000
- Cereals	124,292	85,600	500,000	124,292	500,000
- Forest	1,597,957	1,418,698	1,900,000	2,297,957	1,900,000
- Total	10,897,143	7,527,685	9,900,000	10,897,143	11,000,000
Yields					
- Milk solid (kg/cow/year)	380	631	530	380	380
- Meat from beef (kg/an)	155	140	170	155	170
- Meat from sheep (kg/an)	20.2	25.7	22	20.2	22
- Horticulture (t/ha)	19.6	28.3	25	19.6	25
- Cereals (t/ha)	8.2	11	10	8.2	10

Table A1. *Cont.*

Indicator	2019 (Current)	BAU 2050	Optimisation and Technology	Carbon Farming & Forestry	Reduction of Dairy Demand
Animal/ha					
- Dairy cattle	2.81	3.26	3	2.81	2.81
- Beef	1.43	1.50	1.08	1.67	1.43
- Sheep	6.65	8.01	5	7.18	6.65
Value					
- Milk solid (NZD/kg)	9.63	21.8	12	12	6
- Beef (NZD/kg)	4.871	10.1	8	8	8
- Sheep (NZD/kg)	6.331	12	8	8	8
- Horticulture (NZD/tonne)	2342.45	4565	3000	3000	3000
- Cereals (NZD/tonne)	231.86	483	300	300	300
- Forest (NZD/ha)	4307.3	11079	4500	8000	4307.3
Technology					
Irrigation %					
- Dairy irrigation	19.14	20.8	35	19.14	10
- Livestock irrigation	2	6.5	2.3	2	2
- Cereals irrigation	62	100	50	62	80
- Horticulture irrigation	86.8	62.4	50	86.8	60
Irrigation efficiency gain %					
- Dairy	-	0	50	0	30
- Livestock	-	0	50	0	30
- Horticulture	-	0	30	0	30
- Cereal	-	0	30	0	30
Nitrogen fertiliser applied					
- Dairy (kg/ha/year)	100.62	100.62	100.62	100.62	100.62
- Meat prod (kg/ha/year)	12.27	12.27	12.27	12.27	12.27
- Horticulture (kg/ha/year)	46.81	154.14	154.14	154.14	100
- Cereals (kg/ha/year)	154.14	46.81	46.81	46.81	45
Fertilizer efficiency improvement % (by practice and technology)	-	0	50	0	40
Energy used					
- From electricity (tj/tonne)	0.00125	0.00125	0.00125	0.00125	0.00125
- From gas/diesel (tj/ha)	0.001435	0.001435	0.001435	0.001435	0.001435
- From other gas (tj/ha)	0.000372	0.000372	0.000372	0.000372	0.000372
Energy efficiency/green improvement %	-	0	50	0	50
Enteric fermentation (kg CH_4/head)					
- Dairy cattle/Beef/Sheep	90/60/8	90/60/8	90/60/8	90/60/8	90/60/8
Manure management (kg CH_4/Head)					
- Dairy cattle/Beef/Sheep	23.35/1/0.19	23.35/1/0.19	23.35/1/0.19	23.35/1/0.19	23.35/1/0.19
Feed and manure efficiency improvement %	-	0	40	30	10
Outputs					
Irrigation water used (km^3/year)	2.8	3.4	2.6	2.7	2.8
Water quality improvement score	0	2	4	0	2
Food energy production (million kcal/year)	2678	3914	11,460	2678	11,574

Table A1. *Cont.*

Indicator	2019 (Current)	BAU 2050	Optimisation and Technology	Carbon Farming & Forestry	Reduction of Dairy Demand
Emissions (t CO_2eq)					
- From energy	1824.8	1570	1320	1700	1380
- From nitrogen	14,700	15,500	5590	14,600	6750
- From methane	23,150	24,100	10,100	17,200	16,500
Offset					
- Pine plantation area (ha)	0	0	302,000	700,000	302,000
- Native regrowth area (ha)	0	3,370,000	997,000	0	0
- Vegetation offset (t/ CO_2eq)	0	28,100	15,400	16,300	7050
Balance (emissions–offsets, t/ CO_2eq)					
- Remain emissions from energy used	1824.8	0	0	0	0
- Remain emissions from N_2O	14,700	0	0	0	1080
- Remain emissions from CH_4	23,150	13,100	1600	17,100	16,500
Total export value (NZD million)	46,329	133,249	85,590	69,014	74,770

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