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Co-designing and evaluating scenarios for New Zealand's future arable production with an interactive decision support approach

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Introduction: Agriculture in New Zealand (NZ) is facing major disruptions due to the impacts from change drivers, such as climate, environmental regulations, and emerging technologies. Strategies to respond to the risks and opportunities associated with these disruptors are needed to transform and strengthen agriculture to achieve economic and environmental objectives. Focusing on the arable sector is of particular importance as it plays a crucial role to ensure carbon neutrality, profitability, and food security. In this paper, we aim to explore potential pathways and interventions to achieve sustainable and resilient arable agriculture by 2050.

Methods: Working closely with stakeholders from the arable sector, critical scenarios related to food security, climate change mitigation and alternative protein production were co-designed. A decision support tool (DST) that integrates economic, environmental, and production data at the national scale was used to simulate the scenarios.

Results: Results suggest great opportunities for the sector to change and grow. Enhancing food security by producing 700 k tonnes of wheat (i.e., an extra 25 k hectares) and introducing this wheat in a Dairy livestock system could reduce carbon equivalent biogenic emissions by a factor of eight while using one-third less water for irrigation than is normally used for dairying. Complementing animal diets with 30% locally grown grains and reducing the herd by 10% achieves NZ emissions targets for 2050. Developing a pea and fava bean protein extraction market, with the implementation of a new extraction facility (processing 15 k tonne of peas/year), increase in productivity, area planted, and value (yields up from 3.5 to 5 t/ha; value rise from $960/t to $1,200/t; and land area increase to 25,000 ha) would result in a significant growth in arable agriculture profitability ($375 million) and emissions reductions.

Discussion: Beyond these quantitative insights, the study demonstrates the value of participatory modelling as a policy-support mechanism: by aligning scientific outputs with stakeholder knowledge, the DST strengthens evidence-based dialogue on land-use planning, regional diversification, and the transition toward carbon-neutral agriculture.

KEYWORDS
climate mitigation, decision support tool, profitable agriculture, scenario, sustainability

1 Introduction

The global agricultural landscape is currently confronted with multiple challenges that have profound implications for food security, greenhouse gases emission reduction, and the exploration of alternative production (Boliko, 2019; FAO, 2021; Menegat et al., 2022). As the world's population is forecasted to reach 8.5 billion by 2030 and 9.7 billion by 2050 (United Nations, 2023), there is an escalating demand for food production, necessitating agricultural systems that are both high-yielding and sustainable. Yet, the environmental footprint of agriculture raises concern, with emissions of greenhouse gases (GHG) such as methane and nitrous oxide being the two major GHG sources from agricultural production (Hui et al., 2022). Addressing these emissions, mitigating their impact, and adapting agricultural systems to future changes, intersects directly with global and national food security challenges. Additionally, there is a growing recognition of the need to diversify production methods through innovative approaches (i.e., technology and biotechnologies like vertical farming or cellular agriculture - Mouat and Prince, 2018; Klerkx and Rose, 2020) and food production (i.e., alternative proteins - van der Weele et al., 2019; Ismail et al., 2020) to alleviate resource constraints, enhance resilience, and ensure a stable food supply. In this context, understanding the intricate interplay of these challenges and identifying holistic solutions is of great importance to shape the future of agricultural systems and secure global food supplies while safeguarding the environment. This article, focussing on the NZ arable agricultural sector at the national scale, explores the multifaceted dimensions of these challenges and provides insights into the ongoing research and developments aimed at addressing them. In NZ, the arable sector refers to land-based cropping systems that produce cereals, grains, seeds, and other field crops for human consumption, animal feed, and processing, and plays a supporting role in wider livestock and food production systems (Ministry for Primary Industries, 2022).

Agriculture in NZ is vital for its economy and food security. However, the sector is facing multiple challenges due to the impact of climate change, trade agreements, diet changes, diseases and pandemics, socio-economic factors, and emerging technologies that affect current profitability, resilience and sustainability (Driver et al., 2022). Profitability in NZ agriculture refers to the NZ MPI strategy, by producing high-value food and primary production to build prosperity for all New Zealanders (Ministry for Primary Industries, 2021). Resilience of the agricultural system is defined as the ability of the system to cope–withstand and/or adapt-from multiple challenges (Tendall et al., 2015; Bullock et al., 2017; Meuwissen et al., 2019). Sustainability focuses on food security and climate change mitigation and adaptation in the NZ context. Climate change is driving compulsory reductions in greenhouse gas emissions (UNFCCC, 2015; Ministry for the Environment, 2019), stringent environmental regulations are being proposed to reduce unwanted discharges, and emerging technologies such as animal-free food products are forcing government and industry to rethink agriculture in NZ and beyond (Knickel et al., 2018). Medium to long-term strategies are needed to respond to the risks and opportunities associated with these and other socio-economic, environmental and technological disruptors (Ausseil et al., 2019; Renwick et al., 2022).

To develop informed strategies to comply with Carbon Neutrality and freshwater objectives, there is a need to assess options, scenarios, pathways, and interventions for transforming and strengthening the agricultural sector over the next 5–30 years. Prospective modelling of new trends and break-away scenarios and adaptation options to the NZ primary sector at the national scale will help government, industries, and stakeholders plan for disruptive changes. Scenario-building methods have advanced from exploratory and normative frameworks toward participatory and model-integrated approaches (Oriol et al., 2024; Riera et al., 2025). Their main strength lies in promoting stakeholder engagement and adaptive decision-making under uncertainty, using combined qualitative narratives and quantitative simulations. National- and regional-scale agricultural system models have been widely applied internationally to explore future production pathways, climate mitigation strategies, and land-use trade-offs under uncertainty. In Europe, integrated modelling frameworks such as CAPRI (Britz and Witzke, 2014), MAGNET (Woltjer et al., 2014), and FarmDyn (Britz et al., 2014) have been used to assess the impacts of policy, climate change, and dietary shifts on crop–livestock systems, often highlighting the potential of cereal expansion, efficiency gains, and reduced livestock intensity to meet emission targets while maintaining food supply. Similarly, modelling efforts in Australia and North America, including APSIM-based (Holzworth et al., 2018; Zhang et al., 2022; Richetti et al., 2024) and system dynamics approaches, demonstrate that yield improvements and targeted land-use reallocation can increase cereal output and reduce resource use without proportional increases in environmental pressure. These studies consistently show that mixed cropping–livestock systems offer significant mitigation and resilience benefits (Herrero et al., 2017), but they often remain either highly technical or weakly connected to stakeholder decision-making (Klerkx and Rose, 2020; Wagner et al., 2023).

In contrast, NZ applications have largely focused on livestock-dominated systems, with limited quantitative exploration of arable sector pathways at the national scale. In NZ, the Our Land & Water (OLW) research programmes have established strong foundations through the Matrix of Drivers and Next Generation Systems projects, which systematically identify key disruptors and enable participatory prioritisation across land uses (Driver et al., 2022). These initiatives provide robust qualitative frameworks and multi-criteria decision-making methods for exploring sustainability transitions. Recent outputs couple biophysical modelling with climate projections to map system vulnerabilities across major farming systems (Lilburne et al., 2025). Complementary OLW work has produced interactive spatial tools that show where land-use change is needed to meet water-quality limits, linking scenario outcomes to on-the-ground mitigation portfolios (Online Tools Show Where Land-Use Change Needs to be Considered, n.d.). Their main limitation is that most remain descriptive or exploratory, offering limited quantitative integration of sector-specific data—particularly for the arable sector, where cross-sector trade-offs in productivity, emissions, and water use are not yet simulated. Alternatively, a literature-based scoping review on modelling approaches and existing agricultural systems' model examples at the regional to national scale (Vannier et al., 2022a) has highlighted the use of Decision Support Tools (DST) under Systems Dynamic approach to be the best suited to enable stakeholders' participation and understanding, and for improving land planning and policy formulation. An interactive systems tool for quantifying agricultural productivity, emissions, and other factors at the national level to explore pathways for future agriculture in all sectors was developed (Vannier et al., 2022b), however needing subsequent developments for sectoral based analysis. The results presented here are broadly consistent with international findings—particularly regarding the role of cereals and legumes in reducing emissions intensity and improving water efficiency—but extend this work by explicitly integrating arable–livestock interactions within an interactive, stakeholder-driven decision support framework tailored to the New Zealand context.

There is a clear research gap in understanding how future disruptions—arising from climate change, trade dynamics, socio-economic shifts, and emerging technologies—will affect NZ agricultural productivity and environmental performance, and conversely, how adaptive changes in agricultural practices could support national sustainability and resilience goals (Ausseil et al., 2019; Driver et al., 2022; Renwick et al., 2022). Although global literature highlights the need for integrated, systems-level approaches to address such cross-sectoral challenges (Intergovernmental Panel on Climate Change, 2014; Porfirio et al., 2018; Stephens et al., 2020), few studies have systematically explored how the NZ arable sector can contribute to national food security, emissions reduction, and agricultural diversification as a nexus. Existing modelling frameworks and scenario studies in NZ have largely centred on livestock and general land-use systems, offering limited resolution for arable production and few opportunities for stakeholder co-design (Vannier et al., 2022a; Vannier et al., 2022b). This limits the capacity to test realistic, sector-specific pathways for transformation. Furthermore, the role of arable cropping in achieving carbon neutrality—through local grain supply, alternative livestock feeds, and plant-based proteins—remains poorly quantified (Beukes et al., 2019; Horn and Isselstein, 2022). Addressing these gaps requires integrated and participatory process that combine biophysical, economic, and technological dimensions, enabling quantitative exploration of trade-offs between productivity, profitability, water use, and emissions (Bizikova, 2019; Liu, 2023; Wagner et al., 2023). This study responds to that need by developing and applying a dynamic DST, co-designed with the Foundation for Arable Research (FAR), to simulate national-scale scenarios for the arable sector. By focusing on three major stakeholder-defined themes—food security (wheat self-sufficiency), climate mitigation (feed and herd management), and alternative proteins (pea and fava bean development)—this work provides the first integrated assessment of how NZ arable sector can contribute to achieving carbon neutrality and sustainable agricultural growth by 2050.

This paper aims to explore potential pathways and interventions for the arable sector to achieve food security, emission reduction and alternative protein production through the co-development of new trends and disruptive scenarios. The objectives of this work were to (1) include stakeholder participation for formulating scenarios that are of interest for the NZ arable agricultural sector; (2) demonstrate the challenges and opportunities of those scenarios; and (3) propose and develop an interactive DST for increased stakeholders' engagement.

2 Methodology

2.1 The arable sector in New Zealand context

The arable sector is a cornerstone of NZ agricultural production system, contributing to food security, economic stability, and environmental sustainability. It provides the nation's staple crops—such as wheat, barley, maize, oats, and other cereals—which form the foundation of both human nutrition and livestock feed (Arable food Industry Council, 2022). Many of these crops also serve as essential raw materials for the food processing industry, including wheat, soybeans, nuts, and sugar, thereby adding value to the agricultural economy and supporting domestic food manufacturing (Indicators | Stats NZ, 2022). In addition, the sector plays a crucial role in supplying feed for NZ extensive dairy and livestock industries, particularly through maize silage and grain production, which are indispensable for sustaining dairy cows, beef cattle, and other livestock (Arable food Industry Council, 2022).

Although arable products directly account for only about 0.5% of NZ total export earnings, they underpin the much larger export sectors of dairy, meat, and processed foods, which depend heavily on locally produced grain and feed inputs (Ministry for Primary Industries, 2022). Arable farming practices also enhance long-term sustainability through crop rotation and system diversification, helping to maintain soil health, reduce pest and disease pressure, and improve system resilience (Antille et al., 2022). Economically, the arable sector supports rural communities by providing employment and generating income through the production and sale of crops, farm equipment, and associated services (Indicators | Stats NZ, 2022; Ministry for Primary Industries, 2022).

To help achieve NZ environmental and economic objectives, the arable sector plays an increasingly strategic role by delivering co-benefits across the food security, economic, and environmental nexus. Its capacity to produce locally sourced grains and feed reduces reliance on imports, supports national food resilience, and contributes to emission reductions by lowering the embedded carbon footprint of feed supply chains. At the same time, the sector offers complementarity and trade-offs with livestock production systems: arable crops can mitigate the environmental impacts of the dairy sector by providing lower-emission feed alternatives and reducing the costs and uncertainties associated with overseas grain purchases (Beukes et al., 2019; Horn and Isselstein, 2022). Due to its significant contributions to food security, economic prosperity, and potential for enhancing environmental sustainability, the arable sector holds a vital position within NZ agricultural landscape. Its continued growth and development are essential for meeting the challenges posed by global uncertainties and ensuring a thriving agricultural sector for the future (Ministry for Primary Industries, 2022).

Building on this foundational role, the following sections introduce the DST developed to model how the arable sector's production systems can evolve under future scenarios and support stakeholder decision-making toward sustainable and low-emission pathways.

2.2 Decision support tool

We developed a Decision Support Tool (DST) to explore different pathways and interventions for increasing the profitability, resilience, and sustainability of agriculture in NZ over the next 5–30 years. This user-friendly interface makes it possible to explore scenarios related to the development of a particular crop, changes to the whole sector, the evolution of prices, changes in yields, as well as the environmental effects of changes in agricultural practices (fertilization, irrigation, livestock feed).

Methods used for the national level multi-sector DST are detailed in Vannier et al. (2022a). Briefly, a linear statistical model, the first of its kind, was developed to represent the whole agricultural system of NZ 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 baseline data of 2019–2020, 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 explore pathways to reach government objectives of ensuring high export value production and carbon neutrality by 2050.

Beyond its technical capacity, the originality of the DST lies in its interactive and participatory design, which directly supports evidence-based decision-making. Through iterative and immediate (live) scenario simulations, stakeholders—including the Foundation for Arable Research (FAR)—used the DST to test assumptions about land use, emissions targets, and profitability under real policy and market constraints. This approach enabled a shared understanding of trade-offs and synergies across sectors, improving the transparency of strategic discussions and the alignment between scientific outputs and on-farm realities. The DST therefore serves not only as a modelling tool but also as a decision facilitation platform that bridges research and practical policy formulation.

2.2.1 Arable module organisation

For this study, an additional module was developed focusing on arable sector production (Figure 1) which interacts with the national level multi-sector DST. The model has three main parts: the inputs (land, production and value), the technology (irrigation, fertilisers, land use change from Dairy sector), the outputs (calories and proteins produced from cereal, irrigation water used, GHG emissions from nitrogen, and the sector monetary value). The input and technology parameters are set with current data and customisable by the user for projections. The seven major crop types are represented in the model (wheat, maize grain, maize silage, barley, oat, peas, seed).

The model assumes that the land sustains the crop production. Production is represented in the model by the crop yields. Crop production is then multiplied by a mean market value to calculate export value per crop. The technologies selected contribute to productivity and sustainability outcomes. The model accounts for the average use of irrigation and nitrogen fertilisers and estimates GHG emissions from nitrogen. 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.

A large range of outputs are computed by the model: the amount of calories produced by cereals; the amount of proteins produced by cereals; the amount of water used by irrigation for the agricultural production; GHG emissions from fertilisation; and the overall grain value and cereal export value (Figure 1).

2.2.2 Model data inputs

The arable module baseline data used is 2021, sourced from AFIC, StatsNZ and FAOSTAT datasets (Table 1). Users can modify the "Arable production inputs" and the "Technology and mitigation

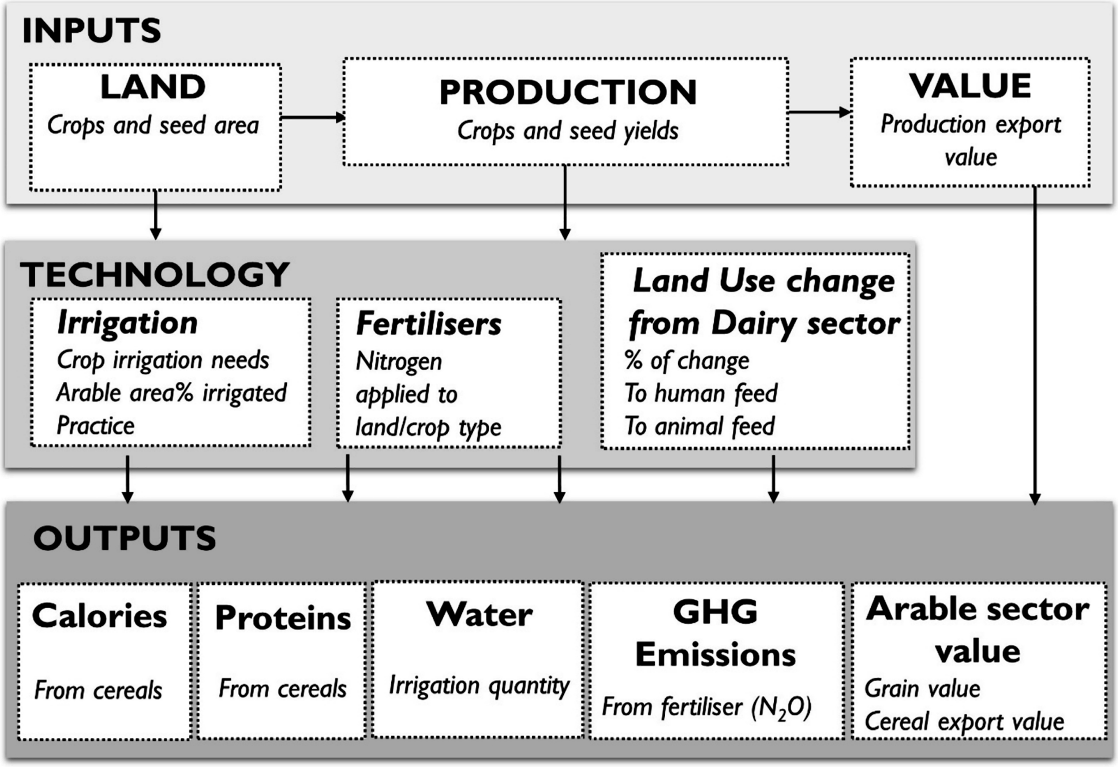


FIGURE 1
The arable module framework consisting of inputs, technology, and outputs.

options" values according to their simulation or scenario requirements. The model produces outputs on calories, proteins, irrigation water use, emissions, and export values (Equations 1–5).

2.2.3 Model outputs

2.2.3.1 Irrigation water use

The amount of water used by arable production 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:

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

Where IWU is the irrigation water use, L_k is the land type area where k is the crop type, W_k is the average water used per ha per crop type k, and Ef is the percent efficiency improvement from the baseline in 2021.

2.2.3.2 Calories from cereals

Food energy production is expressed as calories produced each year from cereals. The amount of production (tonnes per crop product) is multiplied by mean energy per weight (Equation 2).

$$\mathrm{Fe} = \sum\nolimits_{c} \left(\mathrm{P}_c \times \mathrm{E}_c \right) \tag{2}$$

Where Fe is the food energy in calories, P is the production (tonnes) for each crop type c, and E is the mean energy for products in each crop type c (i.e., 12.3 kcal/100 g of barley; 33.4 kcal/100 g of maize grain; 38 kcal/100 g of oat; 32 kcal/100 g of wheat; 8 kcal/100 g of peas). Calories outputs are computed assuming a 100% edible fraction of cereal production; the model does not account for post-harvest losses, processing efficiencies, or non-food allocations.

2.2.3.3 Proteins from cereals

Food protein production is expressed as tonnes produced each year from cereals. The amount of production (tonnes per crop product) is multiplied by mean protein per weight (Equation 3).

$$\mathrm{Fp} = \sum\nolimits_{c} \left(\mathrm{P}_c \times \mathrm{E}_c \right) \tag{3}$$

Where Fp is the food protein in tonnes, P is the production (tonnes) for each crop type c, and E is the mean protein value for products in each crop type c (i.e., 23 g/kg of barley; 63 g/kg of maize grain; 130 g/kg of oat; 150 g/kg of wheat; 50 g/kg of peas). Protein outputs are computed assuming a 100% edible fraction of cereal production; the model does not account for post-harvest losses, processing efficiencies, or non-food allocations.

2.2.3.4 Nitrogen emissions

Emissions from nitrogen are computed from nitrogen fertiliser used per agricultural crop type (kg/ha/year), the amount of land use associated per crop, and a carbon dioxide conversion factor. Nitrogen emissions are estimated using FAOSTAT aggregated emission factors and represent direct N_2O emissions from synthetic fertiliser application only, expressed as CO_2-equivalents; indirect emissions and non-fertiliser nitrogen sources are not included. An efficiency improvement percentage is also considered in the calculation (Equation 4).

$$\mathrm{CO_2eq\ N_2O} = \left(\sum\nolimits_{k} \mathrm{N_2OSc}) \times f \right) \times \left(1 - \frac{Ef}{100} \right) \tag{4}$$

Where CO_2eq N_2O is carbon dioxide emissions equivalent from nitrogen (tonnes), N_2O Sk is nitrogen emission from fertiliser (tonnes) per crop type, c is the crop type, f is a conversion factor where 1 tonne of N_2O emitted equals 265 tonnes of CO_2, and Ef is efficiency improvement (%).

2.2.3.5 Export value of arable products

The export value of arable products is expressed in NZDs (millions) and consists of the production times the mean value for each product (Equation 5).

$$\mathrm{Ev} = \sum\nolimits_{s} \left(\mathrm{Ap}_s \times \mathrm{Mv}_s \right) \tag{5}$$

Where Ev is the export value (million NZDs), Ap is the arable production (tonnes), Mv is the mean value ($NZD), and s is the arable crop type. Ap is computed from the arable specific land use area times the production yield for that specific land use.

2.2.4 Model interface

The model was developed with Stella Architect® (Figure 2), a modelling platform developed by ISEE systems designed for Systems Dynamics model implementation. The arable sector DST module is freely accessible online: exchange.iseesystems.com/public/vannier/future-ag-full-and-regional/index.html#page1.

2.3 Stakeholders engagement and scenario building

This study involved collaboration with stakeholders from the Foundation for Arable Research (FAR), an applied research organisation involved in specific research programmes driven by the interests of NZ growers: maximising productivity and value; environmental and social best practices; and resilient cropping in farming systems. FAR supports NZ's arable farmers by creating new knowledge, tools, and technologies to support responsible and profitable farming. The scenarios developed in this study emerged from an iterative co-design process with FAR. Through an initial workshop (June 2022), a subsequent work/study site visit (November 2022), continuous email and online interactions, and a final workshop (December 2022), a reliable partnership with FAR was established. Stakeholders were invited to identify the types of agricultural production most important to them, reflect on recent and long-term changes in the arable sector, and discuss current and anticipated challenges, including market dynamics, regulatory pressures, and the impacts of climate change on productivity and resource use. These exchanges helped clarify stakeholder

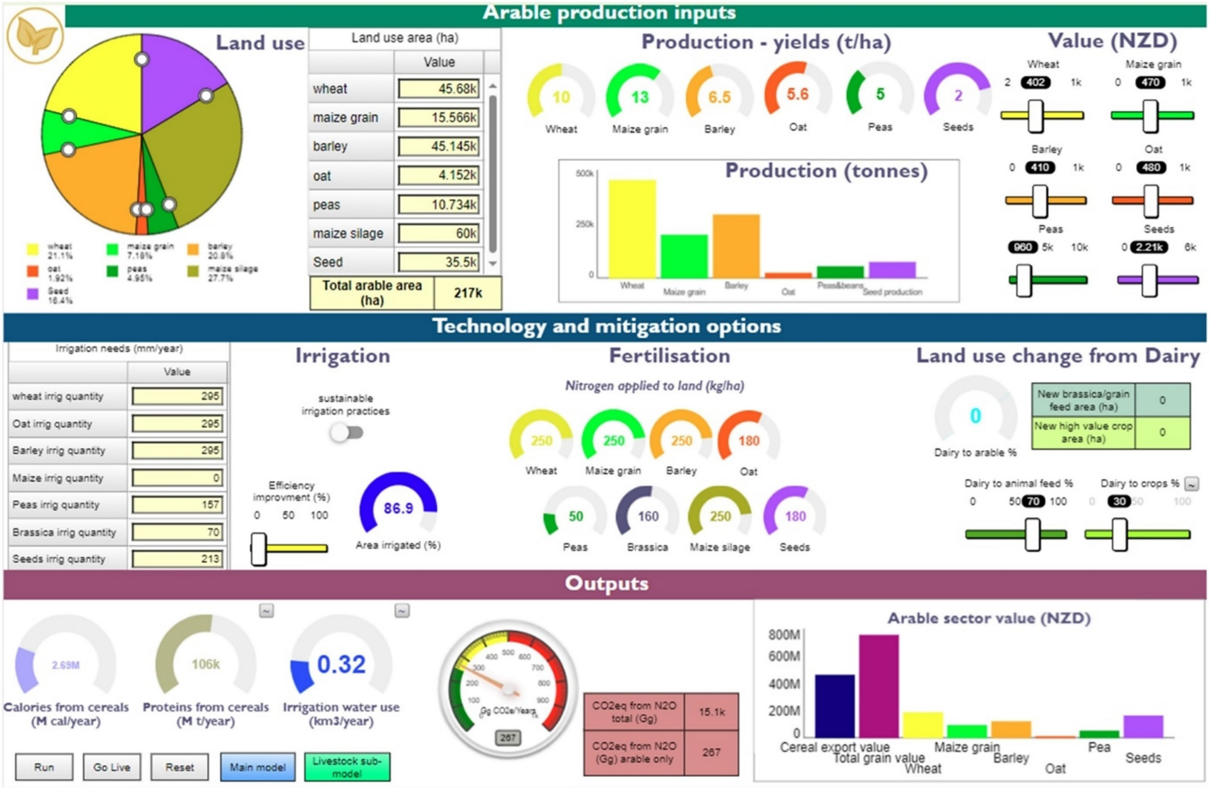
TABLE 1 Model development from 2021 data: parameters, determination methods, data sources and values.

Parameters	Method	Data sources	Value 2021
Inputs			
Land area (ha)	Data provided	AFIC (Arable Food Industry Council) Stats NZ Food and Agriculture Organization - FAOSTAT	
• Wheat			45,680
• Maize grain			15,566
• Barley			45,145
• Oat			4,152
• Peas			10,734
• Maize silage			60,000
• Seeds			35,500
• Total			216,777
Yields (t/ha)	Proxy	Stats NZ AFIC (Arable Food Industry Council)	
• Wheat			9.9
• Maize grain			12.8
• Barley			6.5
• Oat			5.6
• Peas			5.0
• Seeds			2.1
Value (NZD/t)	Proxy	AFIC (Arable Food Industry Council) Ministry for Primary Industries PwC	
• Wheat			410
• Maize grain			465
• Barley			410
• Oat			475
• Peas			960
• Seeds			2,208
Technology			
Irrigation (mm/year)	Phenomenological	FAR (Foundation for Arable Research) expertise CROPWAT (FAO)	
• Wheat			295
• Maize grain			0
• Barley			295
• Oat			295
• Peas			157
• Seeds			213
• Brassica			70
Nitrogen fertiliser applied (kg/ha)	Phenomenological	FAR (Foundation for Arable Research) expertise (Khaembah and Horrocks, 2018; Khaembah et al., 2019)	
• Wheat			250
• Maize grain/silage			250
• Barley			250
• Oat			180
• Peas			50
• Seeds			180
• Brassica			160
Outputs			
Irrigation water used (km3/year)	Proxy (Equation 1)	FAR, CROPWAT, FAOSTAT	0.32

(Continued)

TABLE 1 (Continued)

Parameters	Method	Data sources	Value 2021
Calories from cereals (million kcal/year)	Phenomenological (Equation 2)	Food and Agriculture Organization - FAOSTAT	2.69
Proteins from cereals (million t/year)	Phenomenological (Equation 3)	Food and Agriculture Organization - FAOSTAT	97,000
Emissions (Gg CO_2 eq)	Phenomenological (Equation 4)	FAOSTAT (computed at Tier 1 of the IPCC Guidelines for National GHG Inventories) FAR (Foundation for Arable Research) expertise	
- Total nitrogen			14,700 267
- Nitrogen from arable only			14,700 267
Total export value (NZD million)	Proxy (Equation 5)	Ministry of Primary Industries	462



Land use area (ha)	Value
wheat	45.68k
maize grain	15.566k
barley	45.145k
oat	4.152k
peas	10.734k
maize silage	60k
Seed	35.5k
Total arable area (ha)	217k

Wheat 2 402 1k
Maize grain 0 470 1k
Barley 0 410 1k
Oat 0 480 1k
Peas 960 5k 10k
Seeds 0 2.21k 6k

Irrigation needs (mm/year)	Value
wheat irrig quantity	295
Oat irrig quantity	295
Barley irrig quantity	295
Maize irrig quantity	0
Peas irrig quantity	157
Brassica irrig quantity	70
Seeds irrig quantity	213

New brassica/grain feed area (ha)	0
New high value crop area (ha)	0

Dairy to animal feed % 0 50 70 100
Dairy to crops % 0 30 50 100

CO2eq from N2O total (Gg)	15.1k
CO2eq from N2O (Gg) arable only	267

FIGURE 2
Model interface – arable module desktop.

priorities and decision needs, leading to the identification of three key themes for scenario development: food security (wheat self-sufficiency), climate change mitigation through arable–livestock interactions, and alternative protein production. For each theme, stakeholders contributed to defining the questions of interest, the elements to be included, and the assumptions to be tested. Researchers and stakeholders then jointly developed narrative descriptions of the scenarios, which were translated into quantitative inputs within the Decision Support Tool, ensuring that the scenarios were both scientifically robust and grounded in real-world industry contexts.

The co-development process ensured that model outputs reflected the information needs of end users rather than theoretical assumptions. During the workshops, stakeholders actively manipulated scenario inputs within the DST interface, which helped them evaluate the feasibility and economic consequences of different strategies. This hands-on exploration was critical for fostering ownership of the results and for integrating model outcomes into practical decision pathways at both farm and policy levels.

2.3.1 Food security: increasing wheat production to gain self-sufficiency (scenario 1)

In 2022, there were 250,000 tonnes shortfall of wheat production for human and animal consumption in NZ. Given the importance of wheat to various sectors in NZ, it constitutes a food security challenge. Current production is 452,000 tonnes (including 115 k tonnes used for human consumption in 2021) and the challenge is to reach 700,000 tonnes a year for NZ to become self-sufficient. A scenario was thus formulated to reach self-sufficiency by 2050 by actioning the following levers:

- increasing the area of production
- enhancing yields

In summary the Decision Support Tool was used to answer the following questions: What is the yield/area balance to grow 700,000 tonnes of wheat in NZ? What are the economic and environmental ramifications? If all Canterbury dairy farms in NZ grow 1 to 5% of cereals, do we achieve grain self-sufficiency?

2.3.2 Mitigating climate change: reducing nitrogen and methane emissions (scenario 2)

The Zero Carbon Amendment Act has set reduction targets of Net zero for carbon dioxide (CO2) and nitrous oxide (N2O) by 2050, and −24 to −47% below 2017 levels of biogenic methane (CH4) to by 2050, including −10% below 2017 levels by 2030. CO2 equivalent emissions from CH4 in 2017 were 23,400 Gigagrams. The objectives is to limit methane emissions to between 12,400 Gg to 17,700 Gg CO2 eq. NZ research and technology development to reduce methane emissions from agriculture and livestock is promising. It includes research programmes on breeding, feeds, inhibitors, vaccine, manure and science of methane mainly led by the New Zealand Agricultural Greenhouse Gas Research Centre. Mitigation options and management strategies like alternative forages introduced in animal diet can significantly reduce the nitrogen emissions on farm. According to recent studies (Sun et al., 2016; Jonker et al., 2017), feeding cows at least 20% and up to 50% of their diet with brassicas can mitigate methane emissions from rumen of about 30%, and introducing alternative forage and low nitrogen feed in livestock diet could reduce N2O emissions by 25% (Ledgard et al., 2019; de Klein et al., 2020).

A scenario was thus formulated to apply known benefits of alternative forage and grain diets to dairy and beef cattle to reduce methane and nitrogen emissions. The following levers were actioned:

- reducing the number of cows (dairy and beef cattle)
- increasing alternative diet

In summary, the Decision Support Tool was used to answer the following questions: How many hectares of alternative forages, forage grains, other grains, do farmers need to grow to reach the government methane emission objectives? How much does planting brassicas and grains contribute to the nitrogen emission reduction? What number of animals is sustainable to reach the government methane reduction objective?

2.3.3 Alternative proteins: developing a pea and fava bean protein market in NZ (scenario 3)

Plant based protein production is an evolving area. Recent estimates show one in every 10 protein products sold in 2035 will come from alternative protein sources (Morach et al., 2021). With investment in the plant protein extraction market, NZ has the capacity to grow and transform pea and fava bean protein on site and create a 100% NZ label (PwC, 2022). Developing a plant-based protein market is also consistent with The Climate Change Commission's recommendations to Government to reduce the size of the dairy, sheep, and beef herds by 14% by 2030. Growing plant based and alternative proteins will lead to a reduction in nitrogen fertilisers and water use for irrigation, as compared to pasture production for dairying. A scenario was thus formulated to analyse the development of land use, management, value chain and market opportunities from alternative protein production by actioning the following levers:

- increasing the area of production
- enhancing yields
- increasing market value

In summary, the Decision Support Tool was used to answer the following questions: How many hectares of pea and fava beans are required to produce 10% of NZ protein needs? What are the economic and environmental ramifications of this production? What price is required to incentivise farmers to grow peas/beans and make a sustainable profit?

3 Results

3.1 Scenario 1 food security: increasing wheat production to gain self-sufficiency

Production area and/or yields were increased to achieve the target of producing 700,000 tonnes of wheat in NZ. To illustrate the effect of multiple bad weather seasons (either droughts or very wet springs), one simulation showing lower yields than 2021 was run (with yield = 8 t/ha). Results show the need to grow significantly more wheat area to achieve grain self-sufficiency (Table 2). Keeping the current average yield of 9.9 t/ha or improving it to 12 t/ha (by using widely the technology of precision agriculture) will require an extra 13 k to 25 k hectares of wheat area. Irrigation water used requirement, if current irrigation standards are applied (i.e., a mean of 295 mm/year for wheat production) would increase by 8 to 30.5%. CO_2 equivalent emissions from Nitrogen (i.e., 267 Gg CO_2eq estimated in 2021) would increase by 9.3 to 31.8%. However, introducing this wheat production in a livestock system (i.e., Dairy) would have a positive impact, producing almost 8 times less CO_2eq biogenic emissions and using one-third less water for irrigation than irrigated pastures. A sensitivity analysis was performed to examine how the results respond to variations in key parameters, particularly crop yields and land area allocation. Results show that the total production and associated emission benefits are highly sensitive to yield assumptions: a 1 t/ha increase in average wheat yield changes national wheat self-sufficiency by approximately ±8–10%. Conversely, variations in the irrigated area have a smaller proportional effect on total emissions than on production. These findings underline the importance of technological and agronomic improvements, but also highlight that the model outcomes depend strongly on yield trajectories that are uncertain over multi-decadal timescales.

The upper bound of 15 t/ha (Table 2) was explored only as a hypothetical best-case limit, representing the combined effect of

TABLE 2 Wheat production scenario for self-sufficiency objectives (Irrigation need and N_2O emission assume the current rates applied).

Yield (t/ha)	Baseline 2021	Scenario 2050			
	9.9	8.0	9.9	12.0	15.0
Area (ha)	45,000	88,000	70,000	58,000	45,000
Production (t)	452 k	700 k	700 k	700 k	700 k
Irrigation need (km^3/year)	0.0132	0.0260	0.0206	0.0171	0.0132
Nitrogen emission (Gg CO_2eq)	61.0	119.3	94.8	78.6	61.0

TABLE 3 Reducing nitrogen and methane emissions by reducing herd number and introducing alternative feed.

Alternative feed (% of overall feed)	0%	10%	20%	30%
Herd (head)				
Current 6.2 m dairy 3.9 m beef	24.2 k Gg CO2 eq from methane 14.4 Gg CO2eq from nitrogen	22.5 k 13.3 k	20.8 k 12.2 k	19.2 k 12.2 k
-5% 5.89 m dairy 3.7 m beef	23.7 k 14 k	22 k 12.9 k	20.3 k 11.8 k	18.7 k 11.9 k
−10% 5.58 m dairy 3.51 m beef	23.4 k 13.2 k	20.7 k 12.2 k	19.2 k 11.2 k	17.7 k 11.3 k
−15% 5.27 m dairy 3.31 m beef	21.2 k 12.7 k	19.9 k 11.8 k	18.4 k 10.9 k	17 k 11 k

Methane emissions targets are: −10% of 2017 levels by 2030 (=21.06 Gg CO2eq) and −24% to −47% of 2017 level by 2050 (=17.8 k to 12.4 k Gg CO2eq respectively). In red, unmet goal, in orange, 2030 met goal, in green, 2050 goal met.

high-yielding cultivars, precision nutrient management, and favourable climate conditions. Although such yields have been occasionally achieved in experimental trials in Canterbury, NZ, and parts of the UK, they remain agronomically exceptional and unlikely to be achieved consistently at national scale by 2050.

Similar scenario analyses in Europe and Australia also highlight cereal self-sufficiency as a viable resilience strategy under climate uncertainty. For instance, the European Commission's "Farm to Fork" projections show that modest increases in cereal area (10–15%) combined with input efficiency gains could offset grain import dependency while meeting emission targets (Menegat et al., 2022). Likewise, Australian modelling using the APSIM platform suggests that yield improvements from precision irrigation can increase significantly wheat output without proportionally raising water demand (Zhang et al., 2022; Richetti et al., 2024). These parallels support the NZ results, indicating that targeted expansion of irrigated cereals can enhance food security with manageable environmental trade-offs.

3.2 Scenario 2 mitigating climate change: reducing nitrogen and methane emissions

Two main levers were tested to reduce emissions, a decrease of herd numbers by 5, 10 and 15% (dairy and beef) and a significant introduction of alternative feed in the animal diet of about 10, 20 and 30%. The amount of methane and nitrogen emitted for those combinations were computed. Table 3 highlights the combinations that meet the government goals for 2030 (−10% of 2017 emission, i.e., 21.06 k Gg CO2eq) and 2050 (−24 to 47% of 2017 emission, i.e., 17.8 k to 12.4 k Gg CO2eq respectively) in terms of methane emissions. It also displays the nitrogen emission reduction for each combination. A herd reduction of about 10 or 15% combined with an increase of 30% of alternative diet (brassica and grains) in the animal feed allow to reach the objective for methane emissions in 2050. This combination also allows reductions of 21% to more than 23% emissions from nitrogen. A herd reduction of about 0 to 5% and an increase of alternative diet at about 20 to 30% allows to reach the 2030 objective for methane emissions. This combination reduces emissions from nitrogen by 15.2 to 18%. From the environmental side, introducing this alternative feed production in a dairy system could have a clear positive impact, as grain production results in almost 8 times less CO2eq biogenic emissions and uses one-third less water for irrigation than dairy pasture.

Comparable mixed-system mitigation scenarios have been tested internationally. In the Netherlands and Denmark, integrated modelling of reduced stocking rates and alternative feeds achieved 25–30% methane cuts, aligning closely with the reductions simulated here (de Klein et al., 2020). Studies in Ireland's Teagasc Marginal Abatement Cost Curve project also show that combining herd efficiency with feed substitution yields stronger GHG benefits than technological fixes alone (Lanigan and Donellan, 2018). These findings confirm that NZ strategy—moderate herd reduction plus feed diversification—is consistent with best-practice international pathways for balancing productivity and emissions goals.

3.3 Scenario 3 alternative proteins: developing a pea and fava bean protein market in NZ

The total protein produced in NZ in 2019 was 97 g/capita/day (source: FAOSTAT). Out of the 97 g/capita/day, 56 g came from animal products and 41 g from vegetal products, i.e., 25 g from crops, 10 g from pulses, oils, roots, nuts and others 6 g from fruits and vegetables. Proteins from cereals mainly comes from wheat (69%). Currently, peas only supply about 1% of the proteins from cereal. Protein from peas in the NZ food supply play a minor role.

Scenarios of combinations of land areas (7 k ha, 17.5 k ha, 25 k ha, 105 k ha), yields (3.5 t/ha, 5 t/ha), and prices (960$/t, 1,200$/t, 3,000$/t) for growing peas to supply up to 10% of the protein needs in NZ have been simulated and presented in Table 4. The scenario parameters assumptions are based on the Feasibility of Pea and Fava Bean Protein Extraction in NZ report and discussion with the stakeholder. The scenario assumes an extraction facility capable of processing 15,000 tonnes of peas and that the cost for that facility is approximately NZD$50 million to establish. Results show that best combinations allow up to 7 extraction facilities by 2050. High environmental gains are expected: peas and beans required half the amount of irrigation water, and 5 times less nitrogen to grow than other mainstream crops, 3 times less than maximum authorized for pastures.

Global scenario work on alternative proteins, such as the Protein 2050 Initiative (Morach et al., 2021) and FAO foresight analyses (FAO, 2022), similarly project strong economic and environmental co-benefits when legumes substitute part of animal protein demand. European case studies in France and the UK found that scaling up pulse crops to 10–15% of cropland could reduce sectoral GHG emissions by 15–20% while boosting farm profitability. These patterns reinforce the NZ findings, confirming that investment in plant-protein processing and value-chain integration is essential to capture both domestic and export market opportunities.

4 Discussion

4.1 Model and scenario challenges and limitations

Our DST allows to simulate and assess a wide range of future scenarios, but it does not consider the transition challenges of implementing the preferred scenarios. Stakeholders' input and feedback in this study have allowed to highlight how the growth in wheat, alternative feed or pea/bean production increase could be achieved, what are the challenges and limitation to trigger these changes, who makes the decisions, and how it could be implemented. Those elements are discussed in the following paragraphs.

Interpretation of the scenario results has been analysed in light of the stakeholder perspectives that guided their development. The scenarios do not represent an exhaustive set of possible futures, but rather reflect the priorities, concerns, and decision contexts articulated by the stakeholders. Stakeholders evaluated scenarios not only on their biophysical and economic outcomes, but also on their perceived feasibility, alignment with existing farming systems, infrastructure constraints, and market realities. For example, scenarios involving increased wheat production or alternative feed integration were assessed by stakeholders in relation to labour availability, machinery requirements, irrigation capacity, and compatibility with dairy system operations, while alternative protein scenarios were considered in the context of processing infrastructure, market certainty, and price signals. As a result, scenario outcomes that appear optimal from a modelling perspective may face significant implementation barriers, whereas more moderate pathways may be viewed by stakeholders as more realistic and actionable. Incorporating these perspectives highlights the value of participatory process for identifying not only technically viable pathways, but also those most likely to be adopted in practice.

Growing grains with the help of the Dairy sector, for example, will require more contractors (work force), machinery, and may raise irrigation pressure points during key growth stages. Most of the 425,000 tonnes of wheat grown annually are produced in the Canterbury plains, where a combination of good soils and irrigation system allow high yields. This makes the region well set up for an increase of wheat production. If we consider a stocking rate reduction in the Dairy system to accommodate wheat, this would also benefit freshwater objectives and GHG emission reduction. To implement such a change, dairy farmers would have to be convinced about profitability margins, including considerations of any required emissions reductions. There are several options to implement this shift for specific farmers: working with their own machinery and tractor driver, doing a reasonable amount of the work themselves; or hiring a contractor for sowing, tillage and harvesting as required; or leasing the land to an arable farmer.

A second side impact of increasing grain production is increasing storage and infrastructure. There are specific requirements around storage and conditioning of grain which would result in a need for

TABLE 4 Pea and fava bean protein market development scenario.

		Baseline 2021		Baseline 2021*2.5			Baseline 2021*3.5			Baseline 2021*15		
Scenario parameters	Land (ha)	7,000		17,500			25,000			105,000		
	Yield (t/ha)	3.5	5	3.5		5	3.5		5	3.5		5
	Dry peas price (NZD/tonne)	1.2 k	3 k	960	1.2 k	3 k	960	1.2 k	3 k	960	1.2 k	3 k
	Protein price (NZD/tonne)	6 k	15 k	4.8 k	6 k	15 k	4.8 k	6 k	15 k	4.8 k	6 k	15 k
Results	Production (tonne)	24.6 k	35 k	61 k	61 k	87.5 k	87.5 k	87.5 k	125 k	367.5 k	37.5 k	525 k
	Protein production (tonne)	4.9 k	7 k	12.2 k	12.2 k	17.5 k	17.5 k	17.5 k	25 k	73.5 k	73.5 k	105 k
	Value (NZD million)	29.5	105	58.5	73.2	262.5	84	105	375	352.8	441	1,575

more facilities, an increase in capacity of some machinery and more transport. However, according to FAR stakeholders, domestic transport deficiencies and relative prices mean that sometimes it's cheaper to bring wheat into the country than grow it in the South Island and transport it up to Auckland (internal transport costs can be higher than bringing product from Australia). Currently there's not enough infrastructure and volume to make it happen. However, considering the effects of climate change, developing new arable land further south in Southland and south Otago as well as in the east and south of the North Island, Waikato and up to Northland, could provide the economy of scale.

Similar requirements apply when it comes to increasing brassica and grain production, i.e., increasing storage, infrastructure, and the need for a larger work force. Home-grown alternative feeds could also reduce our reliance on imported Palm Kernel Extract, which produces even higher levels of methane when digested than pasture. Moreover, nearly one-third less irrigation would be required for such a system, which could see changes in irrigation water used and associated environmental impacts.

Environmental benefits from alternative protein development alone are unlikely to sway growers according to FAR, as peas are not currently a high value crop. NZ is already importing both pea and fava bean protein. Placing greater value on locally grown protein may be a key strategy to develop this market. However, another challenge is the current lack of a protein processing plants in the country. Building the necessary plants is evaluated at $50 million (PwC, 2022), but crop areas will have to increase substantially to make the build worthwhile. Some serious co-operation between growers, processors and food manufactures will be needed to start investing in an alternative protein market, and a premium for the final products must be assured.

An important consideration in these scenarios is whether increased arable land area competes with other land uses, particularly natural ecosystems. In this study, arable expansion is assumed to occur mainly on high-quality soils with existing irrigation infrastructure, which are currently dominated by dairy production rather than native or semi-natural land cover. Given the large scale of the dairy sector, modest reductions in dairy cow numbers, combined with continued efficiency gains, could accommodate increased arable production without reducing overall food output. Such reallocation may also deliver environmental co-benefits, as arable crops typically require less irrigation and generate lower biogenic greenhouse gas emissions per hectare than irrigated dairy pasture.

4.2 Spatial implications and future development needs

The scenarios developed in this study reveal the urgent need to integrate spatially explicit modelling into national-scale analyses. While the current DST provides powerful insights into production, emissions, and resource use at an aggregated national level, its results cannot yet capture regional heterogeneity in land-use potential, climate risk, infrastructure, or water allocation. Understanding these spatial dimensions is critical for supporting targeted policy design, regional investment planning, and place-based adaptation strategies.

At present, fine-scale information on crop rotations, irrigation infrastructure, and land-use transitions remains fragmented or incomplete, which limits the capacity to test how scenarios could unfold across NZ diverse landscapes. As such, several assumptions were required regarding land suitability and crop distribution. These uncertainties point to a major research gap: the lack of integrated spatial datasets linking arable systems with environmental constraints and socio-economic drivers.

Future development of the DST should therefore focus on coupling the existing systems model with geospatial data layers (e.g., soil, climate, and irrigation maps) and remote-sensing products to enable spatially resolved simulations. This would allow decision-makers to visualise where and how scenario interventions—such as wheat expansion or alternative protein cropping—are most feasible, and where they may generate trade-offs with other sectors or environmental limits. It would allow the DST to evaluate multiple climate scenarios by translating projected regional climate changes into crop suitability, yield, and irrigation-demand responses. It would also enable region-specific feasibility and constraint analysis (soil capability, irrigation infrastructure, competing land uses) and catchment-level environmental assessment (water allocation, leaching/erosion risk), improving the tool's capacity to test targeted policies and realistic transition pathways. Integrating these spatial components will transform the DST from a national diagnostic model into a spatial decision-support platform, capable of guiding regional transitions toward sustainable and climate-resilient agriculture.

4.3 Trade-offs and policy relevance of the modelled scenarios

The scenarios generated by the decision support tool reveal clear trade-offs between production, environmental performance, and implementation feasibility. In Scenario 1, increased wheat production improves domestic food security but leads to higher irrigation demand and nitrogen-related emissions when current management practices are assumed. However, these impacts are strongly context-dependent: where expanded arable cropping substitutes for irrigated dairy pasture, both water use and biogenic methane emissions may decline, highlighting the importance of system-level land-use reallocation rather than crop expansion in isolation. Scenario 2 illustrates a trade-off between emissions reduction and production structure, with the largest methane and nitrogen reductions achieved through a combination of reduced livestock intensity and alternative feed use, implying transitional and logistical constraints alongside environmental benefits. Scenario 3 presents lower-input legume systems as environmentally advantageous, particularly in terms of nitrogen use, but economically contingent on market development, processing infrastructure, and supply-chain coordination.

Comparable trade-offs have been observed in international agricultural scenario studies (Kanter et al., 2018; Paul et al., 2022; Sanou et al., 2023; Elia et al., 2025), where cereal expansion or livestock mitigation strategies deliver environmental benefits primarily when supported by efficiency gains, land-use substitution, and value-chain integration, rather than through single-lever interventions.

In New Zealand, several existing policy frameworks partially support the directions explored in these scenarios. The national Emissions Reduction Plan sets explicit methane and nitrous oxide reduction targets as part of the transition to net zero by 2050, including actions to support mitigation adoption in agriculture (Ministry for the Environment, 2022). Freshwater management instruments such as the National Policy Statement for Freshwater Management and the implementation of freshwater farm plans provide regulatory direction to manage water quality and nutrient losses from agricultural land use (Ministry for the Environment, 2025). Reviews of policy impacts further indicate that joint climate and freshwater frameworks influence land management decisions and related environmental outcomes, illustrating how regulatory drivers overlap with the trade-offs identified by the model (Djanibekov and Wiercinski, 2020). However, the scenarios also expose policy gaps, particularly in relation to food-security instruments for arable crops, investment support for processing infrastructure, and incentives for irrigation efficiency. Addressing these gaps through coordinated climate, water, and agri-food policies would enhance the feasibility and effectiveness of the pathways identified by the model, while recognising that transition costs and regional constraints remain important limitations (Zahedi et al., 2024; McElwee et al., 2024).

5 Conclusion

Three scenarios guided by our stakeholder, the Foundation for Arable Research, were simulated using a newly developed Decision Support Tool for arable agriculture. The first scenario investigated the potential of food security by wheat self-sufficiency production within NZ. Enhancing food security, by producing 700 k tonnes of wheat, would require an extra 25 k hectares. Co-benefits by introducing this wheat production in a Dairy livestock system would help reduce carbon equivalent biogenic emissions by a factor of eight while using one-third less water for irrigation than normally used for dairying. The second scenario investigated the effects of changing animal diet for mitigating climate change. Results suggested that complementing animal diets with 30% locally grown grains and reducing the herd by 10% would help achieve NZ emissions targets for 2050. The third scenario explored the development of a pea and bean market development in NZ, with the implementation of a new extraction facility (processing 15 k tonne of peas/year), to reply to the global trend of alternative protein production. Results shown that an increase in productivity, area planted, and value (yields up from 3.5 to 5 t/ha; value rise from $960/t to $1,200/t; and land area increase to 25,000 ha) would result in a significant growth in arable agriculture profitability ($375 million) and potential emissions reductions. Collectively, these results align with a growing body of international evidence that diversified, mixed cropping–livestock systems offer simultaneous benefits for productivity, climate mitigation, and water efficiency. By translating global scenario principles into a NZ-specific modelling framework, this study bridges the gap between conceptual foresight and practical implementation. It demonstrates that national targets for carbon neutrality and food security can be met through locally adapted versions of globally tested strategies.

The main originality of this research lies in demonstrating how a quantitative systems model can be operationalized as a participatory decision-support tool. While numerous modelling studies estimate emissions or production trade-offs, few translate such outputs into an interactive framework that stakeholders can use to test "what-if" futures in real time. In this study, the DST functioned as a negotiation and learning interface—helping growers, researchers, and policymakers converge on realistic strategies for achieving food security, emissions reduction, and diversification within NZ agricultural system. At the same time, the study highlights the importance of clearly communicating the methodological assumptions, system boundaries, and data limitations underpinning the model, particularly given its exploratory and scenario-based nature.

The scenarios explored can then serve as valuable guidelines for policymakers, researchers, and stakeholders to make informed decisions and take proactive actions towards achieving sustainability and resilience in the agricultural sector. The simulation of these scenarios showed that productivity and emissions goals can be achieved in NZ through a variety of initiatives, but it is important to note that these pathways are driven by market demand and a range of disruptive factors. Although the scenarios were co-developed with stakeholders, this work primarily focused on quantitative outcomes. A more systematic assessment of stakeholder perceptions of the results therefore remains an important area for future research. Understanding how stakeholders interpret, prioritise, and respond to scenario outcomes is especially critical given the interactive design of the tool. Explicitly capturing these viewpoints would help better delineate the scope, applicability, and limitations of the DST as a decision-support instrument, and strengthen its contribution to real-world planning, policy dialogue, and transition pathways for sustainable and resilient arable agriculture in NZ.

The newly developed DST was instrumental in exploring pathways together with stakeholders, but further research is needed for understanding transition requirements and spatial planning and implementation of the proposed scenarios.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CV: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. TC: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. IL: Conceptualization, Data curation, Methodology, Validation, Writing – review & editing. LB: Conceptualization, Funding acquisition, Investigation, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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