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Development of LIME-NZ: a generic tool for prompt estimation of economic impacts of disease for New Zealand livestock

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ABSTRACT

Aims: To develop a simple and robust generic tool to measure the impacts of livestock diseases on New Zealand dairy, beef and sheep farms using enterprise gross margin models.

Methods: The most recent (2018–2020) livestock production benchmarking data was extracted from industry-led economic surveys. Gross margin models were built for each enterprise type, accounting for 11 dairy farm types and 16 farm types for beef and sheep. Disease parameters, including changes in mortality, reproduction performance, milk yield, price of animals and culling rate, as well as additional expenses for veterinary intervention, were applied to the infected compartment of the herd/flock using the assumed annual within-herd disease incidence. Farm-level disease impacts were estimated as the difference in annual profit between the baseline and infected farm. The baseline gross margin models were validated against the industry data. The disease impact models were validated using a recently published study on bovine viral diarrhoea (BVD). The impact assessment tool, LIME-NZ, was developed using the statistical software R and implemented in the web-based R package Shiny. The input parameters can be varied interactively to obtain a range of disease impacts for uncertain disease parameters.

Results: The baseline gross margin models demonstrated reasonable accuracy with a mean percentage error of <14% when compared with the industry reports. The estimated annual impacts of BVD were comparable to those reported in the BVD study, NZ$38.5–140.4 thousand and $0.9–32.6 thousand per farm per year for dairy and beef enterprises, respectively.

Conclusions: LIME-NZ can be used to rapidly obtain the likely economic impacts of diseases that are endemic, recently introduced or at increased risk of introduction in the New Zealand context. This will aid communication and decision-making among government agencies and the livestock industry, including veterinarians and livestock producers, about the management of diseases, until refined information becomes available to improve decision-making.

Abbreviations: BVD: Bovine viral diarrhoea; LIME-NZ: New Zealand Livestock Disease Economic Impact Models; MA: Mixed age; NI: North Island; R1: Rising 1-year old; R2: Rising 2-year old; R3: Rising 3-year old; SI: South Island

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Economic analysis; enterprise gross margin; partial budget; livestock disease; decision-making tool

Introduction

Knowledge of the economic impact of livestock diseases is important for increasing awareness among livestock producers and improving surveillance efficiency and overall biosecurity at the farm and national level. Livestock owners are more likely to report diseases when there is an economic incentive for them to do so, such as a direct improvement in livestock productivity or compensation payment (Barnes *et al.* 2015). Information about the economic impacts of endemic diseases may also assist decision makers in disease prioritisation and resource allocation for disease management (Tisdell *et al.* 1999; Rushton 2017). Although immediate response actions are required during an outbreak of an emerging disease, it is challenging to make evidence-based decisions about disease control measures under uncertainty and time pressure and to gain universal approval among stakeholders (Salajan *et al.* 2020). Estimating the severity of the disease and its economic impact are key steps when determining appropriate control measures and undertaking joint and informed decision-making.

Published literature may often be the only source of information on disease impacts when time and resources are limited. Partial budget or enterprise gross margin analyses are commonly used to estimate

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the economic impact of existing diseases, such as bovine viral diarrhoea (BVD; Chi *et al.* 2002; Heuer *et al.* 2007; Han *et al.* 2020), Johne's disease (Bush *et al.* 2008) and Schmallenberg virus (Alarcon *et al.* 2014; Raboisson *et al.* 2014; Häsler *et al.* 2015) on a farm. However, data on the economic impacts of animal diseases are sparse, despite the ongoing efforts to address such issues (Rushton 2017; Rushton *et al.* 2018). This is because field data collection is costly and time consuming. The limitation of literature-based information is that there is historical bias and a gap in marketing-driven health research incentives (Morel 2003). The primary focus tends to be on diseases considered important at the time due to their apparent severity, public health impacts, or trade implications. In contrast, there are far fewer studies on diseases that are emerging, not recognised as important, or only prevalent in low-income countries. The volume of research funding and output may not reflect the true disease burden, especially in the context of neglected tropical diseases (Fonseca *et al.* 2020). In addition, disease impacts reported in a particular study may not be directly applicable to other farming systems because the farm management and price indicators vary across countries and time periods.

New Zealand is primarily an agricultural country, with exports of animal products playing a crucial role in its domestic economy (Chatellier 2021). It is currently free from most high-profile livestock diseases such as foot and mouth disease and African swine fever, but many parasitic diseases (Bisset 1994; Vlassoff and McKenna 1994), leptospirosis (Sanhueza *et al.* 2020), Johne's disease (Gautam *et al.* 2018) and BVD (Han *et al.* 2020) are prevalent, resulting in production losses and consequent economic impacts for producers and taxpayers. As an isolated island nation, the risk of disease introduction in New Zealand is relatively low, but there are occasional incursions of new diseases requiring immediate response, with recent examples including *Theileria orientalis* (Ikeda) in 2012 (Pulford *et al.* 2016) and *Mycoplasma bovis* in 2017 (Bingham *et al.* 2017). Therefore, it is important for New Zealand's agricultural industries to be able to assess the economic impact of animal disease incursions at short notice.

Given the lack of a live, robust and standardised system that integrates livestock population and economic data in New Zealand, and with the challenges in promptly obtaining sufficient information about disease economic impacts, there is a growing need for a simple and robust tool to assess the economic impact of diseases. The objective of this study was to develop an interactive tool that allows prompt estimation of the economic impact of various diseases in typical livestock production systems for dairy, beef and sheep enterprises in the New Zealand context.

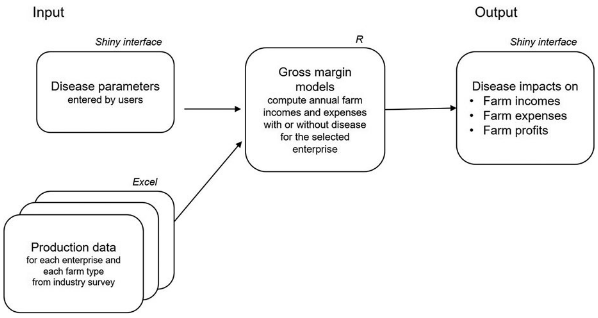

Figure 1. Flowchart illustrating four key components of New Zealand Livestock Disease Economic Impact Models (LIME-NZ) designed to estimate the economic impact of diseases on New Zealand dairy, beef or sheep farms. The user interface allows users to enter parameters related to the disease of interest and to select the relevant enterprise and farm types. The production data module stores recent industry benchmarking data. The gross margin module calculates farm incomes, expenses and profits with and without the disease based on the input parameters and the benchmarking data. The output module presents summary result tables and figures in a user-friendly format.

Materials and methods

New Zealand Livestock Disease Economic Impact Models (LIME-NZ) was developed as an interactive tool containing deterministic enterprise gross margin models for New Zealand dairy, beef and sheep enterprises. It runs for a 1-year period from 1 June in a particular year to 31 May in the following year. The tool was developed using R 4.2.0 (R Core Team, Vienna, Austria, 2022) with a user interface produced by the package Shiny (Chang *et al.* 2023). The current version of LIME-NZ is available at https://shiny.massey.ac.nz/mwada/lime/. The source code is available at GitHub (https://github.com/masakowada/lime-nz). A flowchart illustrating the key components of LIME-NZ is shown in Figure 1. The enterprise gross margin models were developed in R, which took disease parameters and production data as input parameters and returned economic outputs including estimated total incomes, expenses and profits with and without disease, and the difference between the two scenarios. Disease economic impacts were estimated as the difference in the estimated farm profits between the baseline scenario without disease and an alternative scenario with disease. Disease parameters could be varied for each analysis using the user interface, whereas production data were fixed and updated only when needed.

Enterprises and farm type

Three gross margin models were built for dairy, beef and sheep enterprises. Each model was designed to operate independently of the others. For farms with mixed enterprises (e.g. beef and sheep), the effects of disease on production were estimated separately for each enterprise, assuming no cross-enterprise actions were taken to mitigate the overall disease impacts, for example by changing the stocking ratio between the species. The rationale for this design was that farmers strategically optimise their stocking rate and the sheep-to-cattle ratio to maximise profitability, considering a range of factors over years, including stock carrying capacities, pasture demand, market prices, and their preferences. It is unlikely that they would make significant adjustments to these variables during the farming season in response to a single factor, such as disease.

Following classification of farms by their respective industries, the models incorporated 11 farm types within the dairy enterprise (Supplementary Table I), and 16 farm types within the beef and sheep enterprises (Supplementary Table II). Each industry independently chose its categorisation methods to meet its specific needs, and the categories were therefore not compatible between dairy *vs* beef and sheep sectors. Dairy farm types were categorised by three input levels (production systems 1–2, 3 and 4–5 by DairyNZ classification – low, medium and high) or by eight geographical regions (Northland, Waikato, Bay of Plenty, Taranaki, Lower North Island, West Coast-Tasman, Marlborough-Canterbury and Otago-Southland) (DairyNZ 2021). The input levels were determined by DairyNZ based on the season and amount of imported feed given to animals. The regions were based on DairyNZ divisions reflecting the geographical distribution of dairy farms. In this study, we assumed that dairy farmers owned and operated their own herd and land. More than half of dairy farms in New Zealand are owner-operators, although there are other types of dairy farm ownership structures that were not considered in this study (e.g. contract milkers and sharemilkers).

Beef and sheep farm types consisted of eight major farm classes categorised by North Island (NI) or South Island (SI), and production types based on the B+LNZ classifications (Beef+Lamb New Zealand 2021b): NI hill country, NI intensive finishing, NI hard hill country, SI finishing breeding, SI intensive finishing, SI hill country, SI mixed cropping and finishing, and SI high country. These farm classes were further subdivided by geographical locations: Northern NI (Northland, Waikato and Bay of Plenty), Eastern NI (Gisborne, Hawke's Bay and Wairarapa), Western NI (Taranaki, Rangitikei and Manawatū), Central SI (Marlborough and Canterbury) and Southern SI (Otago and Southland). Not all farm classes exist in all regions, resulting in a total of 16 farm types.

Animal subgroups

In the gross margin models, animals within a farm were divided into subgroups by age group and sex, largely following the categorisation used in the industry benchmarking data (Figure 2). For dairy enterprises, animals were categorised into three subgroups: ≥ 2-year-old mixed age (MA) breeding/lactating cows, rising 2-year-old (R2) replacement heifers (12–≤24 months old), and calves born during the current season which then became rising 1-year-old (R1) animals (0–≤12 months old). The calves/R1 category included male dairy calves sold immediately as bobby calves, beef cross dairy calves, and replacement dairy heifers (Edwards *et al.* 2021). Beef cross dairy calves were assumed to be sold as R1 animals for fattening by the end of the season (Edwards *et al.* 2021). Replacement dairy heifers were assumed to be reared from calves, with first mating occurring as R2 heifers (at around 15 months of age), and first calving occurring in 2-year-old heifers. Breeding bulls

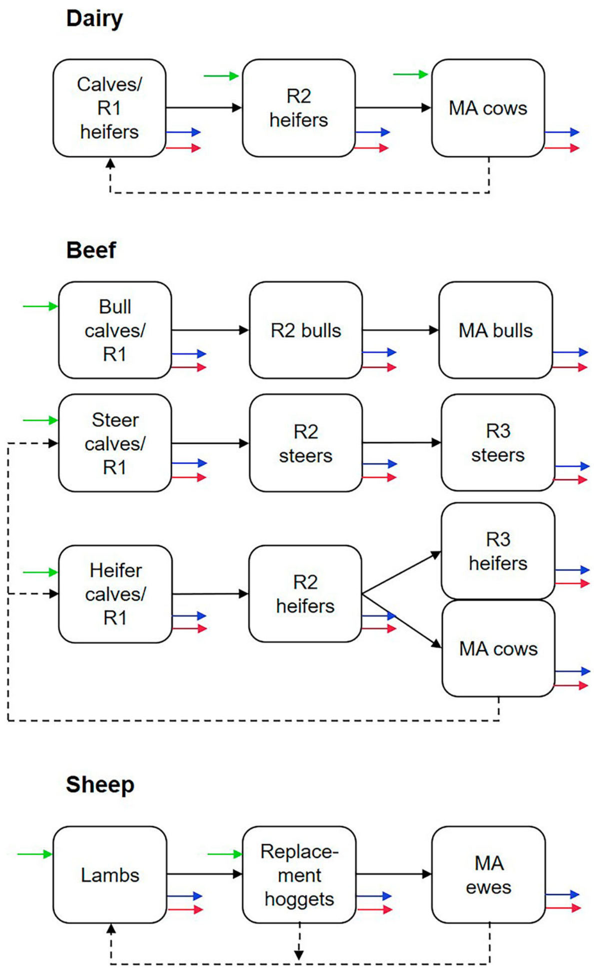

Figure 2. Diagram showing animal subgroups classified by sex, age group (rising 1-year old (R1); rising 2-year old (R2); mixed age (MA); rising 3-year old (R3)) or production stage for New Zealand dairy, beef and sheep enterprises incorporated in the New Zealand Livestock Disease Economic Impact Models (LIME-NZ). The arrows indicate transition (black), birth (dashed), sell or cull (blue), death (red) and purchase (green) over a 1-year time period. The numbers or proportions of subgroups and their dynamics were allowed to vary by farm types. For interpretation of the coloured elements in this figure, the reader is referred to the web version of this article.

were assumed to be leased only during the mating period, and hence unaffected by disease.

For beef enterprises, animals were categorised into 10 subgroups: ≥ 2-year-old MA breeding cows, ≥ 2-year-old MA breeding bulls, and finishing beef aged 0–≤12 months old (calves/R1) (heifers, steers and bulls), 12–≤24 months old (R2) (heifers, steers and bulls) and 24–≤36 months old (R3) (heifers and steers only). R3 bulls were included in the MA breeding bull subgroup. For simplicity, it was assumed that all male calves born on farms were castrated, and bull calves were purchased from dairy farms for fattening or from other beef farms for breeding purposes (Geenty and Morris 2017). Some R1/R2 heifers were reared as replacement animals, with first mating occurring in R2 and first calving in 2-year-old heifers (Geenty and Morris 2017). These replacement animals were included in the finishing heifer calves/R1 and R2 subgroups, with the number of animals calculated from the starting number, deaths and sales based on the benchmarking data.

For sheep enterprises, animals were categorised into three subgroups: 0–≤12-month-old lambs, 12–≤24-month-old replacement female hoggets, and ≥2-year-old MA breeding ewes. It was assumed that all lambs except for replacement female lambs were sold by the end of the season either as prime lambs for slaughter or as store lambs for further rearing (Farrell *et al.* 2020, 2021; Moloney *et al.* 2023). MA ewes and some replacement female hoggets were assumed to deliver lambs during the season, with the number of breeding hoggets calculated from the benchmarking data (Farrell *et al.* 2021). For hogget lambing, replacement female lambs that reached the target weight were mated, and a lower lambing percentage than ewes was used (Pettigrew *et al.* 2018). Due to the absence of data, breeding rams were assumed to be purchased and remained in the flock only during the mating period, and hence were considered unaffected by disease.

Production data

The baseline gross margin models used production data to determine the expected volume and value of animal products over a year for a farm without disease. The full lists of baseline production parameters for dairy, beef and sheep enterprises are provided in Supplementary Tables III, IV and V, respectively. The parameters included the initial number of animals, birth rates, mortality rates, conception rate (dairy), abortion/stillbirth rate (dairy), replacement rate (dairy), milk solids production (dairy), number or proportion of live animals sold, number or proportion of finished animals slaughtered (beef/sheep), milk price (dairy), market value of live animals, cull price, labour costs, animal health costs, breeding costs, feed costs, and grazing expenses. The production parameters were specific to each enterprise because the types of production and data collection methods differ by enterprise. The production parameters were treated as fixed values through the analyses. However, updates can be made to apply the most recent values when the model is run in future.

The latest publicly available industry benchmarking data were downloaded from the DairyNZ and B+LNZ websites in August 2021 (Beef+Lamb New Zealand 2021b; DairyNZ 2021). Data regarding average livestock performance, prices and expenses were extracted for each farm type. Data on livestock prices were supplemented by the national average market prices published annually by Inland Revenue (Inland Revenue 2020). Additional production parameters were obtained from published studies; these included mortality rates (Cuttance *et al.* 2017; Compton 2018), conception rate (LIC 2020), abortion/stillbirth rate (Weston *et al.* 2012), replacement rate (Compton 2018), proportion of calves by use (Edwards *et al.* 2021; Beef+Lamb New Zealand 2021b) and prices of animals (Inland Revenue 2020; Beef+Lamb New Zealand 2021a, 2021b), feed costs for dairy (Anonymous 2018), and price of animals and lambing rates for sheep (Pettigrew *et al.* 2018).

Some of the values reported by B+LNZ were pre-aggregated at the farm level, combining the beef and sheep enterprises (e.g. animal health expenses), and there were no data to divide them into two enterprises. These aggregated values were divided into the beef component and the sheep component based on the average ratio of beef to sheep open stock units for each farm type, using 1 beef = 5.5 stock unit and 1 sheep = 1.0 stock unit defined by Beef+Lamb New Zealand (2021a).

Disease parameters

Disease impacts were estimated as a reduction in the farm profit relative to the baseline due to disease, or a difference in farm profits with and without disease. For estimation of farm profits with disease, animals were divided into an infected compartment and a non-infected compartment, using the assumed annual incidence, which was a user-defined parameter value. For simplicity, the same annual incidence was used for compartmentalisation of all animal subgroups. In addition, for breeding farms, animals born from an infected dam were assumed to be infected. The income, expense and profit were calculated separately for each compartment, and then the sum was computed to derive the farm-level figures.

The productivity of an infected compartment was modified by the disease parameters, which were selected as key variables in measuring the biological and economic impacts of common livestock diseases.

The disease parameters included mortality rate in adult and young animals, abortion rate, infertility rate, reduction in milk production, reduction in the price of animals, and involuntary culling rate, all of which were attributable to the disease, as well as the proportion of animals requiring treatment among animals in the infected compartment and additional treatment costs. The details of the disease parameters are provided in Supplementary Table VI.

Gross margin models

A gross margin model for each enterprise was developed to calculate annual incomes generated from sales of milk (dairy only), livestock or wool (sheep only), and associated expenses based on the baseline production parameters. The time period for the enterprise gross margin calculation was assumed to run from 1 June in a particular year to 31 May in the next year. In New Zealand, this coincides with the standard year for dairy farms. The farming year for sheep and beef farms runs from 1 July to 30 June, but the 1 June to 31 May period encapsulates the same breeding cycle of livestock, starting from calving or lambing and including weaning and mating. The enterprise gross margin models were developed in R, using the production data and disease parameters as input parameters.

The annual income was calculated for each animal subgroup as a product of the productivity parameters, price indicators and the number of animals. The number of animals sold, culled or slaughtered was calculated or obtained from the data, and multiplied by the market value. The amount of milk and wool production was calculated based on the mid-year average number of animals, which was calculated, assuming death, culling and selling occurred evenly throughout the year unless otherwise specified, such as sales of finished lambs sold at the end of the season. The number of animals in each subgroup was obtained from the industry data or computed by the model, allowing for variation by farm type. The details of the assumptions for each enterprise are in Supplementary Information 4. Total annual farm income was computed as the sum of annual incomes from milk (dairy only), wool (sheep only), and sales of live and slaughtered animals for all animal subgroups.

Similarly, the annual expense was calculated for each animal subgroup by multiplying the estimated unit costs of resources by the number of animals. For labour, feed, stock grazing, animal health and shearing costs, the mid-year average number of animals was used, assuming death, culling and selling occurred evenly throughout the year except for seasonal sales of animals occurring at a specific time (e.g. sales of bobby calves). For breeding cost calculation, the number of animals mated was approximated by the initial number of animals. The total farm expense was calculated as the sum of all expenses for all animal subgroups. For dairy enterprise, all of the other expenses (e.g. electricity, vehicle, fuel, repairs, maintenance, etc.) were treated as fixed (unaffected by disease) and included in the model. For beef and sheep enterprises, only the expenses directly associated with beef or sheep rearing were calculated, because the other expenses were not separable by enterprise.

Enterprise profit was calculated as total income minus variable costs (before tax) for beef and sheep enterprises. The total income was equivalent to "cattle revenue" plus "sheep revenue" in the Beef +Lamb New Zealand values. For dairy farms, enterprise profit was calculated as total income less total expenses. Total income, total expenses and profit were equivalent to "net dairy cash income," "farm working expenses" and "dairy operating profit" in the data reported by DairyNZ.

Validation

Validation of the tool comprised two steps. Firstly, to assess the accuracy of the baseline gross margin models, the model-generated total income, total expense, and profit without disease were compared with the industry reported figures as a reference. The difference between the model output and the reference was calculated as the model error and the extent of the error was evaluated for each farm type and enterprise.

Secondly, to assess the accuracy of disease impact estimation, the model-generated disease impacts of an example disease were compared with impacts estimated by a recent New Zealand-based study. We chose BVD as an example and compared its estimated impacts on dairy and beef farms with a previous study by Han *et al.* (2020). Their study estimated the impacts of BVD over 5 years on a dairy farm with 400 MA cows and a beef farm with 150 MA cows, using the simulated BVD incidence within a herd. The parameters used by Han *et al.* (2020) were converted into the format suitable for LIME-NZ (Table 1), and the model-generated impacts of BVD on dairy and beef farms were evaluated.

Results

The LIME-NZ tool was developed incorporating gross margin models for dairy, beef and sheep enterprises to estimate the economic impact of disease on annual total income, expense and profit. Figure 3 illustrates the user interface of LIME-NZ, showing the front end and the input and output panels. Figure 4 illustrates the breakdown of model-estimated baseline annual total incomes and expenses for individual farm types. For dairy enterprises, the scale of annual

Table 1. Input parameters[a] applied in New Zealand Livestock Disease Economic Impact Models (LIME-NZ) to compare the estimated impacts of bovine viral diarrhoea (BVD) in New Zealand dairy and beef farms for model validation.

Parameter	Dairy	Beef	Parameter assumptions and calculation
Annual within-herd incidence	16%	77%	Dairy: simulated maximum incidence of BVD was 63 (60 TI and 3 PI) animals per year in a herd of 400 (63/400; 16%) animals. Beef: simulated maximum incidence of BVD was 116 (110 TI and 6 PI) animals per year, in a herd of 150 (116/150; 77%) animals
Mortality rate in mature animals	0.0%	0.0%	PI was assumed to occur only in young animals, and all infected mature animals were TI. Mortality in TI animals was assumed to be 0%.
Mortality rate in young animals	2.5%	2.5%	Mortality in PI and TI was assumed to be 50% and 0%, respectively. Proportion of PI among all infected animals was 5%. The weighted average mortality in young animals was therefore $50 \times 5 = 2.5\%$
Abortion rate due to disease	8.5%	8.5%	All infected mature animals were assumed to be TI. Daily probability of abortion in pregnant TI animals was 0.121 and 0.174 in 0–41 days and 42–150 days of gestation, respectively, for a gestation period of 281 days. Hence, abortion rate of an infected pregnant cow was $(0.121 \times 42/281$ days$) + (0.174 \times 108/281$ days$) =$ 8.5% per year
Infertility rate due to disease	32%	32%	Conception rate in BVD-infected animals was assumed to be 0.68 times that of non-infected animals.
Reduction in milk yield	6.7%	NA	100% milk loss was assumed during 20 days of a TI period. Assuming a lactation period of 300 days, this was equivalent to 100% x 20/300 days = 6.7% annual milk loss.
Reduction in price of animals	0.2%	0.2%	LWG in TI animals was 0.92 that of non-infected animals during 20 days of a TI period. The price of TI animals is lower than non-infected animals by LWG (kg/d) x 50% (% carcass weight) x 5.76 ($/kg) x (1-0.92) x 20 (days). For slow growing cattle (LWG = 0.5 kg/d) the loss is $2.3. For fast growing cattle (LWG = 1.0 kg/d) the loss is $4.6. This was approximately 0.2% of the cull price of animals.
Involuntary culling rate	0.0%	0.0%	0.0% involuntary culling[b] rate was assumed because PI animals were assumed to die before they reached maturity, and TI animals recover in 20 days without affecting culling rate.

[a]Converted from Han *et al.* (2020).
[b]Involuntary culling is separate from culling due to abortion.
LWG = live weight gain; NA = not applicable; PI = persistently infected; TI = transiently infected.

income and expenses varied by up to five-fold across different dairy farm types. However, the proportions of different types of incomes and expenses were somewhat similar; milk was the dominant source of income for all farm types (88.6–91.9% of total income), while feed was the most significant expense (26.1–38.7%), followed by labour (9.3–19.5%). For beef and sheep, the relative importance of different sources of income and expenses was similar across farm types, except for Central SI high country farms (high income from wool), Northern NI finishing farms (high income from beef) and Central SI mixed cropping and finishing farms (high income from crops).

For validation of the tool, the estimated baseline annual enterprise incomes, expenses and profits were compared with the reference for dairy, beef and sheep enterprises (Table 2). The mean estimated annual farm profits across farm types were NZ$397.7 (95% CI = 256.6–539.4), 142.4 (95% CI = 98.0–186.8) and 278.5 (95% CI = 194.9–362.1) thousand per year per farm for dairy, beef and sheep enterprises, respectively. The mean estimation error across farm types was NZ$24.1 (95% CI = −15.9 to 64.2), −11.9 (95% CI = −39.7 to 15.9) and −53.2 (95% CI = −90.9 to −15.4) thousand per farm, for dairy, beef and sheep enterprises, respectively. The mean percentage error of the estimated profit was 9.5% (95% CI = −3.6 to 22.6%), −12.4% (95% CI = −31.0 to 6.1%) and −13.5% (95% CI = −18.7 to −8.3%) for dairy, beef and sheep enterprises, respectively. In general, the dairy gross margin model estimated higher profit than the reference, while the beef and sheep models estimated lower profit. These estimation errors were driven by errors in the estimates for annual farm incomes rather than expenses. The full comparison of the baseline models and the reference by individual farm types are provided in Supplementary Figures I, II and III.

The mean impacts of BVD on farm profit during the year of peak incidence were estimated to be NZ$71.5 (95% CI = 51.4–91.6; median 64.8; min 38.5, max 140.4) thousand and NZ$14.4 (95% CI = 9.2–19.7; median 11.3; min 0.9, max 32.6) thousand per farm per year for dairy and beef, respectively (Figure 5). Compared with the estimates by Han *et al.* (2020) of NZ$44.4 thousand per dairy farm and NZ$30.9 thousand per beef farm, our estimated mean impact from BVD on a farm was 61% higher for dairy and 53% lower for beef, although both our estimated ranges encompassed Han *et al.*'s estimates. The estimated scales of the peak annual BVD impacts were equivalent to a mean of 19.4% (95% CI = 16.4–22.4%) and 11.9% (95% CI = 8.0–15.7%) of the annual farm profit for dairy and beef, respectively. Dividing the farm-level disease impacts by the initial number of MA cows, the peak mean BVD impact per animal was NZ$179 (95% CI = 175–182) and NZ$237 (95% CI = 150–325) per MA cow per year for dairy and beef, respectively.

Discussion

In this study, we developed LIME-NZ, a simple but novel tool to estimate the economic impacts of diseases at the farm level for 11 types of dairy farm and 16 types of beef and sheep farm for New Zealand, based on the gross margin models developed using the publicly available industry benchmarking data. Similar tools for estimating the economic impacts of diseases have been developed, including ParaCalc for parasitic diseases in dairy farms (Charlier *et al.* 2012), Outbreak Costing Tool for zoonotic diseases

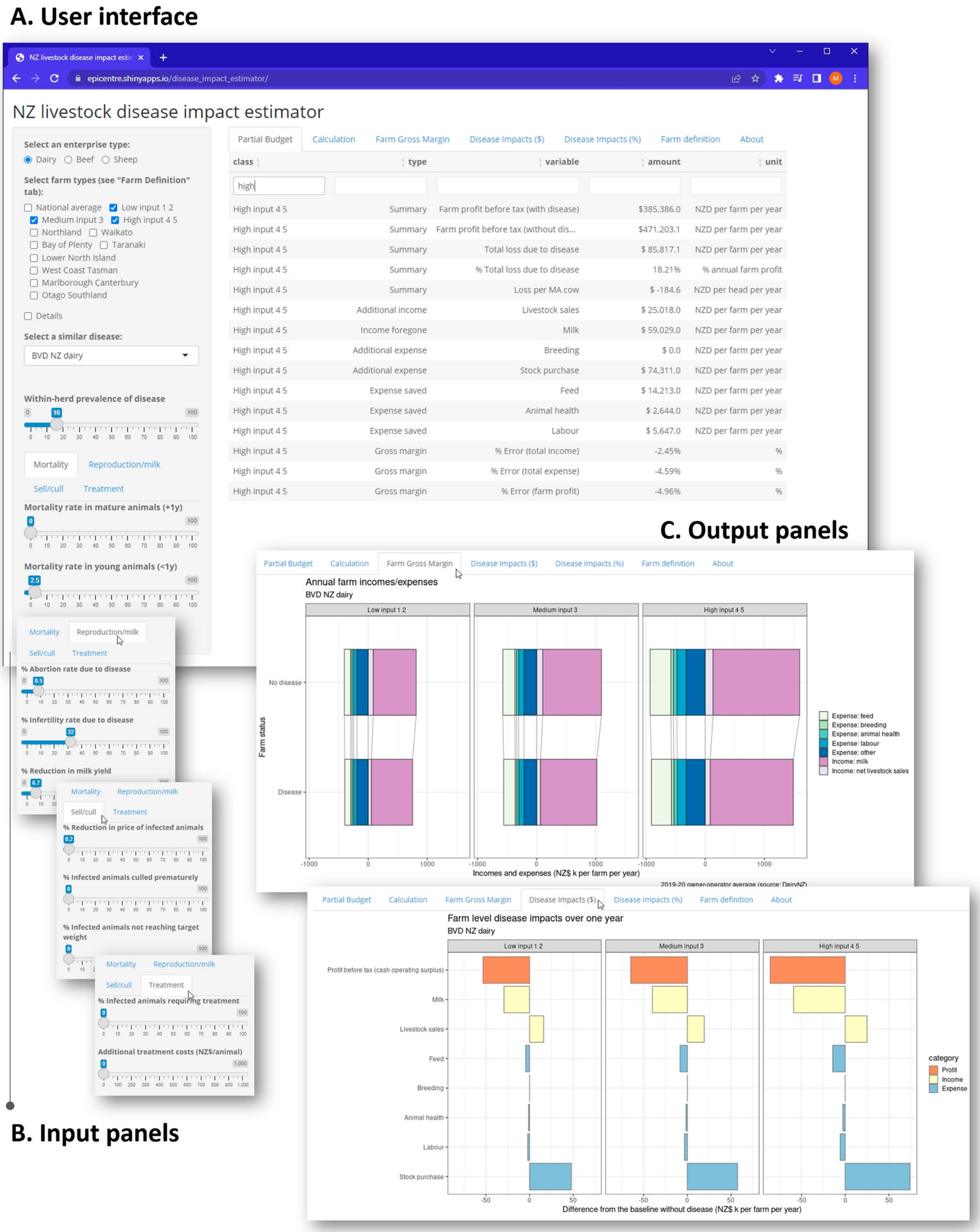

Figure 3. Screenshots of the New Zealand Livestock Disease Economic Impact Models (LIME-NZ) tool designed to estimate the economic impacts of disease at the farm level for New Zealand dairy, beef and sheep enterprises showing (A) the user interface; (B) the input panels where users enter input parameters in each tab, including selection of the enterprise or farm types and disease parameters; and (C) the output panels presenting a range of tables and figures that display the model results obtained from the gross margin models.

(Bodenham *et al.* 2021), and Be-FAST (Fernández-Carrión *et al.* 2016) and OutCosT (Casal *et al.* 2022) for swine diseases. However, these tools impose high data requirements on users or cannot easily be modified or adapted to different farm types or diseases. To the best of our knowledge, there is no such tool currently available allowing prompt estimation of livestock disease impacts in the New Zealand context, taking into account various types of New Zealand livestock farm. LIME-NZ addresses this knowledge gap, integrating the existing industry data for New Zealand livestock.

The mean percentage errors of baseline gross margin models compared with the industry reports

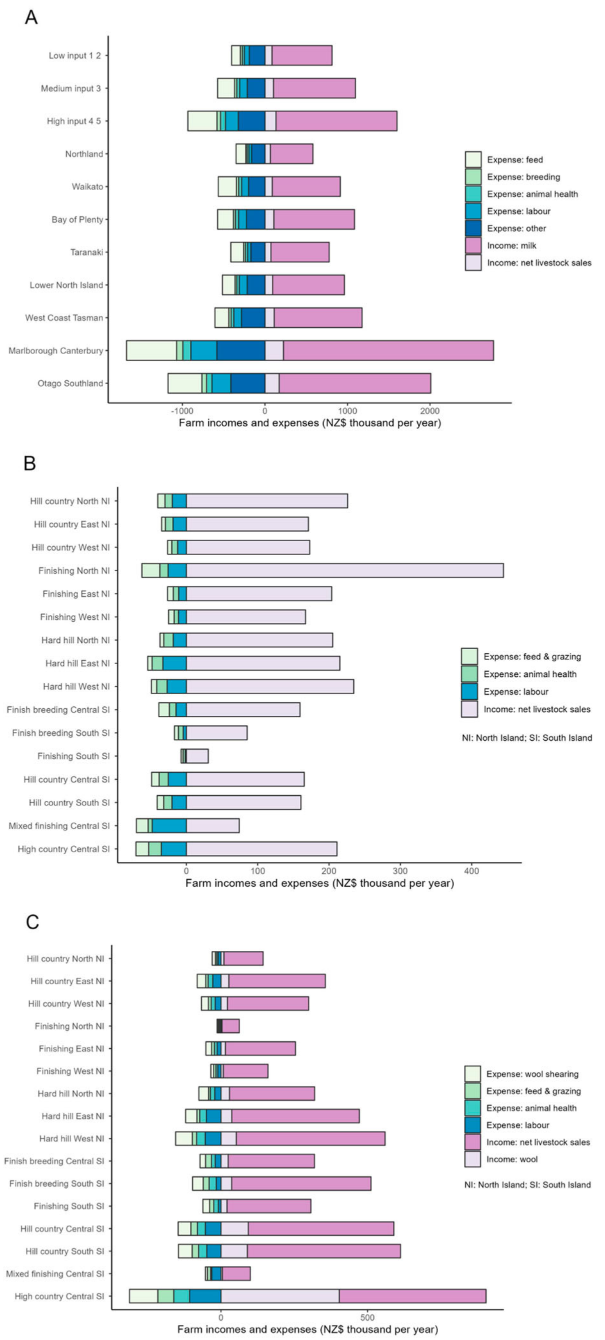

Figure 4. Estimated baseline annual total income and expenses (thousands NZ$ per year) stratified by type of income/expense for individual types of dairy (A), beef (B) and sheep (C) enterprises incorporated in the New Zealand Livestock Disease Economic Impact Models (LIME-NZ). For interpretation of the coloured elements in this figure, the reader is referred to the web version of this article.

were within 14%, demonstrating the reasonable accuracy of LIME-NZ. Considering the simplicity and the deterministic nature of the tool, LIME-NZ could be used provisionally to aid communication with stakeholders by providing timely information about the likely magnitude of disease impacts or initial assessment of disease management until refined information becomes available for improved decision-making. The value of information is dependent on timeliness as well as precision; imperfect information available in time could be sufficient to aid early decision-making, while delayed decision-making due to lack of available information can lead to further spread of disease and higher costs of disease management (Institute of Medicine 2013; Haier *et al.* 2022). In addition, there is likely less payoff in highly precise information if gathering this information is time-consuming and requires high resource use.

We incorporated the industry-specified farm types because they best represented the current farming practices in New Zealand and were well recognised by stakeholders. If disease impact data were required at an aggregated level rather than individual farm types (e.g. nationally, particular areas, or farm types of interest) the outputs of the tool could be combined externally by computing the weighted average. There were some specific farm types for beef and sheep enterprises that had a lower model accuracy. This may be due to: complex purchase and sales transaction pathways across different farm types that were not featured in the benchmarking data (e.g. purchase of store animals); lack of detailed information compared with dairy enterprises, due to difficulty in monitoring and recording biological and economic production parameters; difficulty in breaking down pre-aggregated expenses into beef and sheep components – typically, sheep are more resource intensive on a per stock unit basis; and challenge in capturing specialised businesses focused on non-meat products such as wool (SI high country) and crops (SI mixed cropping and finishing), which would have different farm dynamics, costing and pricing.

We focused on developing a generic, simple and deterministic tool within 1-year time frame; hence LIME-NZ was not designed to consider: prolonged growth or health impacts of some chronic diseases beyond the model timeframe; different disease incidence by different animal subgroups; vertical or horizontal transmission pathways; the season of disease introduction; or intangible costs such as disruption in genetic improvement efforts in breeding farms. Deterministic models are useful when available data only report mean values and require no further assumptions about the distribution of the values, but care must be taken to avoid overinterpretation of the single value model output. Stochastic models are better suited when more robust data on the distributions of some or all of the model parameters are available to account for their uncertainty and provide simulation intervals for model outputs and direct sensitivity analysis of the variables. Sensitivity analyses on production data were outside the scope of this study but could be done to identify influential production data, which may need updating as newer data become available. Future work could include communicating with the industry about data requirements and refining the model details to

Table 2. Summary statistics of the annual total income, expense and profit (thousand NZ$) of a farm estimated by the baseline gross margin models incorporated with the LIME-NZ tool, for dairy (11 farm types), beef (16 farm types) and sheep (16 farm types) enterprises and difference from the industry-reported values[a] (error, percent error).

	Estimate				Error				Percent error			
Enterprise/variable	Mean	Median	Min	Max	Mean	Median	Min	Max	Mean	Median	Min	Max
Dairy												
Total income	1,252.9	1,084.6	581.1	2,768.9	42.5	48.4	−40.1	139.1	3.8%	2.6%	−3.1%	13.4%
Total expense	707.3	572.8	349.5	1,676.4	5.3	1.9	−44.9	66.6	0.6%	0.5%	−4.6%	5.2%
Profit	397.7	354	122.3	845.5	24.1	30	−56.6	133.5	9.5%	4.5%	−14.1%	46.8%
Beef												
Total income	182.9	171.9	30.6	444.6	−11.9	−19.6	−99.6	126.5	−8.8%	−11.7%	−57.3%	39.8%
Total expense	40.5	39.4	7.3	70.6	< −0.1	< −0.1	0.0	0.0	< −0.1%	<−0.1%	0.0%	0.0%
Profit	142.4	141.4	4.1	382.3	−11.9	−19.6	−99.6	126.5	−12.4%	−14.5%	−96.1%	49.5%
Sheep												
Total income	373.2	319.3	62.5	904.2	−42.3	−23.6	−271.5	3.8	−7.4%	−7.8%	−23.1%	6.6%
Total expense	94.7	73.4	13.5	312.2	10.9	9.0	3.3	25.8	16.0%	14.6%	6.6%	32.0%
Profit	278.5	246.3	47.1	592.1	−53.2	−33.3	−297.3	0.6	−13.5%	−13.2%	−34.9%	1.2%

[a]Dairy data were from DairyNZ Economic Survey (DairyNZ 2021), beef and sheep data were from Sheep & Beef Farm Survey (Beef+Lamb New Zealand 2021b).

address such issues, which will then allow consideration of specific disease scenarios in the New Zealand context.

It should be noted that we could not directly compare the estimated BVD impacts of our models with Han *et al.*'s (2020) study due to differences in the model design; Han *et al.* reported the mean annual loss due to BVD averaged over 5 years, while our model estimated the loss during a particular year when the incidence peaked (third year). Our estimated ranges of farm-level annual costs of NZ$38.5–140.4 thousand and NZ$0.9–32.6 thousand for dairy and beef, respectively, were comparable to Han *et al.*'s estimation of NZ$44.4 thousand per dairy farm and NZ$ 30.9 thousand per beef farm. Dividing the costs by the number of MA cows, our models estimated BVD costs of NZ$179 (95% CI = 175–182) and NZ$237 (95% CI = 150–325) per MA cow per year for dairy and beef, respectively. This was 6–8 times that of Han *et al.*'s estimation of NZ$22.22 and NZ$41.19 per MA cow per year for dairy and beef farms, respectively. In addition to the difference by peak *vs* average year, the simplified assumptions of our models (i.e. same disease incidence for all animal subgroups, averaging the time of death, calving, etc.) and price differences due to the different years in which the studies were conducted likely contributed to the differences reported in Han *et al.*'s study. Refinements to the model may be needed for specific diseases that have impacts that differ greatly among stock classes.

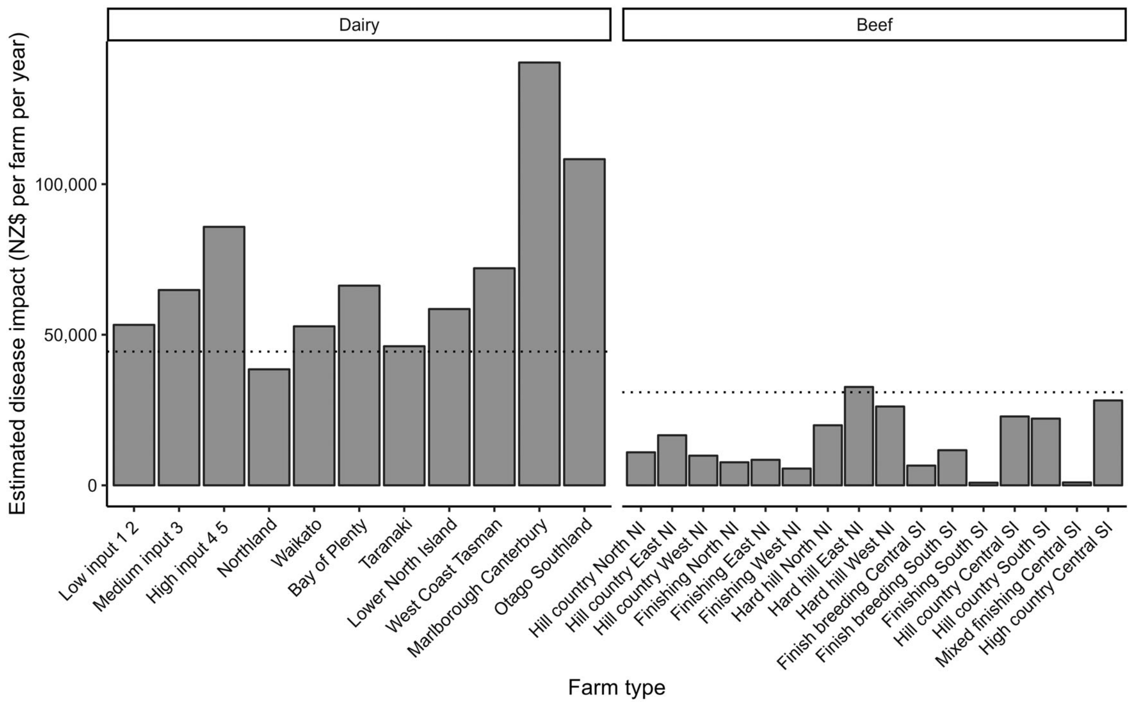

Figure 5. Estimated annual farm-level impacts of bovine viral diarrhoea on dairy and beef farms for different farm types (as classified by DairyNZ and Beef+Lamb New Zealand respectively) as estimated using the New Zealand Livestock Disease Economic Impact Models (LIME-NZ) tool. The economic impact estimated by a reference study (Han *et al.* 2020) is indicated by dotted lines (dairy: NZ$44.4 thousand; beef: NZ$30.9 thousand).

Uncertainty in some disease parameters (e.g. incidence and mortality) that are often unknown initially until more data become available means that the model needs to be used with caution. It is therefore important to perform sensitivity analysis when there is uncertainty in disease parameters, such as at an early stage of disease incursion when data are not sufficient to estimate the key parameters. The tool's interactive functionality allows users to vary input parameters and obtain the corresponding outputs instantly. The results of the sensitivity analysis will inform the range of the estimates as well as priority around parameters for which to collect field data. The estimated industry benchmarking data are likely to vary each year due to complex factors including the current international and domestic markets, price of animals, presence of major disease outbreaks, and climatic conditions, as well as variation in the economic survey methods. It is therefore recommended to regularly update the production data or use the average values of recent years.

We anticipate that LIME-NZ, the novel software tool to estimate the economic impact of livestock diseases on farm profit described in this report, will allow the timely communication of information to inform decision making by farmers and regulatory authorities on disease management. The tool can be adapted by the user to a range of known and as yet unknown diseases of pastoral livestock species using commonly available biologic impacts, and permits modelling at regional and farm-system level as the situation requires. It will assist in identifying priority diseases and aspects of those diseases for more precise investigation.

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No potential conflict of interest was reported by the authors.

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