Farm-level cost-effectiveness analysis of in-paddock feeding of methane inhibitors in pasture-based dairy

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Abstract

Various approaches have been proposed to reduce methane emissions from ruminant livestock systems. While methane-inhibiting feed-additives are not yet commercially available in New Zealand, it has been reported that they can reduce enteric methane emissions by 30-90% when fed to ruminant livestock regularly and precisely in total mixed ration systems. This study aims to determine the primary economic performance drivers of using In-Paddock Smart-Feeders (IPSF) for delivering methane inhibitors in pasture-based dairy to understand the conditions in which they are viable. A farm-level financial model is developed, drawing on the Economic Farm Survey produced by DairyNZ. Both a scenario and sensitivity analysis are conducted on the cost-effectiveness of the approach for methane mitigation. The main finding is that the largest cost associated with the approach is the cost of additional supplement, which would acts as a carrier for the methane inhibitor. Therefore, the quantity of additional supplement used prior to adoption is a key determinant of viability. There is a large range in breakeven methane prices depending on the value of assumptions used. More certainty in these assumptions is required to fully understand the potential use of IPSFs to deliver methane-inhibiting feed-additives in-paddock.

Keywords: smart-feeder, methane inhibitor, cost-effectiveness, mitigation

Introduction

In New Zealand (NZ) in 2019, methane emissions represented around 40% of total greenhouse gas emissions, and 89% were from biogenic sources (StatsNZ 2020). The Zero Carbon Act (Climate Change Response (Zero Carbon) Amendment Act 2019) set targets for reductions in biogenic emissions. Significant research is currently focused on determining the potential of a range of mitigation approaches. The policy for addressing and pricing farm-level emissions was under review by the NZ Government at the time of writing. However, as future methane emission pricing mechanisms could involve \$/t CO_2e (cost per tonne of carbon dioxide equivalent) or \$/kg CH_4 (cost per kg of methane), we have provided values for both units in our analysis.

Two methane-inhibiting feed-additives which have sufficient research to estimate their economic performance when fed to dairy cows are 3-Nitrooxypropanol (3-NOP, brand name Bovaer®), a synthetic product produced by DSM Nutritional Products Ltd., and *Asparagopsis taxiformis* (Asparagopsis), an Australasian red seaweed (Beauchemin et al. 2020, Black et al. 2021). In research trials, 3-NOP has reduced methane emissions by 20-40% when fed regularly to dairy cows in intensive farm systems (Beauchemin et al. 2020) Asparagopsis has been shown to decrease methane emissions by up to 80% when fed to housed dairy cows via a total mixed ration, and in feedlot beef, it was shown to reduce methane by 98% (Black et al. 2021). In NZ's less intensive livestock systems, predominantly based on grazed pasture, methane mitigation with inhibitors is more complex. This is due to challenges in delivering inhibitors frequently and consistently to the herd, a characteristic required of methane inhibitors due to their temporary effectiveness (Beauchemin et al. 2020, Black et al. 2021). Such inhibitors may need to be fed as a pre-formulated mix with a concentrate supplement, however few New Zealand dairy farmers currently have technology that could deliver such mixes to animals throughout the day in grazing systems.

In-Paddock Smart-Feeders (IPSF) are an emergent technology that have the potential to meet the requirements of consistent, frequent, and precise delivery of methane inhibitors on pasture-based dairy farms. These machines could control the daily intake of a supplement-inhibitor mix at an individual animal level multiple times per day. The number of interactions, and the quantity of inhibitor distributed can be set via an online portal, and observed data captured via wireless network. Capture of these data is possible via a setup comprised of four feed stations per machine, solar panels, batteries, and mobile networks.

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To assess the potential value of using IPSF to deliver inhibitors in a NZ context, the approach needs to be evaluated under a range of scenarios due to considerable uncertainty around inhibitor effectiveness and cost implications. Farm-level cost-effectiveness models have been used with success in similar contexts, such as to evaluate water pollution mitigation, greenhouse gas mitigation, groundwater conservation, as well as the cost-effectiveness of cattle breeding and mobile machinery to reduce methane emissions (MacLeod et al. 2015).

In this study, the economic viability of IPSF is evaluated in three steps; firstly, 1) a farm-level model is developed where the expected costs associated with adopting the technology into a given farm system are introduced to the financial model. The output of this model is the breakeven methane emission price at which the approach becomes viable (cost-effectiveness), calculated by apportioning costs of the reduction over the mitigated emissions. 2) The economic performance of IPSF is examined using scenario analysis to determine the likely level of economic performance given real-world conditions. 3) The model is then evaluated with a sensitivity analysis to determine which parameters have the most impact on economic viability.

Materials and Methods

A farm-level financial model is developed to estimate the financial performance of IPSF to deliver methane inhibitors. The model is based on the 2019-20 DairyNZ Economic Survey (DairyNZ 2021a), which includes the financial statements of average farms in various regions and farm ownership types. This model utilises owner-operator data due to the complete business perspective amongst these farmers. The financial data used were normalised by milksolid production. The incumbent costs in the base data are simplified by grouping as 'Other Expenses'.

User inputs then dictate which subset of the data is selected and scaled based on region and milksolid production. The costs associated with utilising IPSF are introduced as new line items and are estimated with the following equations. Finally, the quantity of abated emissions is calculated, which can be compared to the costs of abatement to estimate the breakeven methane price.

In-Paddock Smart-Feeder Count

In this study, it is assumed that a single machine can service 200 animals, and the number of IPSF scales the labour and the holistic cost of IPSF to a farm. It is assumed that all animals receiving the supplement and inhibitor mix can access the machine freely regardless of any differences in herds, this is due to the hypothesis that it will be inefficient to allow young or dry stock to access the machines. If this hypothesis is false, the assumption would require revision. Hence, the IPSF count is given by:

$$IPSF = \lceil H/C \rceil \quad (1)$$

Where:
- H refers to herd size
- C refers to capacity (which is assumed to be 200)
- The result is always rounded up to the next whole number, denoted by [.]

Cost of In-Paddock Smart-Feeder Machine

The base model assumes that the monthly IPSF cost is NZD $1,000 per machine (Marmont 2022) and represents all costs associated with the technology. The total farm-level IPSF cost is the product of the estimated cost per machine and the smart feeder count. The farm-level income statement adds the total cost of IPSF to 'vehicles and fuel'. For the analysis in the current study, no maintenance costs are added, however, there is the option to via Eq. 2 where the total cost of ISPF is given:

$$TC_{IPSF} = (R + M) * 12 * IPSF * I \quad (2)$$

Where:
- R and M refer to monthly rental and maintenance respectively
- The implementation period (I) takes a value between 0 (used 0 days a year) and 1 (used 365 days a year) and costs are only faced when IPSF are implemented

Cost of In-Paddock Smart-Feeder Labour

Labour costs in the income statement are increased by the total labour cost associated with IPSF according to Eq. 3. The marginal cost of labour to a farm depends on; the hours required to move and refill the machines each week, the number of IPSF on the farm, and the cost of labour (Full Time Equivalent – FTE). The amount of time each machine requires to be moved and refilled is assumed to be between 3-6 hours per week (Marmont 2022) and the average FTE cost is NZD$55,000 (DairyNZ 2022). The total number of hours per week and the machine utilisation period can be compared to an FTE of 2400 hours to determine total annual labour costs. Therefore Eq. 3 gives the marginal cost of labour:

$$MC_{Labour} = T * \frac{52}{2400} * \$FTE * IPSF * I \quad (3)$$

Where:
- T refers to weekly time requirements related to IPSF measured in hours
- $\$FTE$ refers to the total cost of an FTE

Additional Supplementary Feed Cost

For this study, it is assumed that IPSF require a pelletised supplement containing a methane-inhibiting additive. Since such a product has not yet entered the market, existing pelleted supplement prices are used in conjunction with estimated inhibitor prices to estimate the cost of a pelleted supplement inclusive of the additive. The quantity of supplement used is noted with and without IPSF in the farm system to determine the annual marginal cost of supplement use per cow. The supplement required to deliver the inhibitor compounds is assumed to be 2 kg per cow per day (Marmont 2022) Due to differences in supplement use across farms, there is a potential substitution of supplement between delivery mechanisms. For example, if a high-quality pelletised supplement is being fed through in-shed feeding or on a feed pad, some, or all of the 2 kg in supplement could be diverted to being fed through the IPSF to reduce the marginal cost of IPSF adoption for this farm. The effects of supplement substitution are described by Eq. 4, which compares the supplement profile and cost.

The per cow annual marginal cost is determined by subtracting the cost multiplied by the quantity of supplement used with and without IPSF. A pelletised supplement costs approximately NZD$750/tonne (J. Swap Contractors, personal communication 15 August 2022). The annual per-cow marginal cost is multiplied by the herd size and the IPSF utilisation period to determine the total marginal supplement cost, calculated with Eq. 4 and displayed as additional supplement in the financial statements:

$$MC_{Supplement} = (\frac{A_P * C_P - A_{INC} * C_{INC}}{1000}) * I_d * H \quad (4)$$

Where:
- A_P and A_{INC} refer to the daily allocation (quantity, measured in kilograms) of supplement each cow receives daily in pelletised or incumbent form respectively. It is assumed that A_P is greater than A_{INC}.
- C_P and C_{INC} refer to the cost of pelletised and incumbent supplement respectively (Beauchemin et al. 2020, Black et al. 2021).
- I_d refers to the implementation period in days.

Milk Response to Additional Supplement

An increase in supplement intake is often linked with an increase in milksolids production called the milksolids response rate, which is assumed to be 55 g MS/kg DM (grams of milksolids per kilogram of dry matter) (DairyNZ 2021b). The assumed dry matter content of the supplement needed to deliver the inhibitor is 85% (DairyNZ 2021b). Multiplying marginal supplement by dry matter content estimates the effect of the marginal supplement on milksolids production. The total value of milk response to supplement for the farm is given in Eq. 5 and will later be subtracted from the total marginal cost of adoption in calculating the breakeven methane price.

$$V_{MRS} = (A_P - A_{INC}) * DMC * 0.055 * P_m * H * I_d \quad (5)$$

Where:
- *DMC* refers to the dry matter content of the marginal supplement, assumed to be 0.85.
- P_m refers to the farmgate milk price.

Methane Inhibitor Cost

Currently, no methane inhibitors are commercially available, and little information is available on potential pricing. Therefore, in this study, we estimated costs for 3-NOP and Asparagopsis products. Initially, inhibitor costs are expressed per cow per year, including the ability to deliver inhibitors for parts of the year. Multiplication of annual per cow costs and the herd size determines the total cost to the farm. After selecting a methane inhibitor, the associated total cost is introduced as a new expense - ‘Methane Inhibitor’ - in the income statement following Eq. 6 for 3-NOP or Eq. 7 for Asparagopsis.

The cost of 3-NOP is estimated to be €0.01 per litre of milk (E. Kebreab, personal communication, 10 June 2022), meaning that several assumptions must be made to estimate the cost per cow in NZ. First, the exchange rate needs to be considered, and then milk is converted to milksolids before milksolid production per cow and the implementation period are considered. Hence the total cost of 3-NOP is given by:

$$TC_{3NOP} = C_{3NOP} * €{:}NZD * 11.5 * PROD * I \quad (6)$$

Where:
- C_{3NOP} refers to the price of 3-NOP per litre of milk in European cents.
- €:NZD refers to the exchange rate which is assumed to be 1.6 €:NZD.
- 11.5 is the assumed conversion rate from milk to milksolids (Newman 2015).
- PROD refers to total milk production on a given farm (in kilograms of milksolids).
- Asparagopsis is estimated to cost AUD$5/kg (Cotter et al. 2015). The exchange rate and quantity need to be determined to estimate per-cow costs in NZ. The quantity required is calculated with a dietary inclusion rate and annual DMI. Hence the total cost of Asparagopsis is given by:

$$TC_A = \sum_{j=1}^{J} C_A * AUD{:}NZD * DIR * DMI_S * I \quad (7)$$

Where:
- C_A refers to the price per kg of Asparagopsis.
- *AUD:NZD* refers to the relevant exchange rate, assumed to be 1.12.
- *DIR* refers to the dietary inclusion rate, assumed to be

0.5% (Black et al. 2021).

- DMI_S refers to the dry matter intake of stock class *j* that the inhibitor is fed to, for stock classes.

The cost of 3-NOP and Asparagopsis in farm, cow and production terms is illustrated in Table 1 by applying Eq. 6 and 7 to the average Waikato farm (310 cows, 121,500 kg MS (DairyNZ 2021a)).

Table 1 Potential annual cost of methane inhibitors to the average Waikato dairy farm (Based on 2019/20 average farm size: (DairyNZ 2021a), cost for 3-NOP: Personal communication (E. Kebreab, 2022), cost for Asparagopsis: (Cotter et al. 2015))

	3-NOP	Asparagopsis
Per Farm	$22,356	$40,604
Per Cow	$72	$131
Per kg MS	$0.18	$0.33

Methane Mitigation

The quantity of mitigated methane resulting from adopting the modelled approach is estimated (Eq. 8), generating an emissions profile of the farm. The emissions profile represents the number of animals across stock classes and the duration in which they are in a stock class over the year. Once the emissions profile of the farm is generated, the assumed mitigation percentage is applied to the emissions profile proportionately to the delivery period of the inhibitor for each stock class. Abated methane for a farm is given by:

$$ACH4 = \sum_{j=1}^{J} CC_s * DMI_s * D_s * EF * MM * I_s \quad (8)$$

Where:

- CC_J refers to the cow count in a given stock class, where the summation over all stock classes determines the total quantity of mitigated emissions on a given farm.
- DMI_J is the dry matter intake of a stock class and assumed to be 7 kg/d for dry cows, 15 kg/d for lactating cows, 5 kg/d for rising 1-year-old cows (R1s) and 6 kg/d for rising 2-year-old cows (R2s) based on the potential values these figures can take (DairyNZ 2021b).
- D_J refers to the number of days cows spend in a given stock class, for example how a cow's year is split between drying off and milking.
- *EF* refers to the emissions factor, which is assumed to be 21.6 g/kg DM (Ministry for Primary Industries 2022)
- *MM* refers to the assumed methane mitigation potential and can be specified between 0 and 90% depending on the methane inhibitor used (Beauchemin et al. 2020, Black et al. 2021)
- I_J refers to the implementation experienced by stock class, that is, of the time that the methane inhibitor is fed during a year, what proportion of it is experienced by the stock class in question. For example, if the inhibitor-mix is fed all season, milking cows would have an I_J of 1 as they received the mix the entire implementation period, whereas dry cows would have an I_J of 0 as they received no inhibitor-mix.

Cost of Abated Methane

The cost of abated methane emissions is calculated by adding together the four costs, and subtracting the value of the milk response to supplement as shown in Eq. 9:

$$TC_{\$ACH4} = TC_{IPSF} + MC_{Labour} + MC_{Supplement} + TC_{Inhibitor} - V_{MRS} \quad (9)$$

Where:

- $TC_{Inhibitor}$ refers to the cost of inhibitor depending on which inhibitor is implemented.

Breakeven Methane Price

The breakeven methane price is determined by apportioning the cost of abated methane over the quantity of abated methane emissions, given in Eq. 10:

$$P^*_{ACH4} = TC_{ACH4}/ACH4 \quad (10)$$

Model Output

Once the costs of adoption are integrated into the farm-level financial model, the costs of adoption less the value of the milk response to supplement (Eq. 9) is apportioned over the quantity of mitigated methane (Eq. 8) to estimate a breakeven methane price (Eq. 10). The breakeven methane price measures the cost-effectiveness of the mitigation action (cost divided by mitigation). The breakeven price can be interpreted as the minimum price on methane, set through a climate change policy, that the modelled farm is incentivised to implement the mitigation approach in this study.

Sensitivity Analysis

A sensitivity analysis is utilised to understand the variables that have the largest effect on the performance of the mitigation approach. The range of values in the sensitivity analysis is determined by historical values where possible, such as the ten-year range of exchange rates. Where this is impossible, ranges are determined by consulting the current market or using the values assumed in Eq. 1-6. The values examined in the sensitivity analysis are; milk price, inhibitor prices (3-NOP and Asparagopsis), the exchange rates (€:NZD and AUD:NZD), proportion of the herd accessing the feeder, allowing different stock classes to access the feeder, amount of supplement required (kg/cow/day), methane reduction (3-NOP and Asparagopsis). Ten iterations of the model are recorded for each value as

Table 2 Scenario analysis input summary for four scenarios, using an average Waikato farm as the base case (Based on 2019/20 average Waikato farm size: (DairyNZ 2021a))

Scenario	Parameters	
Poor	Rental: $1500/month/machine	Supplement: 2.6 kg/day, $900/t
	Labour: 6 h/wk, FTE of $66,000	Mitigation: 15% (3-NOP)
	Delivery: all year	Supplement substitution: None
Expected	Rental: $1000/month/machine	Supplement: 1.6 kg/day, $700/t
	Labour: 4 h/wk, FTE of $61,000	Mitigation: 30% (3-NOP)
	Delivery: all year	Supplement substitution: 25%
Best case	Rental: $800/month/machine	Supplement: 0.6 kg/day, $500/t
	Labour: 3 h/wk, FTE of $56,000	Mitigation: 90% (Asparagopsis)
	Delivery: all year	Supplement substitution: 50%
In-shed only	Rental: N/A	Supplement: 1 kg/day, $1000/t
	Labour: N/A	Mitigation: 5% (3-NOP)
	Delivery: All season	Supplement substitution: 75%

Note: mitigation refers to methane mitigation

the values of interest marginally change, holding others constant. During the sensitivity analysis, mitigation for 3-NOP was held at 30%, and for Asparagopsis mitigation was held at 60%.

The base model for this analysis is based on the average Waikato farm (DairyNZ 2021a), with 310 cows on 109ha, producing 121,500 kg/MS/yr. Assumptions for this base farm include: no supplement substitution (no pre-existing use of pelletised supplement), daily allocation of pelletised supplement of 1 kg/day as an inhibitor-mix, and IPSF labour requirement of 4 hours/machine/week. In the base model, the cost of pelletised supplement is $800/t, IPSF rental cost is $1,000/month/unit, FTE cost is $61,000, and milk price is $7/kg MS sold. The sensitivity analysis summary includes the minimum and maximum model inputs and the minimum and maximum cost of abatement.

Scenario Analysis

A scenario analysis is employed due to uncertainty around technology implementation, performance, and how this interacts with heterogeneous farms. Using the Waikato base farm, four scenarios are utilised in this analysis, three theoretical IPSF performance levels (poor, expected, best-case) and an in-shed feeding only scenario. In-shed feeding only is included as a reference point as it is an existing concentrate supplement delivery method on some NZ farms. For a complete analysis, see Marmont (2022), which applies the same approach to the regions of Northland and Canterbury. The particulars of each scenario are specified in Table 2 based on expected technology performance given the divergent development pathways of IPSF. Differences in supplement substitution reflect the prevalence of existing use of appropriate supplements under given technology performance levels, demonstrating how the intensity and farm size may be a driver of viability in different systems. When supplement substitution is 0 the full cost of supplement is faced by the farm, when the supplement substitution is greater than 0 the cost of supplement is discounted by the substitution. For example, 25% supplement substitution means that 75% of the annual allocation multiplied by the cost is faced by the farm. This value is varied as farms in different systems will likely have different quantities of suitable supplement on hand, they can use to offset the total costs.

As there are currently no commercially available IPSF, the rental costs are estimated and varied by scenario depending on the machines performance and eventually come to market. Further, it is assumed in the scenarios using IPSF that they are used to feed the inhibitor-mix year-round, including dry and milking cows with an assumed average lactation length of 300 days. While the in-shed only scenario delivers inhibitors for the whole season.

In the in-shed-only delivery scenarios, the assumed methane mitigation level is 5% because when the methane inhibitors are delivered at a low frequency with a delay between delivery and feed consumption (e.g. being fed in the shed during milking and walking back to the paddock) inhibitors have been shown to

Table 3 Summary results of sensitivity analysis.

Input	Effect	Magnitude
Inhibitor mitigation potential (3-NOP and Asparagopsis)	A higher mitigation potential of the methane inhibitors will increase the amount of abated CH4 without increasing abatement cost leading to a lower breakeven price.	Major
Daily supplement allocation	Optimal usage of supplements reduces supplementary feed costs without reducing inhibitor delivery efficiency. Leading to a lower breakeven price, it also reduces the loss of pasture utilisation.	Major
Milk price	A higher milk price increases the revenue received from the milksolids response to supplement, reducing the breakeven price.	Minor
Inhibitor cost	Cheaper inhibitors mean slightly lower costs and therefore breakeven	Minor
Exchange rate	Favourable exchange rates marginally decrease costs and therefore breakeven	Minor
Proportion of herd accessing feeder	The proportion of the herd accessing the feeder has an ambiguous effect on the breakeven price depending on how the size of the herd compares to the IPSF capacity.	Minor
Delivery to young stock	Feeding inhibitors to young stock with IPSF increase the breakeven price due to the value of the proportion of their emissions relative to the cost of output.	Minor

have negligible effects on emissions (Muetzel et al. 2019). Despite the poor efficacy expected via in-shed delivery, it is included because one third of Waikato farmers currently use in-shed feeding (Dela Rue et al. 2019). This means that the technology could be repurposed at minimal cost.

Results

The modelling results for the average Waikato farm are presented in this section. For a comprehensive analysis of other regions, refer to Marmont (2022).

The sensitivity analysis, which describes how changing one input in isolation affects the cost of abatement in terms of \$/kg CH_4. The relationships between the inputs and the impact on the cost of abatement can be categorised as those with a minor or major effect in Table 3.

The scenario analysis outputs are presented in Table 4 in the form of estimated financial statements of an average farm where IPSF have been adopted to deliver inhibitors. The financial statements estimate the on-farm costs and benefits of adoption with equations 1-10. The income across the four scenarios remains constant, and the value of additional milk production from supplement can be observed in the feed composition section and used to compute the breakeven methane price required for the approach to be viable.

Discussion

Various factors were found to have negligible effects on the breakeven price when viewed from a farm systems perspective. The milk price contributed to the value of the milk response to supplement, which offset the total cost of adoption relative to the reduction in methane emissions. Therefore, as the milk price increased, the cost of abatement decreased. While a higher inhibitor cost increased the abatement cost, the inhibitor's efficiency and the daily supplement allocation required had a greater influence on abatement costs. The exchange rates relative to each inhibitor also behaved the same way as the cost of inhibitors. As the NZD weakened, the inhibitors became relatively more expensive, driving up the cost of abatement. However, the change was relatively small compared to those categorised as major determinants (Table 3).

The inclusion of young stock classes in the modelled approach increased from having no young stock and 310 milking cows to having 200 young stock and 310 milking cows. To contextualise the number of young stock, the replacement rate has been estimated on average to be 22% (DairyNZ 2021b), which equates to 68 R1s, and R2s, or, 136 young stock. As the number of young stock interacting with the IPSF increased, the cost of abatement also increased. This was due to the cost of the ISPF, supplement and the cost structure of labour. The capacity was assumed to be constant regardless of animal age, given young stock would require the same amount of supplement to meet the constant and precise delivery of the inhibitor, leading to the same number of IPSF and labour. This meant that including young stock was similar in per cow costs as other stock classes except for the cost of the inhibitor which was related to

Table 4 Scenario analysis output: Average Waikato Dairy Farm Cash and Non-Cash Effects of Methane Inhibitors in Pasture Based Dairy

	Poor	Expected	Best Case	In-shed only
Dairy Cash Income				
Milk sales (net of dairy levies)	$850,500	$850,500	$850,500	$850,500
Net livestock sales (sales - purchases)	$57,713	$57,713	$57,713	$57,713
Other dairy cash income	$3,375	$3,375	$3,375	$3,375
Net dairy cash income	$911,588	$911,588	$911,588	$911,588
Cash Working Expenses				
Additional Wages	$34,320	$21,147	$14,560	$0
Additional Supplement	$264,771	$95,046	$16,973	$23,250
In-Paddock Smart Feeder	$36,000	$24,000	$19,200	$0
Methane Inhibitor (see table 2)	$22,356	$22,356	$40,604	$18,375
Other Expenses	$529,467	$529,467	$529,467	$529,467
Farm Working Expense	$886,914	$692,016	$620,803	$571,092
Adjustments				
Net Adjustments	-$113,620	-$113,620	-$113,620	-$113,620
Surplus				
Cash Operating Surplus	$24,674	$219,572	$290,784	$340,496
Operating Cash and Non-cash				
Dairy Gross Farm Revenue	$911,588	$911,588	$911,588	$911,588
Dairy Operating Expense	$1,000,534	$805,635	$734,423	$684,711
Dairy Operating Profit	-$88,946	$105,952	$177,165	$226,876
Dairy Profit Margin	-10%	12%	19%	25%
Environmental Performance				
Initial Methane Emissions (kg CH4)	33,179	33,179	33,179	33,179
Abated Methane Emission (kg CH4)	4,977	9,954	29,861	1,507
Percentage of mitigated emissions	15%	30%	90%	5%
Cost of Abatement ($)	$302,125	$159,066	$121,179	$74,967
$/kg Cost of Abatement				
(breakeven price $/kg CH4)	***$60.71***	***$15.98***	***$4.06***	***$49.76***
Cost of Abatement ($/t/CO2e)	***$2,168***	***$571***	***$145***	***$1,777***
Feed Composition				
Total Imported Feed (t/year)	294	181	68	113
Cost of Imported Feed ($/year)	$264,771	$126,728	$33,945	$113,150
Pasture Proportion of Diet				
(relative to pelletised supplement)	81%	88%	96%	93%
Pasture Utilisation Forgone	19%	9%	3%	3%
Additional Milk Production from				
Supplement	$96,274	$44,434	$11,109	$7,609

intake or production. On balance, the costs relative to the reduction in emissions were less favourable given that fewer emissions were mitigated when feeding to younger stock classes due to the link between DMI and methane emissions and young stock having lower DMI and that the fact that young stock do not produce milk to offset the costs via increased production.

The proportion of the herd accessing the IPSF had a different relationship where, as the percentage of the herd accessing the feeder increased, the cost of abatement decreased. However, eventually, the cost of abatement began to increase due to the number of machines required by the number of cows accessing the IPSF. Once the number of cows accessing the IPSF was greater than the animal-to-machine ratio - assumed to be 200 - the number of IPSF required increased, leading to an increase of labour.

The scenario analysis demonstrates that the additional cost of supplement associated with adopting IPSF to deliver methane inhibitors was the largest cost in all scenarios and varied the most across scenarios. This cost is described in Eq. 4 and was determined by the level of supplement substitution, the price of supplement and the amount of supplement required each day. Aside from the cost of supplement, the mitigation potential of the inhibitors (3-NOP and Asparagopsis) was shown to cause large changes in the breakeven price of the approach (Table 4).

To enhance economic performance of the IPSF approach, a range of strategies could be considered. For example, optimising the inhibitor formulation to reduce the frequency of required visits or increase the mitigation potential. Another approach could be dispatching smaller quantities of supplement at each visit. Adopting either of these approaches would reduce the quantity of supplement required, thereby mitigating the largest cost associated with IPSF. However, these strategies would need to consider farm system trade-offs, such as impacts on grazing management or labour costs associated with increased frequency of individual cow visits to the IPSF units. IPSF use could also be prioritised on farms currently using a high quantity of supplement, resulting in a greater supplement substitution rate and limiting increases in overall per-farm supplement use.

These findings illustrate the importance of a high supplement substitution rate to mean that IPSF will be most effective on a farm that already uses a lot of supplement and has a herd size close to but not greater than a multiple of the animal-to-machine ratio.

Conclusions

In NZ, legislation states that agricultural emissions will be priced in the future, but the method with which this will occur and the price path of methane over the coming years is still uncertain at the time of writing. The model outputs described in this paper are relevant regardless of how the policy environment develops. The breakeven price can be compared to the proposed emission price to determine if the approach is viable. The approach can only be considered viable when the breakeven price is less than or equal to the current methane price.

Applying the model to the average Waikato farm showed that adopting IPSF to deliver methane inhibitors was highly sensitive to the level of existing supplement which could be repurposed to be fed through the IPSF. Further, several assumptions were made to estimate the costs of adoption, leading to a range of breakeven methane prices for the use of this approach, under the settings described in this study, of between \$4-\$60/kg CH_4. Further research into aspects such as inhibitor effectiveness, IPSF design, and integration of IPSF within grazing systems would increase certainty in these assumptions leading to a smaller range in breakeven prices. There is potential for this breakeven price to be reduced if the design of IPSF enables the use of less supplement to deliver inhibitors or increases in the number of cows per machine (capacity). Alternatively, if inhibitors can be developed with higher mitigation rates, or extended time periods for effective operation in the rumen, this would enable inhibitors to be delivered less frequently and improve the economic performance of the IPSF used to deliver methane inhibitors in-paddock.

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