Adoption of In-Paddock Feeding of Methane Inhibitors in Pasture-Based Dairy: An Application of the ADOPT model and a Farm-Level Cost-Effectiveness Analysis

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Abstract

Methane emissions represent over 40% of New Zealand's total greenhouse gas emissions. Of these emissions, almost all are biogenic, meaning they come from living organisms such as ruminants. Given that methane has 27-30 times the warming potential of carbon dioxide, reducing methane emissions is an important part of addressing climate change. Many countries are beginning to legislate a reduction of methane emissions in a global effort to reduce the impact of climate change. In New Zealand, where livestock plays a large part in the economy, unique challenges have arisen around reducing biogenic methane emissions. One approach to mitigate methane in the dairy industry is the delivery of methane-inhibiting compounds, which, when added to the diet of ruminants, can reduce their methane emissions significantly. However, these compounds generally require frequent and precise delivery, a characteristic that is difficult to fulfil in New Zealand's pasture-based sector.

This thesis explores the potential adoption of a novel approach using emergent technology, in-paddock smart-feeders, and how they could deliver methane inhibitor compounds in a New Zealand dairy farming context. The research is conducted in two phases. Firstly, the likely adoption outcomes are assessed, which depends on how in-paddock smart-feeders fit into the range of New Zealand farm systems. In order to evaluate adoption outcomes, the Adoption Diffusion Outcome Prediction Tool (ADOPT) model is utilised in conjunction with a dairy expert consultation and farmer focus groups. After establishing a base case of adoption outcomes, the results are tested with a sensitivity analysis to determine those ADOPT variables impeding increased modelled adoption outcomes. Then, a scenario analysis is conducted to explore different technology performance levels. This chapter finds that the technology is unlikely to become widely adopted unless it is shown to be economically viable. The critical adoption factors are then shown to be trialability, ease and convenience and environmental performance.

The third chapter explores the economic properties of in-paddock smart-feeders by developing a farm-level cost-effectiveness model. This model takes average farm data, introduces the expected costs of the approach and then apportions the associated

costs of the quantity of mitigated methane to estimate the breakeven methane price at which the approach becomes viable. The main output of this model is the breakeven methane price, that is, the methane price, where it becomes viable to adopt IPSFs. Similarly to the first chapter, these results hinge on technology performance which is currently relatively uncertain as there is not existing technology to base performance. Therefore the results are explored at length using sensitivity and then scenario analysis. The scenario analysis shows that the breakeven price is most favourable in Northland out of the regions assessed, and the technology was viable only in a best-case scenario.

Ultimately for this novel approach to become economically viable and, therefore, widely adopted by the dairy farmers of New Zealand, the manufacturers of both in-paddock smart-feeders and methane inhibitors will need to make improvements to their products. If these improvements eventuate, a clear path to reducing methane emissions in pasture-based dairy may result.

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List of Abbreviations

3-NOP	3-Nitrooxypropanol
ADOPT	Adoption Diffusion Outcome Prediction Tool
AKAP	Awareness, Knowledge, Adoption, Productivity
AU	Australian
AUD	Australian Dollar
CH4	Methane
COVID-19	Coronavirus Disease of 2019
DM	Dry Matter
DMI	Dry Matter Intake
DSM	Dutch State Mine (Full Company Name - Royal DSM)
ETS	Emissions Trading Scheme
EURO	Euro
FTE	Full Time Equivalent
HWEN	He Waka Eka Noa (Primary sector climate action partnership)
IPSF	In-Paddock Smart-Feeder
LUV	Light Utility Vehicle
MS	Microsoft
NZ	New Zealand
NZD	New Zealand Dollar
OAD	Once-A-Day (Milking frequency)
TAD	Twice-A-Day (milking frequency)
TMR	Total Mixed Ration
USD	United States Dollar
WMS	(University of) Waikato Management School

Chapter 1: Introduction

1.1 Background

This literature review section will first explore the significance of methane emissions for the New Zealand (NZ) dairy industry and the proposed framework to reduce such emissions. Secondly, the various approaches which could be used to reduce methane emissions in pasture-grazed dairy systems will be explored.

In NZ, methane emissions account for a significant proportion (42% in 2019) of greenhouse gas emissions. Of NZ's methane emissions, 80% was biogenic methane (from animals) in 2019. The combination of large cow numbers and a small population result in high per-capita emissions, despite low total emissions relative to other large nations (StatsNZ 2020). Further, research indicates that each dairy cow produces approximately ninety-eight kilograms of methane per annum, 95% is belched. Ninety-eight kilograms of methane is higher than other ruminants on a per-animal basis due to dairy cows consuming greater amounts of dry matter, which has been shown to have a strong relationship with methane emissions (DairyNZ 2022a; New Zealand Agricultural Greenhouse Gas Research Centre 2021).

Reducing methane emissions is not just targeted in NZ, with many nations accepting its importance in minimising global warming (Collins et al. 2018). The large proportion of methane in NZ's greenhouse gas profile makes it a key area of mitigation due to the warming potential of methane relative to other greenhouse gasses. Methane has a more significant warming potential than carbon dioxide but a shorter life span; over twenty years, methane has eighty-six times the warming potential of carbon dioxide. The short-term potency of methane relative to other gases means that reducing methane emissions may be the most economical way of reducing climate change (Dean 2020; New Zealand Agricultural Greenhouse Gas Research Centre 2021; Saunois et al. 2016).

Additionally, NZ's dairy industry is relatively unique in that it is largely pasture-based, leading to systems with low costs, short breeding and calving periods and seasonal milk production (Verkerk 2003). A recent trend of rising herd size and stocking rates has led to NZ dairy farmers looking for increasing quantities and types of feed to supplement their pasture (Wilkinson et al. 2020). However, any given dairy farm may have a unique combination of pasture and supplement, but all NZ dairy farms can be summarised into the five farm systems. System one farmers bring minimal external feed onto their farms, while system five brings significant external feed into their systems. The five farm systems can be observed in table 1 (Hedley et al. 2006).

Table 1 - The Five Production Systems (DairyNZ 2021; Hedley et al. 2006)

Farm System	**Description**
1	100% home-grown feed All grass self-contained
2	90-99% home-grown feed Cows may be wintered off
3	80-89% home-grown feed Supplement used to extend lactation
4	70-79% imported feed Feed used at the start and the end of the season
5	50-69% imported feed Feed used all year

Note: The systems initially identified by Hedley et al have since been updated to those in this table.

1.1.1 International Agreements and their effects

The Kyoto Protocol came into effect in 2005 and is an agreement signed by one hundred and eighty-five countries to address climate change collectively. The first step was to recognise the issue and set some achievable targets, including reducing emissions to 1990 levels (Ministry for the Environment 2021b; United Nations

Framework Convention on Climate Change 2019). The Kyoto Protocol eventually paved the way for the Paris Agreement, which came into force in 2016. This new agreement emphasised climate change and the need to reduce emissions to keep the global average temperature below two degrees above pre-industrial levels, strengthen resilience to climate change at a national level and foster climate resilient and low-carbon economies. Under the new agreement, climate change action is incrementally increased every five years. The primary goal is competitive zero-carbon solutions in many sectors by 2030 (Ministry for the Environment 2020; United Nations Framework Convention on Climate Change 2018).

The commitments in the Paris Agreement were passed into NZ law in 2019 with the introduction of the colloquially named 'Zero Carbon Act.' The following four points summarise the goals of the act (Climate Change Response (Zero Carbon) Amendment Act 2019; Ministry for the Environment 2021a):

- NZ domestic emission standards
    - Reduce net emissions except for biogenic methane to zero by 2050
    - Reduce biogenic methane emissions by 24 to 47% of 2017 levels by 2050
    - Including a step change of a 10% reduction of 2017 emissions by 2030
- Develop an emissions budget to reach the levels laid out in the previous step
- Implement government policy to increase emission mitigation
- Create an independent Climate Change Commission for long-term oversight and guidance.

The first and second goals of the Zero Carbon Act are the most relevant to the dairy sector and the technologies assessed in this thesis. An emphasis is placed on the difference between the short-term and long-term commitments regarding biogenic methane emissions as it affects the time horizon of technology innovation and adoption.

1.1.2 Methane Mitigation Policy

The NZ government is currently consulting on He Waka Eka Noa (HWEN), a proposal for how emissions will be treated in the primary industries. Under the HWEN proposal, agricultural producers would be charged at the farm level based on their emissions and actions to mitigate them (He Waka Eka Noa 2022a). There is also a differentiation of short-term gases, such as methane and long-term gases, such as carbon dioxide under this proposal, called a 'split gas approach.' This differentiation contrasts with the current legislation, which states that agricultural emissions will eventually be included in the emissions trading scheme (ETS), where there is no differentiation of the treatment of short or long-life gases (He Waka Eka Noa 2022d). Short-term gases like methane have lifetimes of less than twenty years, while long-term gases such as nitrous oxide tend to have lifetimes over one hundred years (Allen et al. 2022). The current methane concentration has a half-life of around twelve years, but historically this has been as low as eight years (Balcombe et al. 2018; Doble and Kruthiventi 2007; Lelieveld, Crutzen, and Dentener 1998).

The NZ Government's response to the initial proposal from HWEN was in line with the farm-level split-gas approach raised by HWEN (He Waka Eka Noa 2022b). However, another round of submissions is open, and HWEN is rejecting some of the Government's responses concerning price-setting authority, sequestration, recognition for on-farm planting and scheme governance (He Waka Eka Noa 2022c). Suppose the Government determines that these issues are insurmountable. In that case, there is potential that they may return to placing agricultural emissions in ETS, where there will be no opportunity to value gases based on their longevity or warming effects. Under the ETS, emission pricing would be discounted by 95% with a gradual reduction of the free allocation (He Waka Eka Noa 2022d). At the time of writing, there is still uncertainty around how agricultural emissions will be treated in NZ. For this research, the key message is that HWEN and the government are working towards a farm-level split-gas approach that would ultimately incentivise individual farmers to reduce their biogenic methane emissions.

1.1.3 Mitigation techniques

A significant amount of research is ongoing to reduce methane emissions in ruminants. The broad strategies of methane mitigation will be explained in the following section, including; methane vaccines, system optimisation, early life rumen modification and the feeding of methane inhibitors as supplements.

Using a vaccine to reduce ruminant methane emissions is potentially a low-cost mitigation option for livestock farmers with minimal downsides (Beauchemin et al. 2020; Black, Davison, and Box 2021). However, vaccines that have been trialled have had poor and inconsistent results, with some attempts increasing emissions (Wedlock et al. 2013; Williams et al. 2009; Wright et al. 2004).

Breeding animals that produce lower methane emissions is another potential mitigation option. This approach leverages the natural variability in per-animal emissions; however, it is unknown how selecting low-emission genetics would influence other desirable traits (Beauchemin et al. 2020; Black et al. 2021). The possibility of favourable breeding to mitigate emissions (Hristov and Melgar 2019) is unlikely to get the industry to methane mitigation levels above 10% due to insufficient differences between animals and the fact that dry matter intake tends to be a more influential factor (Black et al. 2021).

Suppose farmers can ensure that animals consume the correct amount of feed and optimise reproduction. In that case, there could be system-level methane mitigation opportunities (indicated to be as high as 20% in beef systems but lower in dairy) (Beauchemin et al. 2020; Black et al. 2021). The positive relationship between dry matter intake (DMI) and emissions is another potential opportunity to target.

Another option is early life intervention which relies on providing a methane-inhibiting treatment early in a calf's life. The treatment aims to alter the animal's rumen function to produce relatively less methane over its entire life. This approach is relatively untested, with minimal published trial results. However, one study found that methane mitigation was observed after an inhibitor was administered and had exited the body of a cohort of calves (Meale et al. 2021). A trial of this nature with goats (another ruminant) found that treated kids produced less methane than untreated siblings (Abecia et al. 2013). As researchers continue to conduct trials, a better understanding of the rumen response to early life rumen modification and its application will emerge.

The final category of methane mitigation strategies most closely relates to the topic of this thesis and is the inclusion of methane-inhibiting compounds in the diet of ruminants. Methane inhibitors have been researched extensively in recent years. The compounds most researched for this application are a synthetic product, 3-Nitrooxypropanol (3-NOP), produced by DSM (DSM 2022) under the brand name 'Bovaer' and a naturally occurring Australasian red macro algae (seaweed), Asparagopsis Taxiformis ‘Asparagopsis’ (Beauchemin et al. 2020; Black et al. 2021). Both of these compounds inhibit the final stage of methane production in the animal's rumen, known as methanogenesis, which naturally leads to lower methane emitted from the animal. 3-NOP and Asparagopsis do not significantly change the characteristics of milk or meat of the animals once consumed. When used as a feed supplement, animals would need the inhibitor to be in their diet consistently regardless of the dose.

1.1.4 *3-Nitrooxypropanol* (3-NOP)

A summary of the many trials of 3-NOP is given by Beauchemin et al. (2020) and Melgar et al. (2019). While trials tend to have divergent methane emission magnitudes, the delivery of 3-NOP to dairy cows yields between 20-40% less methane. A key feature, outlined in the previous papers but explored more thoroughly in Hristov & Melgar (2019), is the frequency with which the inhibitor is delivered to the animals. Methane reduction is the greatest for those animals receiving 3-NOP in a total mixed ration diet (TMR), such as housed animals. Conversely, in animals grazing pasture, a lower level of mitigation has been reported due to frequent and consistent dosing requirements for maximum reduction. The effectiveness of 3-NOP is the greatest immediately after it is fed, but the effectiveness rapidly reduces (Hristov and Melgar 2019). The sharp tail of effectiveness means that if dairy cows are fed 3-NOP irregularly or at long intervals, the inhibitor's effectiveness will be greatly reduced. Methane emissions in cattle is relative to their intake (Richardson et al. 2020). When there is a delay between inhibitor ingestion and peak feedings, such as walking from the milking shed to the paddock, there is the potential to miss the window of peak mitigation. This delay is extended by the requirement to fill their rumen before mitigation can begin.

3-NOP was initially developed in 1990 by (Ogawa et al. 1990) and further developed by the Swiss nutrition company DSM, who has been approved to distribute the product in Brazil, Chile and the European Union (DSM 2021c, 2021b). Furthermore, according to local legislation, the company is partnering for continued research of the product in other nations while developing a facility in Scotland with manufacturing capacity for the large-scale supply of the product (DSM 2021a).

1.1.5 *Asparagopsis Taxiformis* (Asparagopsis)

Asparagopsis is a red marine macroalgae shown *in vitro* and *in vivo* to reduce methane emissions in ruminants (Beauchemin et al. 2020; Black et al. 2021). Ruminant methane emissions stem from methanogenesis, the conversion of hydrogen into methane in the rumen. Inhibitors such as Asparagopsis work by disrupting the process of methanogenesis, explicitly blocking the final step. Methane production accounts for 12% of energy utilisation. If a reduction in methane production can be achieved, animals will become more feed-efficient (Honan et al. 2021; Kinley et al. 2016; Machado et al. 2014). While many seaweeds have been shown to have potential in this area, Asparagopsis has been shown to have the highest mitigation potential (Machado et al. 2014). However, seaweeds contain bromoform, bromine and iodine, which can negatively impact human health, specifically iodine for young children if it becomes part of the food chain (Beauchemin et al. 2020; Stefenoni et al. 2021).

In addition to health concerns related to using seaweed as a methane inhibitor, there are also concerns about the product's commercial viability. Currently, trials use wild-caught seaweed, which is unsustainable and uneconomical. For seaweed to become a mainstream methane inhibitor, it must be farmed commercially to reach the required economies of scale (Black et al. 2021; Honan et al. 2021; Kinley et al. 2016). When scaling up seaweed production, there may be implications for the product's life cycle emissions, which also must be assessed (Beauchemin et al. 2020).

From the animal health perspective, there have been reports that the inclusion of seaweed in the diet of animals has reduced DMI (Roque et al. 2019), potentially stemming from palatability issues. However, Black et al. (2021) refute any palatability issues of *Asparagopsis*. Despite the plausible downsides of implementing seaweed in animals' diets, the potential benefit is more significant than the alternatives. The methane mitigation associated with feeding *Asparagopsis* to dairy cows is as high as 80%. An even more significant reduction of 98% of housed beef cattle has been recorded (Black et al. 2021).

1.1.6 Methane Inhibitor Delivery

One factor guiding the direction of research for both 3-NOP and *Asparagopsis* is the desirable characteristics of the compounds. There are five characteristics of methane-inhibiting compounds described in table 2 (Henderson et al. 2016). For this research, the most important characteristics are 'economic' and 'broadly applicable', which refer to the requirement for the inhibitors to fit into a range of farm systems while remaining economically viable.

Table 2 - Desirable Characteristics of Methane Inhibiting Compounds, reproduced from Henderson et al. (2016)

Characteristic	**Definition**
Specific	Only targets methane production with minimal or no side effects
Safe	Safe for animals and those that consume animal products of animals which have consumed the inhibitor
Effective	Sustained long-term response
Environmentally sustainable	Positive life cycle analysis
Economical	Low cost of manufacturing and delivery. Delivery should be

	possible through different avenues, i.e. feed supplement, water trough, lick block, paddock spraying, bolus slow-release
Broadly applicable	It fits into a broad range of farm systems, i.e. Total Mixed Ration (TMR) or pasture

While 3-NOP and Asparagopsis have been shown to have some desirable characteristics, work is required to develop the slow-release bolus under economic delivery in pasture-based systems (Glasson et al. 2022; Henderson et al. 2016). Further research is needed to develop a lick block as a delivery method for the compounds, as studies of other inhibitors have shown poor results (Alvarez-Hess et al. 2019; Black et al. 2021). However, an issue consistent across the economical delivery methods except bolus delivery is self-regulation of intake. For these delivery methods to be viable, self-regulation must exhibit the precision observed in delivery methods such as TMR systems (Beauchemin et al. 2020). In-paddock smart-feeders (IPSF) is one way to potentially regulate animal intake by meeting the requirements of frequent and consistent intake. These machines assign individual animal intake for a given period via an online portal which is then conveyed to the machines over a wireless network. Additionally, the connection between the machines and the online portal means that actual intake and the number of interactions of each animal are recorded. This is possible via four feed stations, solar panels, batteries, and mobile networks. An example of IPSFs being interacted with by animals is illustrated in figure 1.

Figure 1 Example of an In-Paddock Smart-Feeder (IPSF)

1.1.7 Summary

In summary, there is a need to reduce ruminant methane emissions as part of the global effort to reduce emissions in the face of climate change. NZ has significant ruminant methane emissions. While many methods are undergoing research and development, an economical approach has yet to be found to mitigate methane emissions in pasture-based dairy. This thesis explores a unique approach, combining methane-inhibiting compounds that have been shown to have significant methane mitigation potential but require frequent and consistent dosing with IPSFs, an emergent but relatively untested approach to delivering supplement to animals in-paddock.

1.2 Research Objectives

This thesis has four main objectives, the first two relate to the second chapter, which investigates the adoption outcomes of IPSFs, and the latter two relate to the third chapter, which estimates the economic performance of IPSFs. The objectives are:

- What are is the likely adoption outcomes of IPSFs in a methane-inhibitor delivery capacity?
- What are the key adoption determinants of IPSFs in a methane-inhibitor delivery capacity?
- What is the breakeven methane price for IPSFs to become economically viable in the capacity of methane-inhibitor delivery?
- How does the breakeven methane price change the viability of this approach across farm systems?

1.3 Thesis Structure

This thesis contains four chapters; this first chapter offers the background required to contextualise the need for this research and insights into the novel approach that is explored in the following chapters. Chapter two evaluates the adoption outcomes of the novel use of IPSFs as methane-inhibitor delivery mechanisms. This research utilises focus groups with farmers and industry experts to gather the qualitative data required for adoption modelling. Chapter three develops a cost-effectiveness model which produces financial statements and estimates the breakeven methane price for the approach. After the model is developed, it is then used to explore how the approach would likely perform in various farm systems found throughout NZ. Chapter four is a conclusion, drawing on the discussions and conclusions of the previous two chapters to offer a holistic overview of the approach.

Chapter 2: Adoption Outcomes

2.1 Introduction

This chapter evaluates potential adoption outcomes of in-paddock smart-feeders (IPSF) as methane inhibitor delivery devices. This research is motivated by the dairy industry's commitment to reducing its sizeable methane emissions. A novel way to mitigate methane emissions in the dairy industry is using methane inhibitors, which require frequent and consistent administration but have significant mitigation. More information about methane emissions in the dairy industry and methane mitigation is in the background section of chapter one.

The chapter utilises the Adoption Diffusion Outcome Prediction Tool (ADOPT) to estimate adoption outcomes (Kuehne et al. 2017). Focus groups are used to determine ADOPT inputs and gather feedback essential to widespread adoption. The focus groups follow the Awareness, Knowledge, Adoption, Production (AKAP) framework to record information flows. In addition, a sensitivity analysis illustrates three key factors underpinning adoption outcomes. A scenario analysis framed around technology performance shows unfavourable modelled adoption outcomes in an expected and worst-case scenario. However, in a best-case scenario, there are favourable modelled adoption outcomes in an optimistic scenario.

2.2 Literature Review

The literature reviewed in this section relates specifically to quantifying and discussing adoption. Adoption can be defined as using technology to utilise different resources to change output, where technology refers to new relationships between inputs and outputs (Foster and Rosenzweig 2010). In this instance, the new technology is IPSFs which NZ dairy farmers may adopt to change their methane emissions. Literature pertaining to methane emissions in pasture-based dairy and potential policy implications are presented in chapter one. Further, literature specific to the use of IPSFs is presented to contextualize the innovation. The literature discussed in chapter one is consistent across chapters two and three; therefore, to prevent repetition, it is included in the introductory chapter. The literature review of this chapter contains a critical review of the following five adoption frameworks and models, including examples of their application where applicable:

- Smart Farm Framework
- Roger's Adoption Diffusion
- Responsible Innovation
- Awareness, Knowledge, Adoption, Participation Framework
- Adoption Diffusion Outcome Prediction Tool.

There are several approaches for modelling the uptake of new technologies or practices in a population, but they generally fall into two classes: conceptual models and numerical models (Montes de Oca Munguia, Pannell, and Llewellyn 2021). The former employs diagrams and algebra to evaluate relationships without assigning numerical values, while the latter seeks to quantify inputs and estimate adoption outcomes with mathematical and statistical techniques. This means that the latter can be used to supplement the former. However, using a numerical model to supplement a conceptual model is challenging due to the assumptions and estimations needed in adoption modelling.

A further factor complicating the estimation of agricultural adoption is that on-farm decision-making is complex and unable to be distilled into binary processes or decisions (Montes de Oca Munguia, Pannell, Llewellyn, et al. 2021). This complex decision-making process often leads to the use of heuristics in response to an individual's limited cognition. Heuristics such as the perceived value of an innovation and the time commitments associated with adopting an innovation are crucial to adoption and often overlooked (Pannell et al. 2006). Pannell also found that any interaction between innovation and the adopter was a determinant of adoption outcomes. However, it was not often included in studies (Montes Oca Munguia and Llewellyn 2020; Pannell et al. 2006). One model that does consider the interaction of the adopter and an innovation is the ADOPT model (Kuehne et al. 2017).

The literature surrounding adoption is further complicated by a lack of convergence of adoption models or frameworks with significantly different approaches (Montes Oca Munguia and Llewellyn 2020). Most adoption frameworks and models are underpinned by at least one of three studies that are the basis of adoption modelling; regression modelling (Ajzen 1991), key attribute modelling (Rogers 1962) and behaviour modelling (Griliches 1957).

Regardless of the chosen adoption model, many changes have occurred to adoption modelling over time (Montes Oca Munguia and Llewellyn 2020). These changes raise the question of whether an older and more established model should be applied to answer the question of the adoption diffusion of smart-feeders as an inhibitor delivery system. Alternatively, consideration could be given to newer emergent models. In order to select an appropriate model or framework to estimate the adoption of IPSFs in pasture-based dairy, five adoption models or frameworks will be reviewed in the following sections. The first model or framework is the Smart Farm Framework, the second is Roger’s Diffusion of Innovation Framework, the third is the Responsible Innovation Framework, the fourth is the AKAP framework, and finally, the ADOPT model.

2.2.1 Smart Farm Framework

The Smart Farming framework is described through the dairy industry lens by (Eastwood et al. 2019) and is comprised of three aspects;

- the characteristics of the target population and market (in this case study NZ dairy farmers)
- technical design and innovation (the performance of IPSFs) and the capability requirements
- knowledge exchange (how do farm management and other skills change in the face of adoption).

Smart farming has several other names, such as digital and precision agriculture. The core of smart farming is data-driven decision-making stemming from technology implementation into farm systems (Eastwood et al. 2019). Management decision support services have increased over time as there is a transition toward data-driven decision-making vis-a-vis Smart Farming (Eastwood, Chapman, and Paine 2012; Mackinnon, Oliver, and Ashton 2010). In the NZ context of smart dairying, a socio-ethical concern pertains to the core data of Smart Farming. One prominent issue is the end use and ownership of the data collected in a data-driven system, which has largely been ignored in favour of fast dissemination of the innovation (Eastwood et al. 2019; Wolfert et al. 2017).

The Smart Farm Framework was applied to three case studies relevant to the dairy industry, demonstrating the model's potential suitability for this research (Eastwood et al. 2019). The case studies are; automated body conditioning score, precision grazing management and a soil water outlook tool.

Strengths

This framework offers a holistic perspective of how technology fits into an existing farm system. The Smart Farm framework has many links to other frameworks, such as agricultural innovation systems which leverage technological advancements and institutional change (Klerkx, Aarts, and Leeuwis 2010)

Weaknesses

The framework takes a highly qualitative stance which would be relatively difficult to work through with farmers for this case study, where details are scarce. Further, there is no process to estimate adoption outcomes for the application of in-paddock smart-feeders as a mechanism to deliver methane inhibitors.

2.2.2 Roger's Diffusion of Innovation

The Diffusion of Innovation framework (Rogers 1962) synthesises several years of individual works in the adoption study. Rogers categorises adopters into five categories (Lundblad 2003; Rogers 1962; Sahin 2006):

- Innovators who seek out innovations and introduce them to their system
- Early adopters who are leaders and endorse the innovations with adoption
- The early majority who adopt before most of their peers, but their adoption decisions are slowed because of their distance from leadership
- The late majority, who, despite scepticism, adopt the technology due to economic and social pressure
- The laggards who are relatively more sceptical than the late majority and who's social circles mainly include other sceptics.

The stages are mapped temporally as an S-shaped curve to represent changes in the adoption rate. Due to the distribution of people in the different categories, there are relatively few early adopters and laggards, but the adoption rate is higher for the early and late majority. In addition to the five categories of adopters, Rogers also defined five critical factors of adoption. Rogers's factors of adoption are; relative advantage, compatibility, complexity, trialability, and observability (Rogers 1962).

- *Relative advantage* refers to how much better an innovation is than its' alternative.
- *Compatibility* refers to how easily the innovation can be implemented into existing workflows and practices
- *Complexity* refers to how difficult an innovation is to understand.
- *Trialability* refers to how easily an innovation can be tested before it is committed to and implemented
- *Observability* refers to how easy it is to observe the outcomes of adopting an innovation

Finally, adoption decision-making can be described in five steps:

- Knowledge (aware of an innovation)

- Persuasion (forms an opinion regarding innovation)
- Design (adoption decision is made)
- Implementation (introduced to practices and workflow)
- Confirmation (decision maker experiences positive reinforcement regarding adoption).

The Diffusion of Innovation Framework has been referenced in over 1,000 unique pieces of work, indicating that it can be used broadly, including in agriculture (Lundblad 2003).

Strengths

This framework and its terminology are widely recognised, making conveying adoption outcomes relatively easy. Additionally, the factors of adoption in this framework are well-defined.

Weaknesses

This framework is mainly theoretical, and while the adoption diffusion curve is well-defined, there is no precise method to estimate the time to reach the different stages of the S-shaped curve. The timeliness of adoption is critical in this case due to the need for action on climate change.

2.2.3 Responsible Innovation

Recent technological gains will likely be crucial to productivity, environmental and social gains. However, these outcomes have been historically overlooked (Rose and Chilvers 2018). The development of responsible innovation within agriculture will be essential to the success of the current agricultural revolution, which will include a data-driven approach to farming and a paradigm shift away from the incumbent approach of instinct-driven decision-making. The implementation of such innovations should adhere to responsible innovation. This concept, defined by Stilgoe et al. stipulates the need for innovations to improve efficiency or productivity in conjunction with a social benefit (Rose and Chilvers 2018; Stilgoe, Owen, and Macnaghten 2013).

There are four components of responsible innovation (Stilgoe et al. 2013);

- *Anticipation* (foresighting and scenario building)
- *Inclusion* (stakeholder involvement and mutual learning)
- *Reflexivity* (co-development)
- *Responsiveness* (adaptability and open source).

Inclusion is vital as innovations tend to be devised in a top-down approach and would benefit significantly if stakeholder collaboration is implemented early in the innovation process (MacMillan 2018). In practice, increased validation of innovation frameworks is required to ensure they achieve their goals (Rose and Chilvers 2018). Additionally, Rose and Chilvers note that Responsible Innovation has been tested in practice (Rose and Chilvers 2018) which reduces the potential of this framework for this research.

Strengths

Responsible innovation is a more holistic framework that introduces the social implications of innovation in its assessment. It is an essential aspect of innovations that have widespread social impacts and are potentially funded in part by the government.

Weaknesses

While responsible innovation improves on the earlier models by including socioeconomic factors, it has no outputs as it is a guiding framework rather than an evaluation framework.

2.2.4 AKAP (Awareness, Knowledge, Adoption, Product)

The AKAP sequence addresses the flow of technical information about an unadopted technology; farmer awareness (A), farmer knowledge through testing and experimenting (K), adoption of technology and practices (A), and changes in productivity (P) (Evenson 1997). These steps convey the information, education, and training services required for implementation and knowledge sharing via extension work. These four components have been evaluated in previous studies, although not always in conjunction with each other (Evenson 1997). One of the statements reinforced by this paper is that the services offered by extension professionals are a net substitute for farmer skills. Additionally, extension impacts are more significant on those farmers with lower education. Vecchio et al. (2020) note that younger farmers have more significant potential to understand emerging innovations and adopt them in their systems, while larger farms can absorb the costs associated with adopting an innovation.

The AKAP sequence is applied to Precision Agriculture (leveraging technology to improve profitability and reduce environmental impact) in the European Union by Vecchio et al. (2020) to develop agricultural policy change. The policy change will be essential in the future adoptability of in-paddock smart-feeders. Thus there are parallels between the case study presented by Vecchio et al. and this research, indicating that AKAP may be suitable for conveying technical information.

Strengths

The AKAP sequence is successful in applications similar to this study and offers a defined way to convey information when assessing adoptability. Its discussion-orientated approach aligns with the intention to conduct focus groups. Despite its weaknesses, there is strong potential for this model to be used in conjunction with another.

Weaknesses

In parallel to other frameworks, there is no quantitative output from the sequence as it prescribes information convergence rather than any discussion. Hence it could not be used in isolation to address the research objectives of this chapter.

2.2.5 ADOPT (Adoption Diffusion Outcome Prediction Tool)

The ADOPT model (Adoption, Diffusion, Outcome, Prediction, Tool) estimates the rate of adoption, peak level of adoption, and illustrates key determinants of adoption by constructing a temporal adoption diffusion curve (Kuehne et al. 2017). The model is based on quantifying twenty-two variables spread across four quadrants (figure 2). Each variable is quantified with a multiple-choice question with between five and eight answers which can be found in appendix D where the questions have been contextualised for IPSFs.

The first quadrant of the ADOPT model is the population's relative advantage, which concerns the preferences of the potential adopter. The second quadrant is the learnability of the practice and characteristics of the innovation and its potential inclusion in the adopter’s system. The third quadrant is the population-specific influences on the ability to learn about the practice, which addresses characteristics of the broader population of adopters; for example, one variable in this quadrant is advisory support. The final quadrant addresses the financial and non-financial effects of adopting the innovation. The main outputs of ADOPT are the time to peak and adoption, and peak adoption level, the main determinants of these outputs can be traced through figure two to show that time to peak adoption is primarily determined by awareness, learning of relative advantage, short-term constraints and upfront costs while the peak adoption level is largely determined by relative advantage. However, it is apparent that many factors feed into these main determinants, as shown in figure 2.

In addition to quantifying these outputs, the ADOPT model also serves to deepen the understanding of adopting a given innovation in the context of research, extension, and government policy. Several notable characteristics need to be considered when critically evaluating the ADOPT model. These characteristics include a link between the awareness of innovation and the time to peak adoption, the incorporation of farmers' risk aversion, and the intent to be used in conjunction with other evaluation techniques. Examples of simultaneous evaluation techniques include surveys, economic models, and biological simulation models rather than as a replacement to be used in isolation. This is to say that the following chapter will be required to reinforce the modelled adoption outcomes of this chapter.

The ADOPT model is the only agriculture-specific quantitative model of adoption outcomes. It illustrates cause-and-effect relationships by estimating peak adoption and the adoption rate. Four quadrants comprise the model with two main themes; relative advantage and learning of relative advantage (Montes de Oca Munguia, Pannell, and Llewellyn 2021). Additionally, the ADOPT model has been proven in practice by Monjardino et al., who utilised the model to predict the adoption of legume crops after rice crops in Southeast Asia (Monjardino et al. 2020).

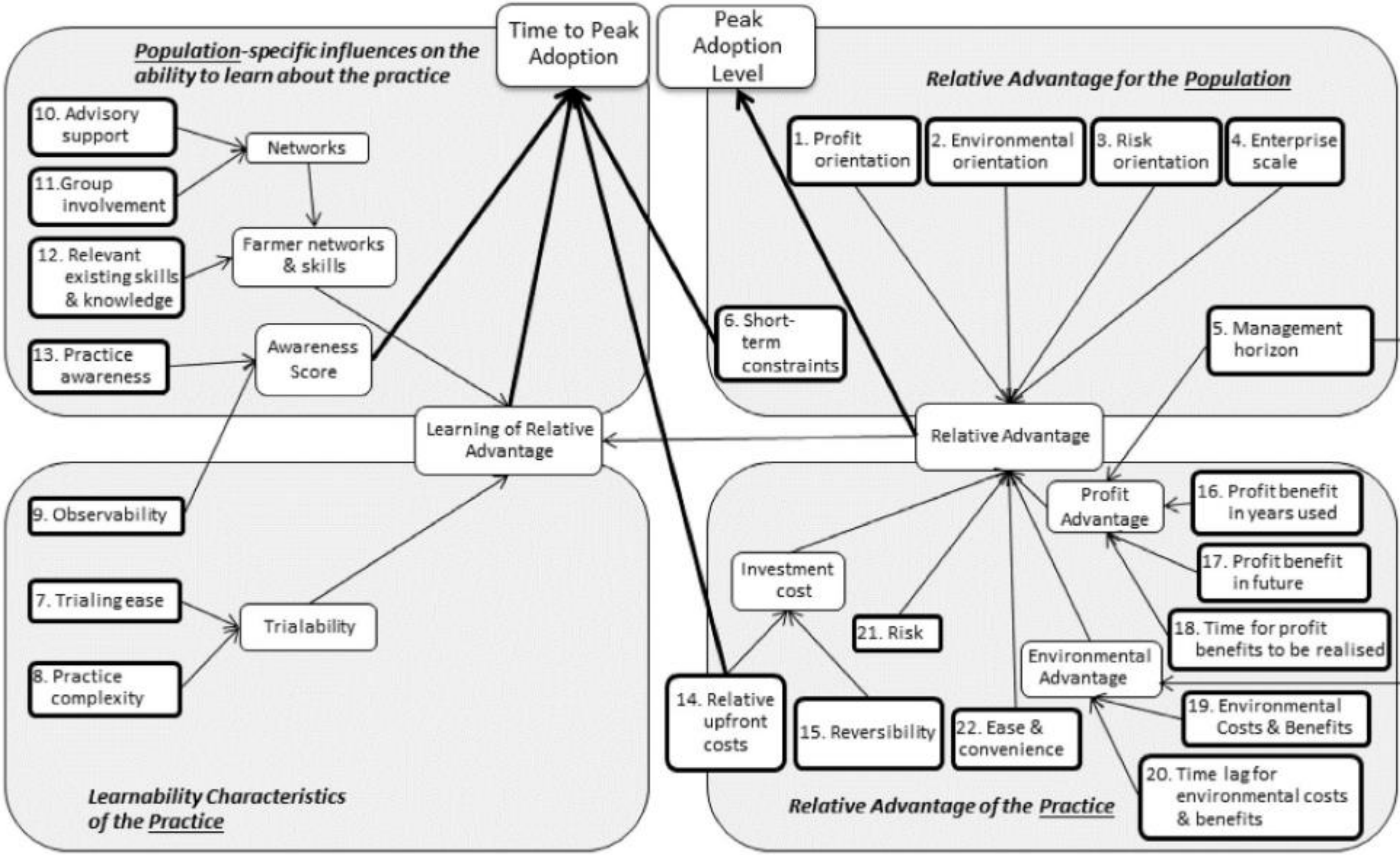


Figure 2 The ADOPT model, reproduced under creative commons (Kuehne et al. 2017)

Strengths

The ADOPT model generates quantitative outputs estimating the adoptability of an innovation, which is advantageous relative to other frameworks. In addition, there is the potential to use another theoretical framework in conjunction with the model to enrich the interpretation of the inputs and outputs.

Weaknesses

The ADOPT model is explicitly designed around agricultural adoption and has twenty-two specific questions as inputs. Being able to answer these input questions accurately is essential to having confidence in model outputs. Further, it would not be possible to extrapolate the use of the model to innovations outside of agriculture, meaning comparability of adoption outcomes between ADOPT and another model would be difficult.

2.2.6 Adoption Model Summary

Several adoption models and frameworks have been developed with unique goals in mind. All of the models or frameworks that were evaluated are theoretical, which is sufficient for some applications. However, for this application, a quantitative output is preferred; therefore, the ADOPT model was chosen. The preference for quantitative outputs stems from comparisons that can be drawn from the gradual tightening of emissions targets under the Zero Carbon Act.

The ADOPT model was selected due to the requirements of quantitative outputs (Kuehne et al. 2017). However, the inputs of the model are relatively complicated. Given the intention to utilise focus groups to determine model inputs, having focus group participants interact directly with the ADOPT model will not be feasible. Hence, another tool is required for delivering information to focus group participants, the AKAP sequence (Evenson 1997), which will augment the ADOPT model to convey relative information about in-paddock smart-feeders in a methane inhibitor delivery role. The AKAP sequence has been used to strengthen knowledge systems in the adoption of agricultural innovations previously (Masi et al. 2022; Vecchio et al. 2020).

2.3 Methodology

This research utilises focus groups, the AKAP sequence and the ADOPT model to quantify likely adoption outcomes of in-paddock smart-feeders as a methane inhibitor delivery mechanism. Firstly, a farm system expert consultation was conducted to determine a baseline and gather feedback on the focus group approach. Secondly, two focus groups were held with farmers as a small sample of the NZ dairy farming population. During the focus groups, participants were informed of the relevant performance characteristics of the approach. Their thoughts and comments were recorded and utilised to inform the inputs of the ADOPT model while following the AKAP sequence. The ADOPT variables were split into two groups: those consistent across the dairy farming population in NZ and those that are approach specific. The former group were addressed by the expert consultation, while the later was addressed by the expert consultation in addition to the farmer focus groups. Differences in the latter group of variables are further investigated using two hypothetical scenarios in which the characteristics and performance of the IPSFs differ.

2.3.1 Farm Systems Expert Consultation

A DairyNZ expert group was held on 28 February 2022 for two hours. This focus group was a combination of online (MS Teams) and in-person. This session aimed to gather participants' insights about how using in-paddock smart-feeders as a methane inhibitor delivery mechanism would fit into NZ's pasture-based dairy farm systems. Specifically, what the participants expected to be the main barriers to adoption and to create a baseline adoption diffusion curve utilising the ADOPT model. In addition, this consultation was required to address some of the ADOPT inputs that were consistent across all NZ dairy farmers. It would not be possible to discuss all ADOPT variables in the farmer focus groups while following the AKAP sequence. Hence those ADOPT variables consistent across the NZ dairy farming population that were able to be addressed with this consultation were omitted from the farmer focus groups. The group comprised nine attendees, including farm staff, farm system specialists, economists, social scientists, plant scientists, and animal scientists with experience in dairy farm systems and varying knowledge of inhibitor and smart-feeder technology.

The expert consultation did not employ the AKAP sequence as there was already a relatively high level of knowledge among participants; hence the group started with the provision of information about the approach. The questions asked during this session can be found in appendix A, and the broad structure of the session was:

- Provision of context, including relevant performance characteristics of methane inhibitors and smart-feeders.
- An initial survey of the most important smart-feeder characteristics and a subsequent discussion.
- Discussion of ADOPT model inputs, with specific reference to those inputs consistent across the dairy sector.
- Discussion of participant preferences between two hypothetical smart-feeders with broadly different performance characteristics.
- Concluding discussion of methane emissions at an industry level and how the approach and method aligned with industry standards and sentiment.

2.3.2 Farmer Focus Groups

Two farmer focus groups were conducted to collect qualitative data from dairy farmers with diverse farm systems. The focus groups were held online (using MS Teams) on March 8 and 10, 2022 for approximately two hours. The online method was chosen to limit the time required from farmers, minimise potential issues associated with the Covid-19 pandemic, and enable farmers from across NZ to participate. Participants were invited to the focus groups based on their DairyNZ farm system classification. Refer to table one on page two for more information.

An ethics application addressing these focus groups was submitted to the University of Waikato Management School (WMS) ethics committee (application 21/238.) The supplementary information for the application, such as the initial contact script and participant information sheet, can be found in appendix B. Note that the researchers for this focus group are Ben Marmont (postgraduate student) and Dr Callum Eastwood (supervisor of Ben). Callum and Ben were assisted with technical information about the approach and the related science during the focus groups by Dr Elena Minnee.

For the 8th March 2022 group, lower input farmers were invited (farm systems one, two or three), while the 10th March 2022 group were higher input farmers (farm systems four or five.) The goal was to have between eight and ten people in each focus group, which is the optimal number for discussion in an online setting (Hinkes, 2021). Ten farmers were invited to each focus group to account for withdrawals, and seven in each focus group committed to attending. However, due to non-attendance, five attendees were in the lower input group and three in the higher input group. The participants of the lower input group were located in Waikato and Northland, and the participants of the higher input group were located in either Waikato or Canterbury.

An overview of the questions asked during these focus groups can be found in appendix C.

Awareness, Knowledge, Adoption and Productivity (AKAP) Sequence

Awareness

The ‘Awareness’ part of the AKAP sequence required an overview of participants' existing knowledge about methane inhibitors and how cows might ingest them, such as IPSFs. This was a general conversation between researchers and participants with no formal surveys.

Knowledge

The 'Knowledge' portion of the focus group provided participants with an overview of methane mitigation in the dairy sector. This knowledge includes different methane mitigation approaches such as; farm system optimisation, vaccine, early life rumen modification, and methane inhibitors as a feed supplement (Beauchemin et al. 2020; Honan et al. 2021). The approach most relevant to the focus groups was methane inhibitors as a feed supplement as it is the only mitigation technique that interfaces with smart-feeders which are central to this research. Hence there was a focus on informing participants about the efficacy and delivery requirements of 3-Nitrooxypropanol (3-NOP), commercially known as Bovaer and Asparagopsis, a type of red seaweed. This section was presented primarily by Dr Elena Minne, a Senior Scientist and subject matter expert on methane at DairyNZ.

Adoption

The ‘Adoption' part of the AKAP model drove the need to understand the features of technology and how it would integrate the technology into existing farm systems. This aspect of the AKAP sequence was explored using a character ranking task via online surveys, which will be expanded in the following section.

Productivity

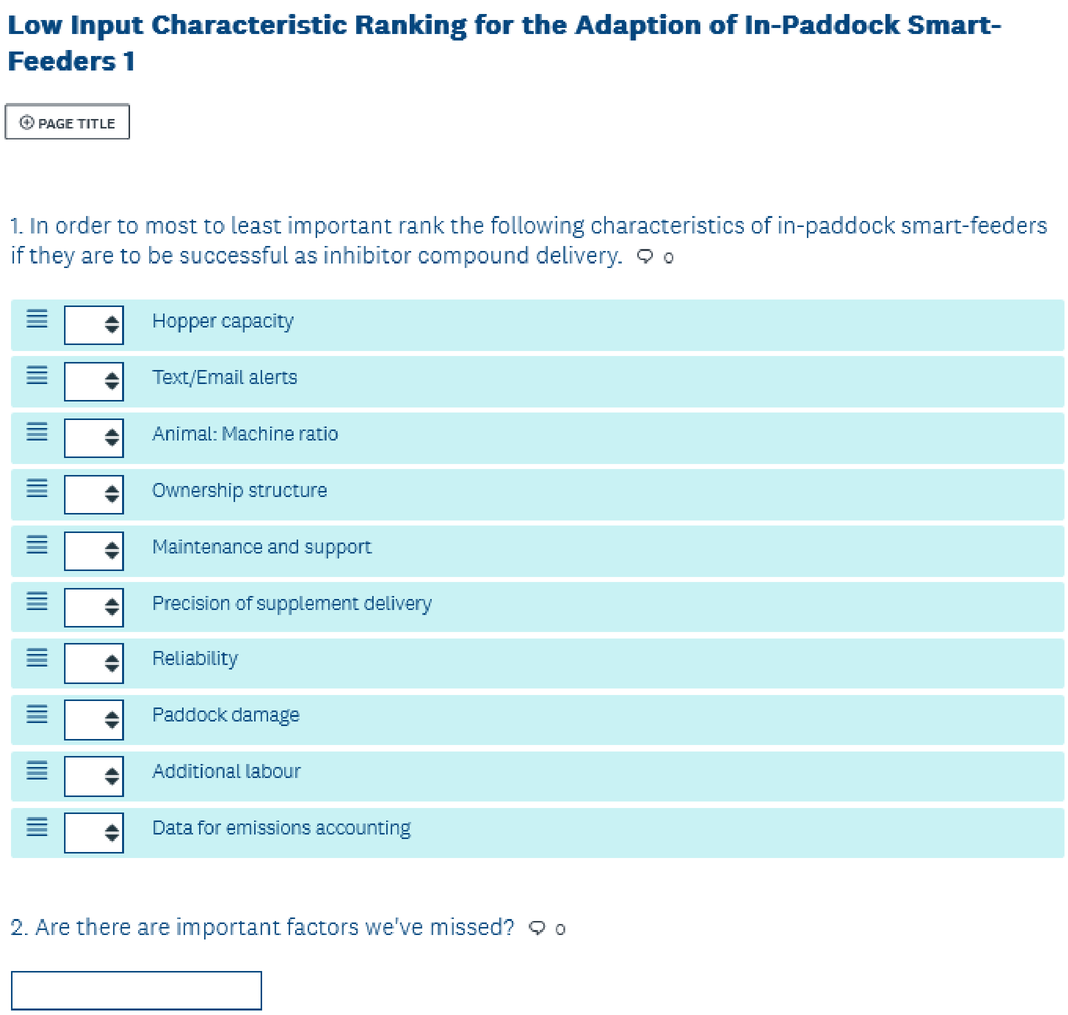
Assessing productivity changes due to adoption is difficult as there is no real-world data to contextualise the associated costs and benefits, however, this question is addressed with a scenario comparison. The scenario comparison utilises two fictional scenarios to elicit preferences around the characteristics. The characteristics presented were related to the efficacy of the technology, and its productivity was discussed organically.

2.3.3 Focus Group Tasks

The focus group approach was designed to identify the critical adoption factors for IPSFs as a supplement and methane inhibitor delivery mechanism. The characteristics were assessed early in the focus group before any discussions to mitigate the impacts of groupthink, which refers to the social convention of maintaining a consensus in a group setting to mitigate disagreements (Janis 1972).

Ranking Task

An online ranking exercise was used to rank the characteristics of in-paddock smart-feeders. The expert consultation informed the characteristics farmers were asked to rank. The online survey tool SurveyMonkey was used to collect responses. An example of the survey structure is presented in figure 3.



Low Input Characteristic Ranking for the Adaption of In-Paddock Smart-Feeders 1

PAGE TITLE

1. In order to most to least important rank the following characteristics of in-paddock smart-feeders if they are to be successful as inhibitor compound delivery. 0

- Hopper capacity
- Text/Email alerts
- Animal: Machine ratio
- Ownership structure
- Maintenance and support
- Precision of supplement delivery
- Reliability
- Paddock damage
- Additional labour
- Data for emissions accounting

2. Are there are important factors we've missed? 0

Figure 3 – IPSF Characteristic Ranking Exercise (Survey Monkey)

Using the online platform SurveyMonkey, participants were asked to drag and drop the characteristics defined in table 3 from most important at the top to least important at the bottom. These characteristics were pre-defined based on feedback from the expert consultation. Participants could also use a text box to add any characteristics they believed were omitted.

A discussion around the results of the ranking exercise was then explored to understand why participants ranked them the way they did. This information was then used to inform the nine ADOPT variables that are technology-specific.

Table 3: Smart-Feeder Characteristics developed for ranking exercise in farmer Focus Groups

Characteristic	**Definition**
Hopper capacity	The size of the hopper and implicitly how often the machines need to be refilled.
Text/email alerts	Automated signal to farmer when the machine is empty or malfunctioning, minimising downtime.
Animal to machine ratio	Number of animals each machine can optimally feed the required amounts of supplement.
Ownership structure	Fixed-term lease or purchased. These two structures may appeal to different individuals depending on the financial structure of their farm.
Maintenance and support	Whether maintenance and support are included in rental/purchase agreement, or additional.
Precision of supplement delivery (feed + inhibitor)	The accuracy of the supplement and methane inhibitor required to prevent overindulging which can have significant health implications. Automatic feeding can induce competitive behaviour between animals and lead to poaching, and thus precision is needed to ensure its affects are minimised. (Herlin and Frank 2007; Nagaraja and Lechtenberg 2007; Nordlund 2003)
Reliability	Likelihood of machine breakdowns and complications.
Paddock damage	High animal concentration in an area, such as around a smart-feeder leads to pugging. Farmers tend to overestimate the cost of pugging (in reality, pugging costs < 3%.) The value of paddock damage may offset the running costs of other inhibitor delivery

	systems if the capital outlay is ignored. (Laurenson et al. 2017; Pitman 2021)
Additional labour	Farmers tend to invest in technology to reduce labour, this approach increases labour input. (Dela-Rue et al. 2019)
Data for emissions accounting (proof of practice)	How auditable is the practice to prove mitigation is occurring on farm.

Note to table 3: Not all characteristics have corresponding references due to the characteristics being unique to this novel approach to methane mitigation.

Scenario Preference

The next step in each focus group was to explore two theoretical IPSF performance scenarios inspired by technology currently available. For those characteristics that could not be determined from existing technology, the expert consultation provided expected values that could differentiate the two scenarios based on likely outcomes. First, these scenarios were described, and participants were then asked which scenario would be preferable and why. Table 4 illustrates the two scenarios relative to the characteristics previously discussed. Scenario one represents a smaller machine that is less effective and requires revenue expenditure. While the machine in scenario two is bigger, more effective and requires capital expenditure.

Table 4 - Smart-feeder Characteristic Differences by Scenario

Characteristic	**Scenario 1**	**Scenario 2**
Hopper capacity	Five days between refills	Ten days between refills
Text/email alerts	When empty and disabled	Text when disabled only
Animal to machine ratio	75 cows: machine	125 cows: machine
Ownership structure	Yearly rental contracts ($1500/month)	Purchase for $50,000
Maintenance and support	Local technician for support and readily available parts	Remote support, lag time for parts
Precision of supplement delivery (feed + inhibitor)	Most cows get allocation (some poaching)	All cows get allocation (no poaching)
Paddock damage	Smaller machine with minimal pasture damage	Bigger machine with moderate pasture damage
Additional labour	Twelve hours per week, per machine	Five hours per week, per machine

Modelling

Base scenario

Following the focus groups, the twenty-two ADOPT questions were answered from the provided drop-down menus in the online ADOPT model hosted by CSIRO, which can be found in appendix D. These questions were answered using the information gathered in the focus groups. This combination of ADOPT inputs serves as a base scenario for modelled adoption outcomes. However, some of the twenty-two ADOPT answers in the base case could not be answered confidently. In order to address the lack of confidence base case answers were ranked as high, medium and low confidence in terms of how subjectively accurate the responses were. Several questions were regarded as high confidence and seven as low confidence. These seven inputs are labelled 'low confidence ADOPT inputs.' The low-confidence ADOPT inputs are prone to variation, and this means that they are more likely to be consistent across the population, i.e., the questions addressed by the farmer focus groups relative to the questions that depend on an individual farm, such as the ADOPT questions answered by the farmer focus groups.

Sensitivity Analysis

The low-confidence ADOPT variables were then used as the basis for a sensitivity analysis. Holding all other inputs constant at the base case level, each of the low confidence ADOPT inputs were stepped through the various multiple choices to determine the effects of uncertainty these inputs possess.

Scenario Analysis

Following the sensitivity analysis, a scenario analysis was employed to simultaneously investigate variation in adoption outcomes related to changes across all the low-confidence variables. The scenarios are framed as best-case (which is an optimistic response to the low confidence inputs), expected-case (which is the base case) and worst-case (which is a pessimistic response to the low confidence inputs.) The base case was duplicated seven times to model these scenarios, one for each low-confidence input. The low-confidence inputs were then stepped through each iteration of the multiple-choice inputs of the model. Each input had between five and eight multiple-choice options. The ADOPT variables for this analysis are illustrated in table 5. The low confidence inputs in table 5 changed in each scenario to how I envision the technology to perform at the given technology performance levels, where technology performance is defined as methane mitigation relative to costs.

Table 5 - Scenario Analysis Composition

	ADOPT Input (question number and name)	**Technology Performance**		
		Low	**Medium**	**High**
Machine 1	7. Trialing Ease	Moderately trialable	Easily trialable	Very easily trialable
	8. Practice Complexity	Difficult to evaluate	Moderately difficult to evaluate	Slight difficult to evaluate
	14. Upfront Costs	Moderate initial investment	Minor initial investment	No initial investment
	16. Profit benefit in years used	Moderate profit disadvantage	Small profit disadvantage	Moderate profit advantage
	17. Profit benefit in future	Moderate profit disadvantage	Neutral profit advantage	Moderate profit advantage
	21. Risk	Small increase in risk	No increase in risk	Moderate reduction in risk
	22. Ease and Convenience	Moderate decrease in convenience	Small decrease in convenience	No change in convenience

Machine 2	7 Trialing Ease	Cannot trial	Difficult to trial	Moderately difficult to trial
	8 Practice Complexity	Difficult to evaluate	Moderately difficult to evaluate	Slightly difficult to evaluate
	14 Upfront Costs	Very large initial investment	Large initial investment	Large initial investment
	16 Profit benefit in years used	Moderate profit disadvantage	Small profit disadvantage	Small profit advantage
	17 Profit benefit in future	Moderate profit disadvantage	Neutral profit advantage	Small profit advantage
	21 Risk	Moderate increase in risk	Small increase in risk	No increase in risk
	22 Ease and Convenience	Large decrease in convenience	Moderate decrease in convenience	Small decrease in convenience

2.4 Results

2.4.1 Expert Consultation Results

The expert consultation was a valuable test of approaches for the following farmer focus groups. Participants outlined that the ADOPT input questions were hard to interpret, and there were inconsistencies in some responses. The inconsistency in interpretation stemmed from the wording of the ADOPT questions. When the underlying questions were adapted to incorporate IPSF, minimal changes were made to preserve the meaning of the questions. An example of such changes was changing 'the technology' to 'in-paddock smart-feeders.' The contextualised version of the ADOPT questions can be found in appendix D. This negligible difference informed the decision to move away from the ADOPT questions for the farmer-facing focus groups and focus more on the characteristics of the machines that would indirectly address the inputs of the ADOPT model. In addition, the characteristics in the ranking tasks for the focus groups would be more specific to reduce ambiguity around interpretation.

In the ranking task, the expert participants said that the animal-to-machine ratio was the most important characteristic, followed by refill frequency, the ability to check the machines remotely and the amount of damage to paddocks. While a maintenance contract, device ownership structure and where the machine was manufactured was relatively less important in descending order.

In the surveys for population-specific ADOPT questions, the expert's answers were generally highly concentrated, and following discussions led to a group consensus. This allows these inputs to be used in the ADOPT model with confidence.

There was less consensus in the surveys for the hypothetical IPSF scenarios due to the variation in interpretation. For this reason, the median response in the group was used as the ADOPT input.

2.4.2 Farmer Focus Group Results

Participants in these focus groups had a range of awareness, including knowing the minimum about the technology and the surrounding area to being well informed about the climate change partnership governing biogenic methane, HWEN. Participant knowledge in the lower input focus group ranged from very well-informed but questioning how the technology would fit into the NZ pasture-based system to knowing very little of the technology. In the higher input focus group, there was also a range of knowledge, from no knowledge of inhibitors with little understanding of biogenic methane to informed participants who were acutely in tune with the governing primary-sector climate action partnership HWEN.

Participants were then provided with sufficient information to understand the in-paddock smart-feeders and the methane-inhibiting compounds they would deliver—this information centred around the need to feed inhibitors multiple times daily to maintain efficacy.

During the ranking exercises, participants rated the characteristics according to the results displayed in table 6.

Table 6 Farmer Focus Group Characteristic Ranking Results

Rank	Low Input Focus Group Characteristic	High Input Focus Group Characteristic
1	Additional labour	Data for emissions accounting
2	Animal to machine ratio	Hopper capacity
3	Hopper capacity	Text/email alerts
4	Data for emissions accounting	Additional labour
5	Precision delivery of supplement	Maintenance and support
6	Paddock damage	Reliability
7	Reliability	Precision delivery of supplement
8	Ownership structure	Ownership structure
9	Text/email alerts	Paddock damage
10	Maintenance and support	Animal to machine ratio

2.4.3 Adoption Modelling Results

The results of the expert consultation and farmer focus groups were used in conjunction to select the appropriate ADOPT inputs. The values were collectively changed to best, expected, and worst-case scenarios. The modelled adoption outputs under the best, expected, and worst cases for both hypothetical machines can be observed in figures 4 and 5. Notably, the first hypothetical IPSF has relatively more favourable adoption outcomes than the second IPSF in terms of greater peak adoption level and a lower time-to-peak adoption. That is to say that the smaller and lower-cost machine is expected to be more adoptable than its counterpart.

However, marginal adoption outcome gains are possible by changing three key determinants; initial investment size (from moderate to minor), short-term profitability (from small disadvantage to small advantage) and long-term profitability (from small disadvantage to small advantage.) Implementing these changes increases projected adoption from 3% after twelve years to 44% after nine years. Marginally changing the financial performance of the innovation inside the ADOPT model illustrates the model's sensitivity to financial performance. The sensitivity to financial performance is problematic in this application as the costs and benefits are not sufficiently understood. This lack of information leads to a shift of emphasis in the farmer focus away from the ADOPT questions towards exploring the characteristics which underpin them.

While there were no unexpected relationships, it was apparent that there is not one factor individually responsible for adoption outcomes. This reinforced the idea of conducting a scenario analysis to augment individual sensitivities. The scenarios utilised the two hypothetical scenarios from the focus groups, with some adaptions to incorporate three levels of technological performance. The three levels of performance were low, medium, and high. The medium technological performance could also be defined as realistic performance, while the low and high performances are akin to worst-case and best-case performance. Notably, best-case performance is relatively unlikely, given the current sentiment about the approach.

The combination of faster and higher adoption rates (figure 4 and figure 5) indicates that machine one is more adoptable than machine two. This is likely because it is easier to trial while also being easier and more convenient. Both were shown to be adoption outcome determinants for this technology in the sensitivity analysis (alongside environmental performance, which is constant for both machines.) In figure 5, machine one reaches peak adoption faster than machine two in all technology performance cases.

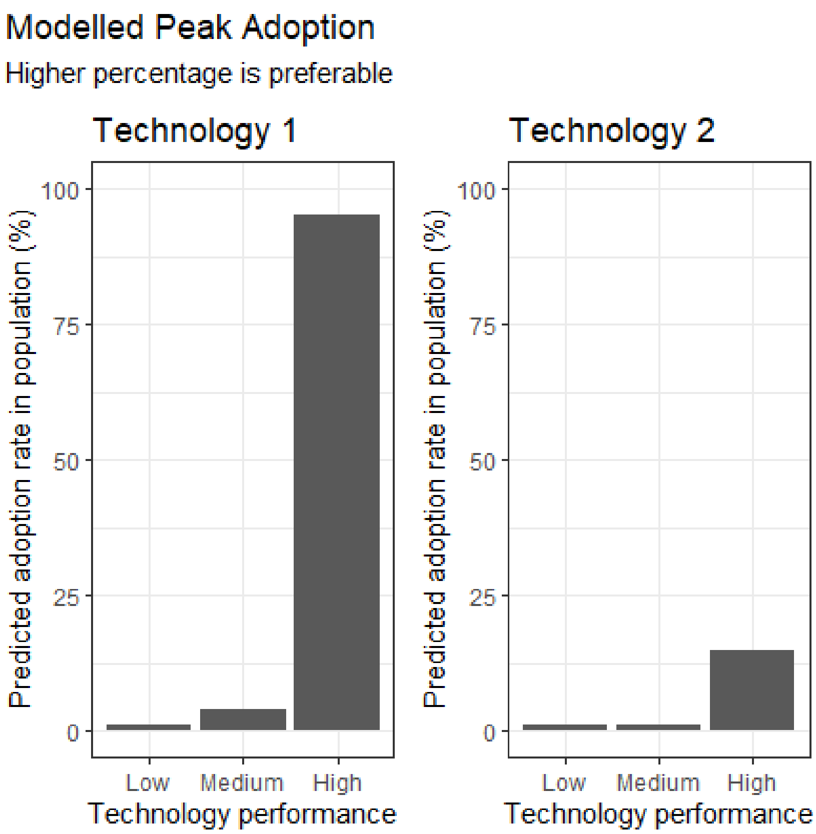


Figure 4 Scenario Analysis Adoption Rates From Focus Groups

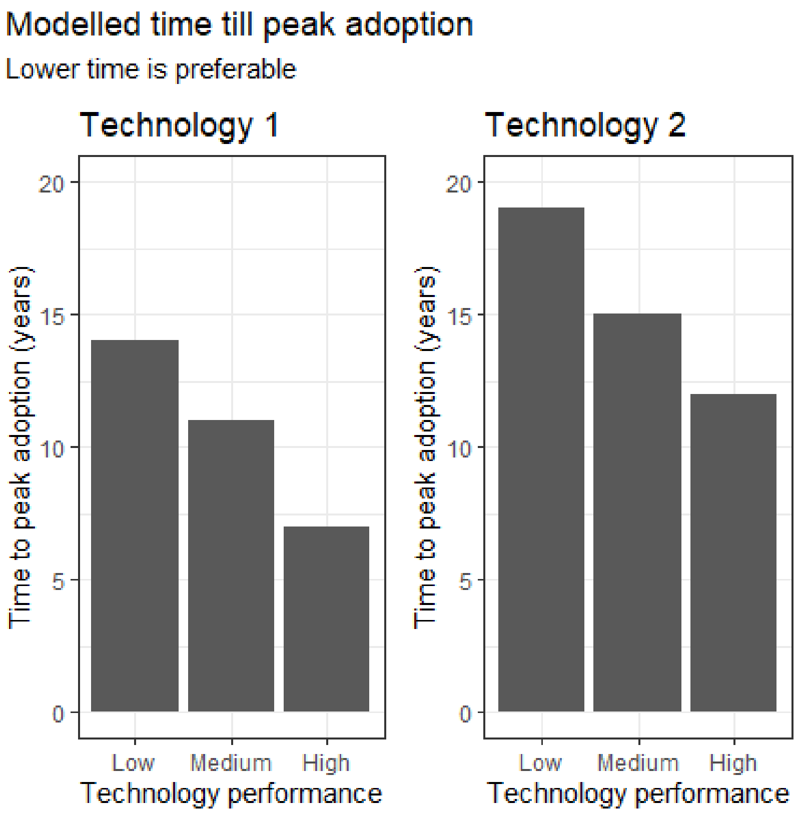


Figure 5 Scenario Analysis Time to Peak Adoption From Focus Groups

Table 7 - Low Confidence ADOPT Inputs

Low Confidence Input	**Definition**	**Corresponding Table for Sensitivity Analysis outputs**
Trialling ease	How easy is it to trial the technology on your own farm	8
Practice complexity	How difficult is it to learn how to use the technology	9
Upfront costs	How much is the initial outlay of the approach	10
Profit benefits in the years used	How does adoption effect profitability while the technology is being used	11
Profit benefits in the future after use	How does adoption effect profitability after the technology is no longer used	12
Risk	How does the technology effect a farms overall risk profile	13
Ease and convenience	How easy is it to introduce the technology into a farm	14

Table 7 illustrates the seven low-confidence variables. The results of these analyses can be found in tables 8 through 14, which ultimately show that the major ADOPT variables holding back greater levels if adoption for IPSFs are ‘trialing ease’, ‘practice complexity’, ‘upfront costs & profitability’, ‘risk’ and ‘ease & convenience.’ Additionally, tables 8-14 show which inputs would have the greatest improvement to the model's time to peak adoption and peak adoption level outputs. These barriers to modelled adoption will be further explored in the following discussion.

Table 8 - Trialing Ease Sensitivity Analysis Outputs

	Not trialable	Difficult to trial	Moderately trialable	Easily trialable	Very easily trialable
Time to near peak adoption level (years)	15	14	13	12	11
Peak adoption level (%)	1	1	1	1	1
Time to 50% adoption (years)	6.8	6.3	5.7	5.2	4.7
Most sensitive question (level)	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits
Most sensitive question (time)	Innovation Complexity	Innovation Complexity	Innovation Complexity	Innovation Complexity	Innovation Complexity

Table 9 - Practice Complexity Sensitive Analysis Output

	Very difficult to evaluate effects of use due to complexity	Difficult to evaluate effects of use due to complexity	Moderately difficult to evaluate effects of use due to complexity	Slightly difficult to evaluate effects of use due to complexity	Not at all difficult to evaluate effects of use due to complexity
Time to near peak adoption level (years)	15	14	13	12	11
Peak adoption level (%)	1	1	1	1	1
Time to 50% adoption (years)	6.8	6.3	5.7	5.2	4.7
Most sensitive question (level)	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits	Environmental Costs and Benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable

Table 10 - Upfront Costs Sensitivity Analysis Outputs

	Very large initial investment	Large initial investment	Moderate initial investment	Minior initial investment	No investment
Time to near peak adoption level (years)	15	14	13	13	13
Peak adoption level (%)	1	1	1	2	2
Time to 50% adoption (years)	6.5	6.1	5.7	5.7	5.7
Most sensitive question (level)	Environmental costs and benefits	Environmental costs and benefits	Environmental costs and benefits	Environmental costs and benefits	Environmental costs and benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable

Table 11 - Profit Benefit in the Years Used Scenario Analysis Output

	Large disadvantage	Moderate disadvantage	Small disadvantage	No disadvantage	Small advantage	Moderate advantage	Large advantage	Very large advantage
Time to near peak adoption level (years)	14	13	13	13	13	12	12	12
Peak adoption level (%)	1	1	1	2	4	7	14	26
Time to 50% adoption (years)	5.9	5.8	5.7	5.6	5.6	5.5	5.4	5.3
Most sensitive question (level)	Environ - mental costs and benefits	Environ - - mental costs and benefits	Environ - mental costs and benefits	Environ - mental costs and benefits	Environ - mental costs and benefits	Environ - mental costs and benefits	Environ - mental costs and benefits	Environ - mental costs and benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable

Table 12 - Profit Benefit in the Future After Use Sensitivity Analysis Output

	Large disadvantage	Moderate disadvantage	Small disadvantage	No disadvantage	Small advantage	Moderate advantage	Large advantage	Very large advantage
Time to near peak adoption level (years)	13	13	13	13	13	12	12	12
Peak adoption level (%)	1	1	2	3	5	9	16	28
Time to 50% adoption (years)	5.8	5.7	5.7	5.6	5.5	5.4	5.3	5.3
Most sensitive question (level)	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable

Table 13 - Net Risk Exposure Sensivity Analysis Output

	Large increase	Moderate increase	Small increase	No increase	Small reduction	Moderate reduction	Large reduction	Very large reduction
Time to near peak adoption level (years)	14	14	13	13	13	13	12	12
Peak adoption level (%)	1	1	1	1	2	3	6	13
Time to 50% adoption (years)	6	5.9	5.8	5.7	5.6	5.6	5.5	5.4
Most sensitive question (level)	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable

Table 14 - Ease and Convenience Sensitivity Analysis Output

	Large decrease	Moderate decrease	Small decrease	No change	Small increase	Moderate increase	Large increase	Very large increase
Time to near peak adoption level (years)	13	13	13	13	13	13	12	12
Peak adoption level (%)	1	1	1	2	3	6	10	20
Time to 50% adoption (years)	5.9	5.8	5.7	5.7	5.6	5.5	5.4	5.3
Most sensitive question (level)	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits	Environ - mental Costs and benefits
Most sensitive question (time)	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable	Trialable

2.5 Discussion

2.5.1 ADOPT barriers to adoption

Trialing Ease

The first hypothetical machine has favourable trialability due to its ability to be rented from a company based in NZ. Given that a farmer has the appropriate machinery to refill and move the trailers (such as a tractor and Light Utility Vehicle – LUV), they would be relatively low cost to trial. Transport and feed costs would be involved, but they would be relatively small. The manufacturer of machine one could improve trialability by subsidising trials of the machines, discounting costs for a trial period, or increasing demonstration presence at industry events.

Machine two is only available for purchase with a fixed-price maintenance contract from an international company, which means it is impossible to trial the machine in NZ. In the best-case scenario, machine two would be made available through feed suppliers or agricultural machinery retailers, mitigating trialability challenges.

Practice Complexity

Technological performance is measured via the data gathered from the machine. Unfortunately, there is no way to directly access the data via the machine, requiring an internet connection to do so remotely. Depending on location and the farmer's technical ability, Internet and technical requirements may be problematic. In both scenarios, practice complexity follows the same trend, difficult to evaluate, moderately difficult to evaluate and slightly difficult to evaluate (from low technological performance to high technological performance.) Upfront Costs and Profitability

There are two questions concerning profitability in the ADOPT model, one in the short term and one in the long term. Machine one has minor upfront costs in the medium performance case for; the feed, inhibitor, and a LUV to move the machine. While for machine two at the same performance level, there is a large upfront cost due to the capital expenditure associated with purchasing it. These costs then flow through into the profitability for the two machines. While both machines have a moderate profit disadvantage, machine two's profit curve is steeper due to the sizable capital expenditure and how interest and depreciation would influence financial performance. Short-term profitability, therefore, is slightly higher for machine one in the high-performance category. This reasoning continues in the short- and long-term profitability questions, in which the answers are consistent for each machine's two time horizons.

Risk

The sixth low confidence ADOPT input regards the risk of the technology, which varies significantly across these machines. Machine one is manufactured domestically and leased. Machine two is manufactured overseas and is available via purchase only. International trade means there are additional risks for machine two in the form of interest rate and exchange rate relative to machine one. Another risk both manufacturers would face is the supply of supplement and inhibitor, which may also introduce exchange rate risk due to its overseas manufacturing. International versus domestic availability for support is another distinction between the two machines. Any time the machines are not working due to breakdowns or malfunctions will have significant opportunity costs regarding the value of forgone methane abatement. Hence any delays arising from international spare parts and support would increase the risk of machine two relative to machine one.

It is essential to consider that the effective use of either of these machines will reduce the quantity of methane emissions for dairy farmers and reduce the risk surrounding methane pricing. Holistically, machine one has a more favourable risk exposure than machine two. In the medium level of technical performance, machine one experiences no net change in risk while machine two experiences a small increase in risk.

Ease and Convenience

The final low-confidence ADOPT input is ease and convenience. The key considerations are the machine size; machine two is noticeably bigger than machine one. This size difference is why machine one can be towed by a LUV and machine two cannot. Both machines are solar-powered and log data to the cloud, so they do not require recharging or manual computer interaction. However, they do require refilling. The frequency with which the trailers need refilling is relatively unknown. This uncertainty depends on the quantity of food required to entice animal interaction and the frequency with which the inhibitor is delivered. It is assumed that machine two needs refilling less often, given that it has a bigger hopper. Future animal trials will be beneficial in gaining an understanding of this area.

2.5.2 Costs and Benefits of Adoption

Participants initially expressed a desire to utilise existing infrastructure already on their farms, such as in-shed feeding. However, this approach has the following flaws;

- In-shed feeding is limited to when cows are milked, at most twice a day but may be less depending on a farm's milking interval.
- Outside of the milking season, there would be no opportunity to deliver the inhibitor.
- Delivering the inhibitor at this frequency in a pasture-based system has been shown to have negligible mitigation potential (Muetzel et al. 2019).

Participants also raised various concerns across regions and farm systems when discussing adopting smart-feeders as a methane delivery mechanism. The main concern regarded the cost of technology in both money and time. It was difficult to provide participants with a picture of costs and benefits due to no commercially available inhibitors, nor are they legislated to be used in NZ. However, 3-NOP (commercial name of Bovaer, soon to be produced by DSM in Scotland (DSM 2021a))) has been given regulatory approval in the European Union, Chile and Brazil (DSM 2021c, 2021b).

Further, it is uncertain how many animals each machine could service with the precision required for methane inhibitor delivery. In real terms, participants could not envision how many IPSFs they would require on their farm. The difference in both time and money costs associated with running one, two, or three or more IPSFs is significant and therefore made it difficult for participants to comment on some aspects of adoption. Regardless of how these uncertain costs culminate, the benefit of adopting the technology is in the value of mitigated methane emissions once an emissions charge becomes legislated.

Part of the costs of adopting IPSFs is additional labour, which was the cost participants were most concerned about. This cost comes from moving and refilling the machines manually. The time required to do these tasks would depend on the farm, terrain, time of year, and the number of machines on the farm. Moving the machines would be significantly more time-consuming and costly if animals were in more than one break per day as it would require moving more often. Refilling the hopper when empty is currently a precarious process as the hoppers do not accept full bags of food in commercially available sizes. However, there is potential for this cost to be minimised if the innovation becomes mainstream, as suppliers may stock bags of supplements of appropriate size with the inhibitor already mixed in. Farmers estimated it would take six hours a week to move the machine, refill it, and conduct any troubleshooting. Participants saw this as a prohibitive time commitment as they were already time-poor.

Another concern raised by farmer focus group participants is the need for adoption to be cost-neutral. Additionally, they said that it needs to be observably cost-neutral such that in the event of any rebates, subsidies, or other incentives, farmers can determine economic viability without complex analysis. Farmers raised the concern that any financial venture needed to be profitable or be mandated for widespread adoption. If there are aspects participants could not conceptualise, then the project's financial performance would be warped, ultimately affecting the adoption decision.

A further implication identified by participants was the potential transition away from NZ's pasture-based dairy system. NZ is among a few pasture-based dairy-producing countries (Moscovici Joubran et al. 2021). Within the NZ dairy sector, farmers fit into one of five farm systems depending on how much feed they import (see table 1 on page 2.) If this technology were universally adopted, there would be a near paradigm shift as the supplement level would increase for many farmers, shifting adopters into a higher farm system. Increasing supplements unilaterally would lead to redefined farm systems and potentially erode NZ's image of a pasture-based system.

An additional cost of concern to farmers was paddock damage stemming from high traffic in one area, i.e. around the smart-feeder (Laurenson et al. 2017). One participant said that using smart feeders would prevent grass from growing in the area it was located for the entire season. Some participants were less concerned, and others were unconcerned by paddock damage caused by smart feeder use. Concerns related to paddock damage may relate to soil type and the subsequent ability of pasture to return after damage. This discussion led to participants enquiring about making smart-feeders self-propelled via either a motor or a winch to mitigate paddock damage. These comments oppose Pitman's findings; farmers tend to overestimate the costs of paddock damage due to being readily observable and front-of-mind for farmers (Pitman 2021).

Participants explained that choosing how they would deploy the smart feeders and having the flexibility to adapt to their different farm environments was vital. This flexibility was further explored to include different parts of the year, such as winter grazing (either on or off the dairy platform.) A potential fringe benefit arose during discussions: the ability to efficiently deliver other supplements/minerals as needed. Aside from this, the main benefit underpinning the endeavour is the methane mitigation associated with delivering methane inhibitors.

2.5.3 ADOPT Model Reflection

The ADOPT model (Kuehne et al. 2017) was chosen after reviewing numerous adoption diffusion models due to its numerical output and agriculture-specific approach.

During the expert consultation, participants indicated that several ADOPT input questions were difficult to interpret even after contextualisation. In the future, the questions could be further contextualised. Rather than discussing the actual questions, the performance relative to the questions could be discussed and the input selections made after the fact by the researcher. This would be an extension of how the ambiguity was addressed in this instance.

As noted in the sensitivity analysis section, the ADOPT model is susceptible to environmental performance, financial performance and trialability. While it is reasonable to make assumptions about the trialability of innovation such as in-paddock smart-feeders as methane inhibitor delivery mechanisms, it is more difficult to make assumptions about such machines' environmental and financial performance. This is because IPSFs are early in their lifecycle, and there is insufficient information regarding several relative costs (methane price, inhibitor price and smart-feeder price) to make accurate assumptions. Additionally, there is little information about the expected level of methane mitigation. This comes from relatively few trials of pulse dosing (i.e. relatively few inhibitor deliveries per day) with an interval between delivery and feed intake, replicating NZ's pasture-based systems.

After conducting the sensitivity analysis, it was clear that the uncertainty surrounding the ADOPT inputs led to significant variation in adoptability. That is not to say that the ADOPT model was not valuable; key factors of adoption diffusion for this approach were identified. The value of the discussions held while evaluating the ADOPT inputs is synonymous with research indicating that models such as the ADOPT model have a value outside of the numbers they generate due to the discussions held when determining their inputs (Montes de Oca Munguia, Pannell, and Llewellyn 2020). Additionally, it was evident that the use of ADOPT would be better suited to a more mature technology, as inputs could be answered with greater confidence.

2.5.4 Limitations

The farmer focus groups utilised in this chapter had fewer attendees than expected, which diminished the robustness of the findings. In addition, there were some areas where specific performance information could not be provided to participants as the information was not currently available.

2.5.5 Future Research

To improve this area of research, a better understanding of the costs and benefits of using IPSFs would allow better modelling of adoption outcomes. Additionally, once the economics of IPSFs are understood larger focus groups could be repeated with the costs and benefits in real terms.

2.6 Conclusion

This chapter explored likely adoption outcomes of in-paddock smart-feeders as methane inhibitor delivery devices using a combination of focus groups, farm system expert consultation, and ADOPT. Output from the focus groups and expert consultation were used to inform use of the ADOPT model. The technology's adoption outcomes are predicted to be relatively poor, unless methane mitigation levels are sufficiently high and estimated financial impacts are both understood and favourable (see figures 4 and 5). These conditions come from the scenario analysis of the model in this approach.

The sensitivity analysis employed in this chapter showed that barriers to higher levels of adoption were trialability, ease and convenience and environmental performance. Which can largely be addressed with improvements by the manufacturers of both smart-feeders and methane inhibitors.

When viewing the innovation through a lens of technological performance, i.e. scenario analysis, it is evident that adoption outcomes are poor in realistic and pessimistic cases. However, adoption outcomes are favourable primarily due to favourable economics in an optimistic technological performance setting. A further aspect of the scenario analysis showed a preference for a smaller machine that required filling more often but was easier to use. Notably, this hypothetical machine was a rental as opposed to the purchased alternative.

Chapter 3: Economic Modelling

3.1 Introduction

This chapter aims to describe the economic performance of in-paddock smart-feeders (IPSF) and the situations in which they perform most favourably. Chapter two of this thesis outlines the need for favourable economic performance to achieve widespread adoption of IPSF through the New Zealand (NZ) dairy farming population. As inhibitors and IPSF suitable for their delivery are not currently available, a modelling approach to evaluate the potential economic impact of using this technology on farm is used. This approach has the flexibility that once pricing and performance information becomes available, the model can estimate any changes to economic performance. Additionally, smart-feeder and inhibitor manufacturers can employ the findings of this chapter to inform future research and development.

The economic viability of IPSF as an inhibitor delivery mechanism will be evaluated through three steps in this chapter

- The development of a farm-level cost-effectiveness model to predict the breakeven methane price for the approach
- Evaluation of the model using a sensitivity analysis
- Determining the conditions required for favourable economic performance via scenario analysis.

In the chapter, I will summarise sixty-two model outputs between the scenario and sensitivity analysis to ensure the model works as expected and determine the conditions required for favourable economic performance. It is expected that the economic performance of the approach will not be favourable in most situations due to large costs associated with the additional feed and labour required by the approach relative to the value of any abated methane emissions.

3.2 Literature Review

3.2.1 Analysis Design

This chapter first develops a cost-effectiveness model of IPSF economic performance. The model looks beyond profitability and towards pasture utilisation and imported feed to look at how farm systems might change by adopting IPSF, avoiding the narrow framing discussed by Kahneman (2003). The model is then evaluated with scenario and sensitivity analyses. The model is designed with the flexibility required to address uncertainty around future policy decisions (Dudley et al. 2019) and allow users to align their farm systems with those required by IPSF.

In this situation, the economic problem is whether IPSFs are an economical way to reduce methane emissions, and if so, what conditions are required to maximise their economic performance. Cost-effectiveness models address this economic problem by minimising costs while achieving environmental outcomes (Pacini et al. 2015). Farm-level cost-effectiveness models are well documented; previous examples can be found in Cuttle et al., who modelled the cost-effectiveness of farm-level water pollution in England and Wales (Cuttle et al. 2016). While Pacini et al. modelled farm-level cost-effectiveness of environmental performance under the European common agricultural policy (Pacini et al. 2015). Further, Blanco- Gutiérrez et al model farm and basin level cost-effectiveness of groundwater conservation in Spain (Blanco-Gutiérrez, Varela-Ortega, and Flichman 2011).

Additionally, a literature review of the cost-effectiveness of agricultural greenhouse gas mitigation measures by MacLeod et al. covers 65 studies and 181 activities (MacLeod et al. 2015). Some of 181 activities covered in MacLeod et al relate to methane emissions in the dairy industry such as cattle breeding and mobile machinery (MacLeod et al. 2015). The literature consistently shows that cost-effectiveness modelling at the farm level is a common and effective way to evaluate a given action, with a specific note to environmental outcomes. Therefore, a cost-effectiveness model is suitable for evaluating IPSFs to mitigate methane emissions in pasture-based dairy.

Evaluation of the model relies on sensitivity and scenario analyses (Pannell 1997). Previous studies of farm-level analyses used numerous iterations of the model with step changes of one variable holding another constant (Beukes et al. 2013). A base case can also be a reference point (Daigneault, Eppink, and Lee 2017).

3.2.2 Approach specific costs

The previous section outlines the use of average farm financial data in the Economic Farm Survey (DairyNZ Economics Group 2021), which includes cost figures. Four additional costs are associated with using IPSF as a methane inhibitor delivery system. The costs are; smart-feeder costs, labour costs, methane inhibitor costs, and additional supplement costs.

The first cost associated with IPSF is the rental or purchase of the feeder itself. No smart-feeders currently on the market are suitable for this approach. However, there are some smart-feeders that, with some adaptions, may be suitable. The lack of market offerings requires an estimation of the price of these machines based on those that may be adaptable for this approach. The first option is only available for rental, with no opportunity for purchase, and therefore smart-feeder costs are taken explicitly as rental costs in the model. This machine is estimated to cost approximately NZD$1,000/month (E. Minnee, personal communication, 11 October 2022). While there is no option to purchase this model, a second smart-feeder is available to researchers for approximately USD$100,000. The manufacturer of this second machine intends to make a producer version of this researcher machine available to global markets in the future (K. Pederson, personal communication, 27 April 2022).

The combination of favourable cost modelling (not needing to define a discount rate, asset life, or depreciation method due to rental rather than ownership) and closeness to the market led to the decision to utilise the machine available for rental. Smart-feeder costs scale directly with the number of machines required on a farm. The number of smart-feeders required relates to the number of animals a machine can successfully feed and the number of animals on a given farm. This model makes two assumptions about smart-feeders; firstly, smart-feeder rental costs have no economies of scale. Secondly, farms have a small number of herds for each machine, so there is always an opportunity for cows to interact with the machine. These assumptions infer that farmers can optimise their systems such that herd size equals the number of cows a machine can service.

The second cost associated with IPSF is labour costs. While smart-feeders deliver supplements automatically, they still require manual refilling and moving so that they are always in the same place as the animals. These human interventions mean there are additional labour requirements on the farm. The focus groups in chapter two of this thesis determine the required hours. The labour required to move and refill the smart feeders is estimated to be a minimum of three hours/week/machine. At the same time, the labour cost is taken from NZ Dairy Statistics 2020-21 (DairyNZ 2022b) to be NZD$55,000 per FTE.

The third cost of IPSFs is discussed in depth in chapter one but regards the methane inhibiting compounds cost. Such compounds are experiencing a range of research and development to get them market-ready at scale, even though they are not currently available. The cost of 3-NOP is estimated to be one European cent per litre of milk (E., Kebreab, personal communication, 10 June 2022.) A series of conversions were conducted to estimate the cost of 3-NOP in NZD. The first conversion is from Euros to NZD based on the expected exchange rate at the time of writing is approximately 1 Euro:1.6 NZD (XE Currency Converter 2022a). The second conversion is from litres of milk to kilograms of milksolids using a conversion rate of 11.5 litres of milk:1kg milksolids (Newman 2015). With these two conversions to the estimated price from the personal communication, the price of 3-NOP in NZD per kg of milksolids can be estimated and then applied to milk production to determine the cost per cow per year.

The alternative methane inhibitor is Asparagopsis which is not commercially farmed, and therefore the seaweed used in trials is wild-caught at an estimated price of NZ$224 per kg (Cotter et al. 2015). However, this could be reduced to NZ$5.6/kg if it was commercially farmed (Cotter et al. 2015). Transforming this price into a per cow cost can be achieved by converting from AUD: NZD at the time of writing; the conversion rate is 1.12:1 (XE Currency Converter 2022b) and then applying a dietary inclusion rate of 0.5% (Black et al. 2021) to the intake of the animal.

Some farmers will require additional supplement due to low or non-current supplement use, which is the fourth cost associated with IPSF. Conversely, other farmers would not need additional supplement due to fundamental farm system differences. Such differences create the need for pasture substitution based on current and projected supplement levels, as defined in the following sections. The small quantity of inhibitor delivered in one instance means they do not act as a replacement to feed and require a supplement to act as a delivery mechanism. If the inhibitor used is Asparagopsis, it will account for 0.05% of the diet, and 3-NOP would account for less than a teaspoon a day (Black et al. 2021; Muetzel et al. 2019).

It is assumed that the market would eventually provide feed pellets with the inhibitor included, given that the technology was viable. The contra to buying methane-inhibiting pellets means farmers would need to store large amounts of inhibitors on the farm, which may have regulatory impacts due to the current controlled nature of inhibitors. In addition, farmers would require infrastructure to mix inhibitors into feed with the potential of inconsistent doses or stratification of feed and inhibitor in the hopper. This means that the feed price considered for this approach must be consistent with that of high-quality pelleted feed, such as distiller gains. Such pellets at the time of writing are between NZD$650-$850/tonne, and before the COVID-19 pandemic, between NZ$150-$200/tonne less (J. Swap Contractors, personal communication 15 August 2022). It is estimated that a minimum of 2kg of supplement per cow per day is needed to deliver methane inhibitors in this manner (E. Minnee, personal communication 14 September 2022).

3.3 Methodology

The baseline model uses an average farm in the Waikato region with the following characteristics: 109 ha, 310 cows, 121,500 kg/ms, no supplement substitution, $800/t of premium supplement, 1kg daily allocation of supplement, feeding 3-NOP with assumed methane reduction of 30%, smart-feeder rental of $1,000/month, FTE cost of $61,000 and labour requirements of 4 hours/machine/week. The following subsections will then explain where the average data comes from, how it is transformed and what the outputs mean.

3.3.1 Farm Financials

The model utilises data from the New Zealand Economic Farm Survey (DairyNZ Economics Group 2021). The Economic Farm Survey draws on data from DairyBase, a benchmarking tool to offer farmers comparability to their peers (DairyNZ n.d.-b). The New Zealand Economic Farm Survey includes an owner-operator regional profitability statement (table 7.1 2020/2021 Season Economic Farm Survey.) This table offers average income and expenditure across a region, expressed in cents on a milksolids basis, alongside the physical descriptors of such an average farm. Using a milk solids basis is critical as it allows the model to scale values up based on the production levels of a farm.

The dataset from the Economic Survey used for this model is the owner-operator by region. This business type was selected due to Owner-operated farms having a more straightforward decision-making process and more control over their decisions while representing most NZ dairy farms (Payne et al. 2007). Secondly, the region was chosen rather than the farm system because a consequence of using smart-feeders in this application is that supplement use tends to increase. An increase in supplement use often leads to a high farm system classification leading to inconsistent model output analysis.

Regardless of the farm system or region, farmers must address their methane emissions. Farmers will either pay the rate dictated by the ETS with a fee discount or a methane-specific amount determined by HWEN. Please refer to chapter 1 for more information on biogenic methane pricing. During this chapter, I will state the methane price in two ways, in terms of \$/kg ch4, or \$/t/co2e (dollars per kilogramme of methane, or dollars per tonne of carbon dioxide equivalent.) The \$/kg/ch4 refers to the recommendation of the HWEN proposal of a charge of no more than eleven cents per kilogram, plus incentives of up to twenty times the charge. In contrast, the \$/t/co2e refers to the price under the ETS, which increased from ~\$18 to ~\$70 over the last five years and at the end of 2022 is between NZD \$80-85/t co2e (Commtrade 2022; Leining 2022).

3.3.2 Data import and transformation

The data source is table 7.1 of the New Zealand Economic Farm Survey (DairyNZ Economics Group 2021). This table contains regional average income statements of owner-operator dairy farms on a production (milksolids) basis. After downloading the data, costs not relevant to this approach are grouped into 'O*ther Expenses'* to simplify and increase the readability of the financial statements. Other expenses include; animal health, breeding & herd improvement, farm dairy, electricity, stock grazing, support block lease, fertiliser, irrigation, regrassing, weed & pest, freight & general, insurance, ACC, and rates. The remaining costs are; wages, net feed (made, purchased, cropped), vehicles & fuel, repairs & maintenance, and other expenses. Adjustments are simplified by taking the net value rather than the individual components, as the components are unchanged by adopting IPSFs.

3.3.3 Data scale up

User inputs inform the model of which data set to use and then generate average farm data for their region and production level. The regions in this dataset are; Northland, Waikato, Bay of Plenty, Taranaki, Lower North Island, West Coast-Tasman, Marlborough-Canterbury, or Otago-Southland. Figure 6 illustrates these regions via a map of NZ's dairy farming regions. Once the user has selected their region, average farm financials are scaled according to their production levels to estimate appropriate farm financials in dollar terms. Profitability metrics are then introduced to summarise the financials: dairy gross farm revenue, dairy operating expenses, dairy operating profit, and dairy profit margin.

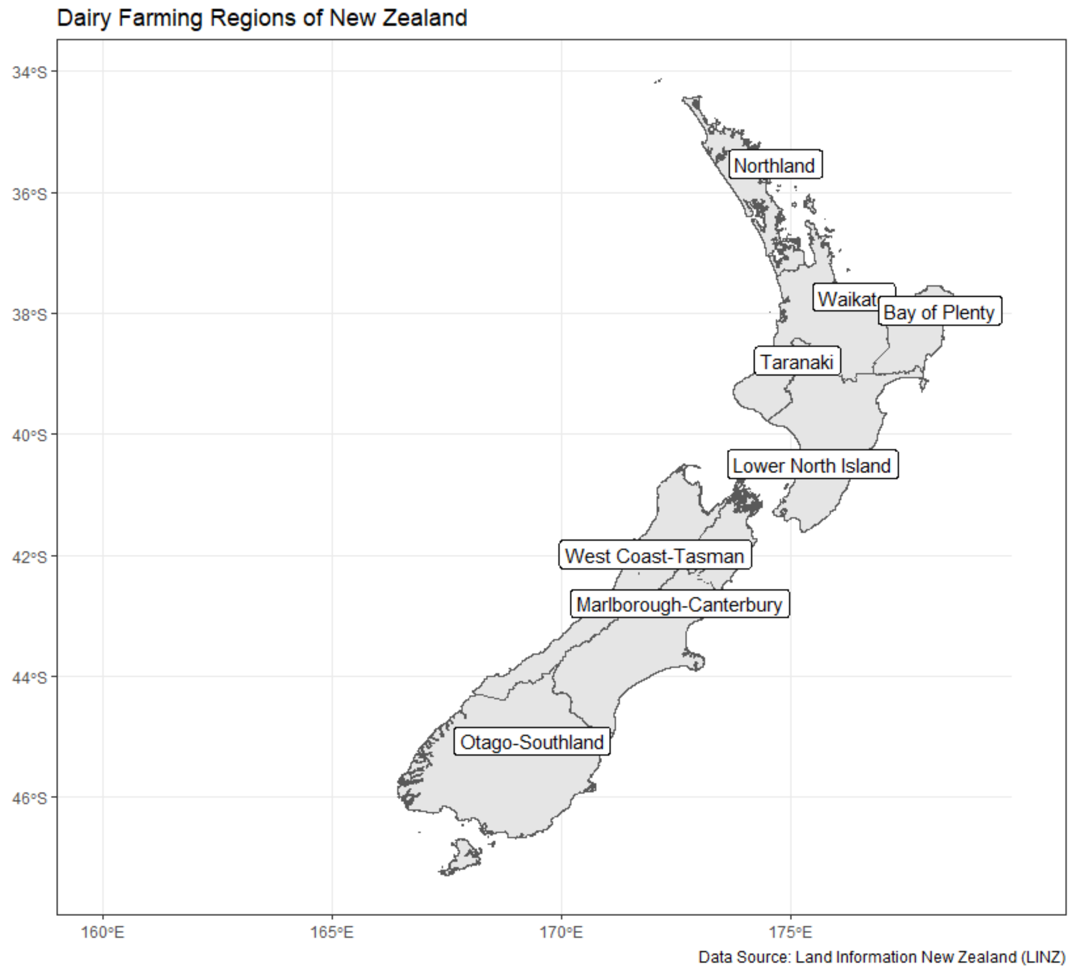


Figure 6 - Dairy Farming Regions of New Zealand

3.3.4 Sub-models

The following subsections will document the model's components concerning where the underlying data comes from and how it is treated to estimate the breakeven methane price ultimately. You can find the excel workbook model on my GitHub[1] alongside the R code to generate the map in figure 6.

[1] If the embedded link doesn't work you can use the following URL instead; tinyurl.com/z2uyd2fs or alternatively search for BenMarmont on GitHub and navigate to the 'Masters-Thesis' repository.

Smart-Feeder Count

The number of smart-feeders required on a given farm depends on two factors, the number of animals on the farm and the number of animals a smart-feeder can provide sufficient delivery frequency to (referred to as the animal-to-machine ratio.) The number of smart-feeders required comes from dividing the number of animals by the animal-to-machine ratio and then rounding the number of machines up to a whole number. The number of smart-feeders scales the labour and the holistic cost of smart-feeders to a farm. The animal-to-machine ratio requires trials once market-ready machines are available to have confidence in the value. The default input for the model is two hundred cows: machine. The number of IPSFs required on a given farm can be determined with equation 1.

(Eq. 1) $$Smart\ Feeder\ Count\ (rounded\ up\ to\ whole\ number) = \frac{herd\ size}{animal: machine}$$

Smart-Feeder Cost (Machine)

I estimate the cost of smart-feeders capable of the precision required in this approach because no such machine is currently on the market. Then multiply the cost per machine in terms of rental and maintenance by the number of machines required by a given farm and the length of time smart-feeders are to be used. The farm-level income statement adds the total cost of smart-feeders as a machine to 'vehicles and fuel'. The cost is estimated to be NZD$1,000 per machine per month (E. Minnee personal communication 11 August 2022). In this instance, there is no maintenance costs, based on the previous personal communication, however, there is the option to introduce it. The smart-feeder machine costs can be calculated with equation 2.

(Eq. 2) $$Smart\ Feeder\ Machine\ Cost = (smart\ feeder\ count * monthly\ rental + smart\ feeder\ count * monthly\ maintenance) * implementation\ period$$

Where:

- *implementation period* refers to the duration in which methane inhibitors are delivered with IPSFs.

Smart-Feeder Cost (Labour)

The total cost of labour to a farm depends on the number of hours required by each machine to move and refill them each week, the number of smart-feeders on the farm and the cost of one FTE. The amount of time each machine requires to be moved and refilled is estimated to be between 3-6 hours per week (E. Minnee personal communication 11 August 2022), and the average cost of an FTE in the industry is NZD$55,000 (DairyNZ 2022b). The total number of hours per week and the machine utilisation period can be compared to an FTE of 2400 hours to determine total labour costs. Labour costs in the income statement are increased by the total labour cost associated with smart-feeders with equation 3.

$$\text{(Eq. 3)}\ Smart\ Feeder\ Labour\ Cost = weekly\ hours\ per\ machine * \$FTE * smart\ feeder\ count * \frac{52}{2400} * implementation\ period$$

Where:

- *$FTE* refers to the cost of an FTE
- *Smart feeder count* is determined in equation 1.

Additional Supplementary Feed Cost

Smart-feeders require high-quality pelleted supplement as a methane inhibitor delivery mechanism. Some farms may already use a high-quality pelleted supplement, while others may not. The modelled use of supplement is noted with and without smart-feeders in the farm system to determine the per-cow annual marginal cost of supplement use. Due to differences in farms supplement use with and without IPSFs there is a potential substitution of supplement between delivery mechanisms, for example, if a high-quality supplement is being fed through in-shed feeding or on a feed pad, this supplement could be diverted to being fed through the IPSFs to reduce the cost of supplement for this farm. Hence supplement substitution is implicit in the model and is a key determinant of total additional supplementary feed costs. The per cow annual marginal cost depends on the cost and quantity of supplement used with and without smart-feeders. The high-quality supplement cost is approximately NZD$750/tonne (J. Swap Contractors, personal communication 15 August 2022). The annual per cow costs are multiplied by the herd size and smart-feeder utilisation period to determine the total marginal supplement cost. The income statement adds total marginal supplement cost to 'Net feed made, purchased and cropped' following equation 4. The supplement required for this approach is estimated to be 2kg per cow per day (E. Minnee, personal communication 14 September 2022).

(Eq. 4) $$Additional\ Supplementary\ Feed\ Cost = \left(\left(daily\ allocation_P * \$premium * \frac{365}{1000}\right) - \left(daily\ allocation_I * \$incumbent * \frac{365}{1000}\right)\right) * implementation\ period$$

Where:

- *daily allocation* refers to the quantity of supplement each cow receives daily in kg of either premium (P) or incumbent (I) supplement
- *\$supplement* refers to the price of either the premium or incumbent supplement.

Milk Response to Additional Supplement

The introduction of supplement into a farm system (or the increased use of supplement in a system) causes an increase in milksolids production called the milksolids response rate, which for this research it was assumed to be 55g MS/kg DM (grams of milksolids per kilogram of Dry Matter) (DairyNZ 2021). The assumed dry matter content of the supplement needed to deliver the inhibitor is 85% (DairyNZ 2021). Multiplying marginal supplement by dry matter content estimates the effect of supplement on milksolids production. This is then scaled up by the number of cows on a farm and added to the baseline milk sales revenue in the income statement in accordance with equation 5.

(Eq. 5) $$Value\ of\ Milk\ Production\ Response\ to\ Additional\ Supplement = additional\ supplement * supplement\ DM\% * milksolid\ response\ to\ supplement * milk\ payout * herd\ size$$

Where:

- *additional supplement* is in terms of kg/cow/per annum

- *supplement DM%* refers to the dry matter percentage in a given supplement, in this case 85% assuming that distillers grains are the chosen supplement
- *milksolid response to supplement* refers to the expected increase in milksolids production associated with increasing supplement use. On commercial farms this tends to be 55g MS/kg DM
- *milk payout* refers to the price farmers received on average from the dairy processors.

Methane Inhibitor Cost

There are currently no methane inhibitors or their pricing on the market. The lack of pricing information leads to the price estimation of 3-NOP and Asparagopsis (the inhibitors used in this model). Conversions to these estimations are needed to generate a total inhibitor cost to a farm. 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 in the income statement following equation 6 for 3-NOP or equation 7 for Asparagopsis.

(Eq. 6) $$Total\ cost\ of\ 3NOP = \$cost * euro{:}nzd * 11.5 * total\ farm\ milksolid\ production * implementation\ period$$

Where:

- *$cost* refers in the price per liter of milk
- *11.5* refers to the conversion of milk to milksolids.

(Eq. 7) $$Total\ cost\ of\ Asparagopsis = \$cost * aud{:}nzd * dietary\ inclusion\ rate * yearly\ DMI * \text{implementation period}$$

Where:

- *$cost* refers to the price per kg
- *Dietary inclusion rate* is taken as 0.5%.

Methane Emission Calculator

Biogenic methane emissions are those emissions from animals such as ruminants and are linked to animal intake. Biogenic methane production can be characterised by 21.6 grams of methane for each kilogram of DMI (21.6gCH_4/kg DM intake), known as an emission factor (Ministry for Primary Industries 2022). Generation of a farm's emission profile is possible using the emission factor and total intake across stock classes, which means that the emissions factor is constant. However, DMI changes across stock classes which is why different stock classes have different emissions. However, the emission factor does not apply when considering calves, as milk consumption does not lead to methane production. Due to different intake levels across stock classes (young, dry and milking), each class must have its unique profile. Establishing a robust emission profile makes it possible to view emission changes by targeting different stock classes with methane inhibitors. Dairy cows have the highest intakes of 15kg/dm/day compared to the 7kg/dm/day of dry cows (DairyNZ 2021). The higher intake means that dairy cows produce relatively more emissions than other stock classes. In order to maximise cost efficiency, the emissions profile will only be considered for lactating dairy cows due to the largest methane mitigation potential. Excluding dry stock means that inhibitors will not be fed all year. Representation of inhibitor delivery duration is achieved by an input with the options of; half of the season, the whole season, half a year, or the whole year. The income statement is expanded to include an environmental performance section containing the total emissions of a farm with and without feeding inhibitors.

Methane Mitigation

The amount of reduced methane comes from an exogenous methane mitigation rate applied to the methane emission profile. The reduction needs to be exogenous due to insufficient data to produce an equation to describe the mitigation potential relative to the dose and frequency of inhibitor delivery. However, there are many trials to inform the chosen mitigation rate. Generally, 3-NOP is accepted to reduce methane emissions in dairy cows by 30-60% (Beauchemin et al. 2020; Hristov and Melgar 2019) in TMR dairy systems where delivery frequency and precision are relatively more manageable than in pasture-based systems. In contrast, the mitigation potential of Asparagopsis is above 90% in the same systems (Beauchemin et al. 2020; Machado et al. 2014; Stefenoni et al. 2021). Please refer to chapter one for more information about methane inhibitor efficacy. The income statement reflects mitigated methane emissions in the environmental performance section.

$$\text{(Eq. 8)}\ Abated\ Methane = \sum_{stock\ class\ i}^{stock\ class\ n}(stock\ class\ cow\ count * stock\ class\ DMI * days\ in\ stock\ class * emissions\ factor * assumed\ mitigation * \%\ of\ delivery\ period\ in\ stock\ class)$$

Where:

- *Summation for stock classes* means that the calculation should be repeated for each stock class the inhibitor is fed to
- *Stock class cow count* refers to the number of animals in a given stock class
- *Stock class DMI* is assumed to be 7kg/day for dry cows and 15kg/day for lactating cows
- *Emissions factor* is assumed to be 21.6g/kg DM, this is consistent across stock classes but emissions do change due to different intake levels
- *Assumed mitigation potential* is a model input and can be specified between 0 and 90% depending on the methane inhibitor used
- *% of delivery period in stock class* refers to how much of the delivery period is experienced by a given stock class.

3.4 Profitability and environmental performance

A comparison of the total costs determines the cost of implementation, which is apportioned over abated methane emissions, resulting in the breakeven methane price. This breakeven price has two components, the explicit emission charge and any implicit incentives (which are not stipulated in the He Waka Eka Noa proposal.) In order to offer a benchmark, two sets of model outputs are offered, one is the model outputs after the implementation of IPSF, and the other is the baseline data without the added costs. The two sets of financials include profitability and non-financial sections (environmental performance and feed composition.) In either case, no emissions charge is introduced due to uncertainty around the form it will take.

Therefore profitability should be viewed with the distinction that there would be a payable emission charge on remaining emissions.

3.5 Sensitivity analysis

A basic sensitivity analysis is utilised to understand some of the uncertainty previously discussed. Additionally, Pannell finds that a simple sensitivity analysis is a good fit for practical decision-making (Pannell 1997). When possible, the range of values in the sensitivity analysis is determined by historical values, i.e. milk price, AUD: NZD, and Euro: NZD. Earlier in the chapter, price components were defined with the most recent publications and literature. These values act as the centre of the range for the sensitivity analysis. For values not previously described, such as the milk price, current prices serve as the midpoint of the analysis. The values examined with the sensitivity analysis were; milk payout, inhibitor price (3-NOP), inhibitor price (Asparagopsis), the exchange rate (EURO: NZD), and exchange rate (AUD: NZD). Ten iterations of the model are recorded as the studied values change, holding others constant.

Further, the default setting was *3-NOP* at a 30% mitigation. However, evaluation of Asparagopsis-specific inputs (AUD: NZD, and the price of Asparagopsis per kg) use Asparagopsis as the inhibitor with a 60% mitigation level. The summary of the sensitivity analysis includes five key model outputs: dairy operating revenue, dairy operating profit, dairy operating profit, operating profit margin, and cost of abatement (both in co2e units and kg/ch4.)

3.6 Scenario analysis

In addition to a sensitivity analysis, a scenario analysis is employed to contextualise the numerous inputs of the model. Twelve scenarios are utilised, framed around three regions and four performance levels. The regions change the financial data that underpin the model, the physical characteristics of the average farm in the region and the level of supplement substitution. While the overall performance pertains to; mitigation level, smart-feeder rental, labour costs, supplement costs, delivery duration and supplement allocation. The three regions examined are Waikato, Canterbury, and Northland, and the performance levels are; poor, expected, best-case, and in-shed only. Including in-shed only is a reference point for an existing delivery method that farmers tend to prefer based on the focus groups in chapter two. The aforementioned performance levels were specified to those in table 17 based upon how I expect the technology to perform given three technology development pathways.

In the in-shed-only delivery scenarios, the assumed methane mitigation level is 5%, which is optimistic. When methane inhibitors are delivered at a low frequency (i.e. twice a day) and include a delay between delivery and feed consumption (to mimic being fed in the shed and walking back to the paddock), has shown to have negligible effects on emissions (Muetzel et al. 2019).

Table 15 - In-shed Feeding Diffusion Rates (data supplied by A. Renwick (personal communication)

Region	**In-shed feed rate**
Northland	24%
Waikato	32%
Bay of Plenty	26%
Taranaki	38%
Lower North Island	29%
West Coast-Tasman	42%
Marlborough-Canterbury	55%
Otago-Southland	58%

In the expected and best-case scenarios, in-shed feeding increases the inhibitor's delivery frequency and therefore does not have any flow effects on costs. For reference, not all farmers have in-shed feeding systems. Approximately a third of

Waikato farmers do, a quarter of Northland farmers do, and half of Canterbury farmers do. Refer to table 15 for complete in-shed feeding system diffusion data supplied by Alan Renwick (A. Renwick, personal communication 29 June 2022).

Table 16 shows the consistent physical characteristics across the scenarios for each region. The table illustrates how intensity and farm size differs by region, which may be a driver of viability in different systems.

Table 16 - Scenario Analysis Region Physical Characteristics

Physical Characteristics	**Waikato**	**Marlborough-Canterbury**	**Northland**
Effective hectares	109	210	110
Peak cows milked	310	780	230
Kg milksolids sold	121,734	362,262	75,423
PAYOUT RECEIVED: $/kg MS sold	$7	$7	$7

Source: DairyNZ Economic Farm Survey 20-21

Table 17 - Scenarios Analysis Input Summary

Scenario	Waikato	Canterbury	Northland	All Regions
Poor	• No in-shed feeding • 15% mitigation*	• No in-shed feeding • 15% mitigation	• No in-shed feeding • 15% mitigation	• Rental $1500/month • 6 hrs/wk @ FTE of $66k • Delivered all year • 2.6kg/day of supp • Supp** cost of $900/t • 3-NOP
Expected	• TAD in-shed • 30% mitigation • 25% supp substitution	• TAD in-shed • 30% mitigation • 50% supp substitution	• TAD in-shed • 30% mitigation • 25% supp substitution	• Rental $1000/month • 4 hrs/wk @ FTE of $61k • Delivered all season • 1.6kg/day of supp • Supp cost of $700/t • 3-NOP
Best case	• OAD in-shed • 90% mitigation	• OAD in-shed • 90% mitigation	• OAD in-shed • 90% mitigation	• Rental $800/month • 3hrs/wk @ FTE of $56k • Delivered all season

	• 50% supp substitution	• 75% supp substitution	• 50% supp substitution	• 0.6kg/day of supp • Supp cost of $500/t • Asparagopsis
In-shed only	• TAD In-shed only • 5% mitigation • 75% supp substitution	• TAD In-shed only • 5% mitigation • 75% supp substitution	• TAD In-shed only • 5% mitigation • 75% supp substitution	• No additional machine or labour costs • 1kg/day of supp • Supp cost of $1000/t • 3-NOP

Note:*mitigation = methane mitigation, and ** supp = supplement

3.7 Results

The following section presents the results of the farm-level cost-effectiveness developed to determine the breakeven price of IPSFs and how this value changes in different farm systems. First, the sensitivity analysis results are presented, followed by the scenario analysis results. In order to offer a reference point for these results, the financials of the average Waikato farm discussed during the methods section are displayed in table 18.

Table 18 Baseline Farm-Level Model Financial Statement

Physical Characteristics	**Baseline**
Region	Waikato
Effective hectares	109
Peak cows milked	310
Stocking rate (cows/ha)	2.84
Kg milksolids sold	121,500
Milksolids sold per hectare	1,115
Milksolids sold per cow	392
PAYOUT RECEIVED: $/kg MS sold	$7.00
Dairy Cash Income ($)	
Milk sales (net of dairy levies)	$850,500
Net livestock sales (sales - purchases)	$57,713
Other dairy cash income	$3,375
Net dairy cash income	$911,588
Cash Working Expenses ($)	
Wages	$74,887
Net feed made, purchased, cropped	$165,568
Vehicles & fuel	$23,795
Repairs & maintenance	$40,951
Methane Inhibitor	$0
Other Expenses	$224,266
Farm Working Expense	$529,467
Adjustments ($)	
Net Adjustments	-$113,620
Surplus	
Cash Operating Surplus	$382,121
Operating Cash and Non-cash	
Dairy Gross Farm Revenue	$911,588
Dairy Operating Expense	$643,087
Dairy Operating Profit	$268,501
Dairy Profit Margin	29.45%

3.7.1 Sensitivity analysis

The sensitivity analysis showed the expected trend for all variables assessed; some had a much smaller impact than others, in line with the research aim of understanding the sensitivities to the breakeven methane price. The first is the milksolids price (the price farmers receive for the milk they produce) which causes revenue, profit and profit margin to increase when production and costs remain constant. Table 19 illustrates the effects of a changing milk price. At the recent milk price of ~$7/kg/ms (DairyNZ Economics Group 2021), the profit margin remains positive, while breakeven costs are higher than the reference value of $2.31/kg/ch4. The reference methane price under HWEN is $2.31/kg/ch4 and is based upon a maximum of charge of $0.11/kg in addition to undefined incentives up to twenty times the charge (He Waka Eka Noa 2022d). As the milk price rises, so does profitability, and the break-even cost falls. At the highest assessed milk price of $12/kg ms, profitability is strong, but the breakeven price does not reach a level low enough to be considered viable. The forecast milk price for the coming season is $8.50-$10kg ms (Fonterra 2022), meaning that IPSF may become more viable on farms than it would at the current milk price.

Secondly, the cost of 3-NOP used is the best estimate of one European cent/litre of milk. The method section (section 3.3) outlays the conversions from this value into the final cost. For this analysis, one European cent is the centre of the assessed values range. This analysis is illustrated in table 20 and shows that as the cost of 3-NOP increases, the cost of abatement rises and profit and profit margin falls. These trends are expected given that methane mitigation is held constant, but the cost of using IPSF is increasing.

Thirdly, table 21 assesses the price of Asparagopsis. In this analysis, I assume Asparagopsis causes a 60% methane mitigation. The maximum price in the range is AUD$200 (Cotter et al. 2015) which stems from the cost of wild-caught seaweed historically used in trials. At the expected price of $5/kg, there is a profit of 0.3%, but profitability decreases as the price increases. It is perceivable that if more than 60% mitigation was possible, then profitability may be possible at higher prices, ceteris paribus. In some trials, Asparagopsis has a mitigation potential greater than 60% (Black et al. 2021). Profitability when using Asparagopsis decreases as the cost increases; however, its profitability decreases slowly as the price increases. Suppose it is not possible to farm Asparagopsis commercially. In that case, it will not be viable to feed wild-caught seaweed due to the prohibitive cost, regardless of whether there was sufficient supply. Conversely, suppose it is possible to purchase Asparagopsis for less than AUD$5/kg. In that case, IPSF will become marginally more viable, Cotter et al. (2015) postulate that the cost of production could be as low as AUD$1.50/kg.

The combination of tables 22 and 23 illustrate that changes in the exchange rate have minimal effect on the cost of abatement and, therefore, the profitability of a farm that has adopted in-paddock smart feeders to deliver methane inhibitors.

Table 19 - Sensitivity to Milksolids Price

	$ kg/MS									
Metric	3	4	5	6	7	8	9	10	11	12
Dairy Operating Revenue	$425,588	$547,088	$668,588	$790,088	$911,588	$1,033,088	$1,154,588	$1,276,088	$1,397,588	$1,519,088
Dairy Operating Expense	$772,968									
Dairy Operating Profit	-$347,381	-$225,881	-$104,381	$17,119	$138,619	$260,119	$381,619	$503,119	$624,619	$746,119
Dairy Profit Margin	-82%	-41%	-16%	2%	15%	25%	33%	39%	45%	49%
Cost of Abatement ($/kg CH4)	12.9	12.4	12.0	11.5	11.0	10.5	10.0	9.6	9.1	8.6
Cost of Abatement ($/t/co2e)	462	444	427	410	393	376	359	341	324	307

Table 20 – Sensitivity to 3-NOP Price (European Cents/Litre of Milk)

	European Cents per Litre of treated Milk									
Metric	0.25	0.5	0.75	1	1.25	1.5	2	3	4	5
Dairy Operating Revenue	911,588									
Dairy Operating Expense	759,187	763,781	768,375	772,968	777,562	782,156	791,343	809,718	828,093	846,467
Dairy Operating Profit	152,401	147,807	143,213	138,619	134,026	129,432	120,245	101,870	83,495	65,120
Dairy Profit Margin	16.7%	16.2%	15.7%	15.2%	14.7%	14.2%	13.2%	11.2%	9.2%	7.1%
Cost of Abatement ($/kg CH4)	$9.5	$10.0	$10.5	$11.0	$11.5	$12.0	$13.0	$15.1	$17.1	$19.1
Cost of Abatement ($/t/co2e)	$338	$357	$375	$393	$411	$429	$466	$538	$611	$683
Note	Assumed Methane Reduction of 30% for 3-NOP									

Table 21 - Sensitivity to Asparagopsis ($AUD per Kilogram)

	$AU/KG									
Metric	2	3	4	4.5	5	5.5	6	7	8	200
Dairy Operating Revenue	911,588									
Dairy Operating Expense	767,943	774,617	781,292	784,629	787,966	791,304	794,641	801,316	807,990	2,089,513
Dairy Operating Profit	143,645	136,970	130,296	126,959	123,621	120,284	116,947	110,272	103,597	-1,177,925
Dairy Profit Margin	15.8%	15.0%	14.3%	13.9%	13.6%	13.2%	12.8%	12.1%	11.4%	-129.2%
Cost of Abatement ($/kg CH4)	$5.2	$5.6	$6.0	$6.1	$6.3	$6.5	$6.7	$7.1	$7.4	$78.3
Cost of Abatement ($/t/co2e)	$187	$200	$213	$219	$226	$233	$239	$252	$266	$2,797
Note	Assumed Methane Reduction of 60% for Asparagopsis									

Table 22 - Euro:NZD Exchange Rate (3-NOP)

Baseline	Euro:NZD (based on 20 year range)									
Metric	1.5	1.55	1.6	1.65	1.7	1.75	1.8	1.85	1.9	1.95
Dairy Operating Revenue	911,588									
Dairy Operating Expense	771,820	772,394	772,968	773,542	774,117	774,691	775,265	775,839	776,413	776,988
Dairy Operating Profit	139,768	139,194	138,619	138,045	137,471	136,897	136,323	135,748	135,174	134,600
Dairy Profit Margin	15.3%	15.3%	15.2%	15.1%	15.1%	15.0%	15.0%	14.9%	14.8%	14.8%
Cost of Abatement ($/kg CH4)	$10.9	$10.9	$11.0	$11.1	$11.1	$11.2	$11.3	$11.3	$11.4	$11.4
Cost of Abatement ($/t/co2e)	$388	$391	$393	$395	$397	$400	$402	$404	$407	$409
Note	Assumed Methane Reduction of 30% for 3-NOP									

Table 23 - Exchange Rate AUD: NZD (Asparagopsis)

Baseline	AUD:NZD (based on 20 year range)									
Metric	0.95	1	1.05	1.1	1.15	1.2	1.25	1.3	1.35	1.4
Dairy Operating Revenue	$911,588									
Dairy Operating Expense	$783,156	$784,659	$786,162	$787,666	$789,169	$790,672	$792,176	$793,679	$795,182	$796,685
Dairy Operating Profit	$128,432	$126,928	$125,425	$123,922	$122,419	$120,915	$119,412	$117,909	$116,405	$114,902
Dairy Profit Margin	14.1%	13.9%	13.8%	13.6%	13.4%	13.3%	13.1%	12.9%	12.8%	12.6%
Cost of Abatement ($/kg CH4)	$6.1	$6.1	$6.2	$6.3	$6.4	$6.5	$6.6	$6.6	$6.7	$6.8
Cost of Abatement ($/t/co2e)	$217	$220	$223	$225	$228	$231	$234	$237	$240	$243
Note	Assumed Methane Reduction of 60% for Asparagopsis									

3.7.2 Scenario Analysis

Table 24 Income Statement of Average Waikato Dairy Farm

Average Waikato Dairy Farm Cash and Non-Cash Effects of Methane Inhibitors in Pasture Based Dairy				
	Performance Level			
	Poor	Expected	Best Case	In-shed only
Dairy Cash Income ($)				
Milk sales (net of dairy levies)	$852,138			
Net livestock sales (sales - purchases)	$57,824			
Other dairy cash income	$3,381			
Net dairy cash income	$913,343			
Cash Working Expenses ($)				
Wages	$109,352	$92,412	$86,999	$75,032
Net feed made, purchased, cropped	$430,657	$244,006	$179,836	$189,136
Vehicles & fuel	$59,840	$43,566	$39,621	$23,840
Repairs & maintenance	$41,030	$41,030	$41,030	$41,030
Methane Inhibitor	$22,399	$18,410	$33,373	$18,410
Other Expenses	$224,698			
Farm Working Expense	$887,977	$664,124	$605,558	$572,147
Adjustments ($)				
Net Adjustments	-$113,838			
Surplus				
Cash Operating Surplus	$25,367	$249,220	$307,786	$341,196
Operating Cash and Non-cash				
Dairy Gross Farm Revenue	$913,343	$913,343	$913,343	$913,343
Dairy Operating Expense	$1,001,815	$777,962	$719,396	$685,985
Dairy Operating Profit	-$88,472	$135,381	$193,947	$227,358
Dairy Profit Margin	-10%	15%	21%	25%
Environmental Performance				
Intial Methane Emissions (kg ch4)	33,179			
Abated Methane Emission (kg ch4)	4,977	9,040	27,119	1,507
Cost of Abatement ($)	$278,361	$97,116	$65,941	$34,052
Cost of Abatement (breakeven price $/kg CH4)	$55.93	$10.74	$2.43	$22.60
Cost of Abatement (breakeven price $/t/co2e)	$1,998	$384	$87	$807
Feed Composition				
Total Imported Feed (t/year)	294	181	68	113
Cost of Imported Feed ($/year)	$264,771	$126,728	$33,945	$113,150
Pasture Proportion of Diet (relative to premium supplement)	84%	90%	96%	94%
Pasture Uitilisation Forgone	16%	8%	2%	2%
Value Additional Milk Production From Supplement	$79,129	$36,521	$9,130	$7,609

Table 25 Income Statement for Average Canterbury Dairy Farm

Average Canterbury Dairy Farm Cash and Non-Cash Effects of Methane Inhibitors in Pasture Based Dairy				
	Performance Level			
	Poor	**Expected**	**Best Case**	**In-shed only**
Dairy Cash Income ($)				
Milk sales (net of dairy levies)	$2,535,834			
Net livestock sales (sales - purchases)	$155,120			
Other dairy cash income	$357			
Net dairy cash income	$2,691,311			
Cash Working Expenses ($)				
Wages	$415,950	$348,194	$326,539	$278,670
Net feed made, purchased, cropped	$933,337	$398,179	$284,689	$325,639
Vehicles & fuel	$113,949	$81,401	$73,510	$41,949
Repairs & maintenance	$98,388	$98,388	$98,388	$98,388
Methane Inhibitor	$66,656	$54,786	$83,971	$54,786
Other Expenses	$926,139			
Farm Working Expense	$2,554,419	$1,907,086	$1,793,236	$1,725,571
Adjustments ($)				
Net Adjustments	-$247,001			
Surplus				
Cash Operating Surplus	$136,892	$784,225	$898,076	$965,740
Operating Cash and Non-cash				
Dairy Gross Farm Revenue	$2,691,311	$2,691,311	$2,691,311	$2,691,311
Dairy Operating Expense	$2,801,420	$2,154,087	$2,040,237	$1,972,572
Dairy Operating Profit	-$110,109	$537,224	$651,075	$718,740
Dairy Profit Margin	-4%	20%	24%	27%
Environmental Performance				
Intial Methane Emissions (kg ch4)	83,482			
Abated Methane Emission (kg ch4)	12,522	22,745	68,234	3,791
Cost of Abatement ($)	$743,035	$233,540	$169,464	$94,142
Cost of Abatement (breakeven price $/kg CH4)	$59.34	$10.27	$2.48	$24.83
Cost of Abatement (breakeven price $/t/co2e)	$2,119	$367	$89	$887
Feed Composition				
Total Imported Feed (t/year)	740	456	171	285
Cost of Imported Feed ($/year)	$666,198	$318,864	$85,410	$284,700
Pasture Proportion of Diet (relative to premium supplement)	84%	90%	96%	94%
Pasture Uitilisation Forgone	16%	5%	1%	2%
Value Additional Milk Production From Supplement	$199,099	$61,261	$11,486	$19,144

Table 26 Income Statement of Average Northland Farm

Average Northland Dairy Farm Cash and Non-Cash Effects of Methane Inhibitors in Pasture Based Dairy				
	Performance Level			
	Poor	Expected	Best Case	In-shed only
Dairy Cash Income ($)				
Milk sales (net of dairy levies)	$527,961			
Net livestock sales (sales - purchases)	$61,714			
Other dairy cash income	$2,431			
Net dairy cash income	$592,106			
Cash Working Expenses ($)				
Wages	$37,394	$33,159	$31,806	$28,814
Net feed made, purchased, cropped	$292,957	$154,474	$106,864	$113,764
Vehicles & fuel	$39,276	$31,139	$29,166	$21,276
Repairs & maintenance	$38,635	$38,635	$38,635	$38,635
Methane Inhibitor	$13,878	$11,406	$24,761	$11,406
Other Expenses	$140,634			
Farm Working Expense	$562,773	$409,447	$371,865	$354,529
Adjustments ($)				
Net Adjustments	-$109,260			
Surplus				
Cash Operating Surplus	$29,333	$182,659	$220,241	$237,577
Operating Cash and Non-cash				
Dairy Gross Farm Revenue	$592,106	$592,106	$592,106	$592,106
Dairy Operating Expense	$672,033	$518,707	$481,125	$463,789
Dairy Operating Profit	-$79,927	$73,399	$110,981	$128,317
Dairy Profit Margin	-13%	12%	19%	22%
Environmental Performance				
Intial Methane Emissions (kg ch4)	24,616			
Abated Methane Emission (kg ch4)	3,692	6,707	20,120	1,118
Cost of Abatement ($)	$178,192	$56,478	$39,219	$23,011
Cost of Abatement (breakeven price $/kg CH4)	$48.26	$8.42	$1.95	$20.59
Cost of Abatement (breakeven price $/t/co2e)	$1,724	$301	$70	$735
Feed Composition				
Total Imported Feed (t/year)	218	134	50	84
Cost of Imported Feed ($/year)	$196,443	$94,024	$25,185	$83,950
Pasture Proportion of Diet (relative to premium supplement)	84%	90%	96%	94%
Pasture Uitilisation Forgone	16%	8%	2%	2%
Value Additional Milk Production From Supplement	$58,709	$27,096	$6,774	$5,645

Introducing smart-feeders into average farms across the three regions studied (Waikato, Canterbury and Northland) has the same unit costs. However, the number of units required and the substitution of supplement vary by region. Such variation leads to slight differences in the overall financial performance of IPSF across regions. Tables 24-26 show the income statements of the three regions with poor, expected, best-case and in-shed-only performance levels. IPSF is not economically viable in the poor and in-shed-only performance levels regardless of the region. In Waikato and Canterbury, the best-case performance scenarios are nearly viable, where viability means a breakeven price less than or equal to the methane price. The HWEN implies a breakeven of $2.31/kg/ch4 (proposed maximum charge of 11 cents per kg plus incentives up to twenty times the charge (He Waka Eka Noa 2022d)). However, a favourable breakeven price is observed in Northland of $1.95/kg CH4. A summary of breakeven prices across scenarios is presented in table 27, showing the breakeven methane prices across various scenarios. This table illustrates that despite Canterbury's higher supplement substitution, IPSF is more viable in the other regions where farmers tend to be lower input.

Table 27 - Summary of Breakeven Prices ($/kg/CH4)

Region	**Poor**	**Expected**	**Best Case**	**In-shed Only**
Waikato	$55.93	$10.74	$2.43	$22.60
Canterbury	$59.34	$10.27	$2.48	$24.83
Northland	$48.26	$8.42	$1.95	$20.59

Despite having the lowest breakeven price in the best-case scenario of $1.95/kg CH4, Northland also has the lowest profit margin after introducing IPSF. The profit margin in Northland is 19% relative to 21% in Waikato and 24% in Canterbury. These differences are expressed in table 28 in comparison to actual historical values.

Table 28 - Summary of Scenario Operating Profit Margins

Region	**Poor**	**Expected**	**Best Case**	**In-shed Only**	**Actual**
Waikato	-10%	15%	21%	25%	28%
Canterbury	-4%	20%	24%	27%	34%
Northland	-13%	12%	19%	22%	20%

Source of Actuals: Dairy NZ Economic Farm Survey 20-21

The utilisation of smart-feeders in this approach leads to increased supplement use. In the poor performance scenarios across regions, forgone pasture utilisation is the greatest at 16% (table 24), and the value of additional milk production from supplement is the highest. This is due to the 2.6kg/day of supplement when IPSF is in use, with no substitution offsetting this amount in this performance scenario (refer to table 17). While in the best-case scenarios, forgone pasture utilisation is 1-2% due to relatively lower supplement per cow per day.

The poor and in-shed-only technology performance scenarios are not viable in all regions. IPSF is unviable for two reasons. Firstly, the breakeven price exceeded the benchmark of $2.31kg/CH4. Secondly, adoption resulted in negative profit. While in-shed only may seem favourable due to the profit margins, the breakeven price is more significant than the benchmark price. In these cases where the breakeven price is greater than the benchmark, rational decision-makers would pay the emission charge instead of adopting IPSF, which does not lead to progress towards climate change targets.

Similarly, IPSF is not viable in the expected performance scenarios across the regions because the breakeven price is greater than the benchmark despite positive profit margins. Further, where profit margins may be positive, they are often worse than historical profit (refer to table 28.) Therefore, when evaluating IPSF the breakeven price and profitability must be simultaneously considered. Finally, the best-case performance across the regions sees profit margins closer to those experienced historically and a breakeven price close to or less than (in the case of Northland) the benchmark price. This addresses the final research question of how the breakeven price changes in various farm systems. However, the suggestion that in-shed feeding to deliver methane inhibitors is more profitable in Northland than historic profitability assumes that there is 75% supplement substitution in the region, implying minimal extra costs to introducing inhibitors with minimal methane mitigation. The combination of mitigated emissions and low delivery costs leads to greater modelled profit than average historical values. Additionally, only 24% of farmers in Northland have in-shed feeders (table 15), which makes it plausible that this minority would have greater than average profit margins in the region. If a farmer does not have in-shed feeding infrastructure, or does not feed significant supplement profit levels would be significantly lower.

3.8 Discussion

This chapter aimed to explore the financial performance of IPSF as a delivery mechanism for methane inhibitors. This was done in three steps; developing a cost/effectiveness model, reviewing the model via sensitivity analysis and then a scenario analysis. The last steps addressed understanding the model's drivers and the economic impact of using IPSF across farm systems and regions. It has become apparent after exploring the scenarios that for this approach to be viable, two explicit conditions must occur. Firstly, the IPSF can be designed and operated at a level similar to the 'best-case' scenarios. Secondly, the breakeven cost of IPSF is low enough that there is a benefit to adopting the technology rather than paying a charge for emissions. The best-case scenarios are characterised by relatively high inhibitor efficacy and supplement substitution. Suppose methane inhibitor producers can bring a product to market that achieves the level of mitigation seen in housed dairy systems, for example, a product requiring fewer deliveries each day. However, addressing high supplement substitution is more complex, given that some farmers use minimal supplement.

Further, low-quality supplement is not a substitute for the required premium pellets. If IPSF could be optimised to have increased sensitivity, requiring less supplement each day to act as an inhibitor delivery mechanism, supplement costs will decrease. However, cows still require a sufficient incentive to interact with the IPSF, so there will be a lower limit on supplement use. A sufficiently high emissions charge would incentivise the adoption of IPSF. However, a high emission charge may result in significant amounts of dairy farms exiting the industry as they become unprofitable.

The cost-effectiveness model described throughout this chapter incorporates assumptions and estimates of costs in order to assess the economic potential of IPSF under different situations of technological development. The model has been developed with technical development in mind to incorporate performance advances. However, when costs are viewed through the eyes of farmers, practical implications arise. For example, the labour cost of IPSF may be untenable on farm given workloads despite being as low as three hours per week. The additional work may become prohibitive if farms have few or no employees. At the same time, it may be easier to find additional hours in a more extensive operation despite having a higher theoretical breakeven price.

A similar point arises for supplement substitution, which varies across and within regions and refers to the degree to which incumbent supplement use on farm can be diverted to be fed through smart feeders, reducing the additional supplement cost. While Northland has the lowest and thus most favourable breakeven price, it also has a 50% supplement substitution rate. Some Northland farms will experience this, but there will also be farms that use no supplement. When supplement substitution falls to zero, the cost of abatement is substantially greater; therefore, breakeven costs are higher and profitability lower. The scenario analysis represented a broad range of farms and farm systems. However, the model is flexible enough to explore other scenarios if needed.

Further, it is challenging to mention farm systems in this context without recognising the threat to how they are defined if this approach were to become widespread. The degree of supplement use defines farm systems, and introducing IPSF may shift farmers into a higher farm system and eventually a redefinition of farm systems. Nationally shifting into higher input systems may also affect consumer perception of NZ dairy products due to erosion of the pasture-based value proposition. Such a shift may affect farmers' attitudes to adoption because it challenges their idea of a 'good farmer' (Hunt et al. 2013). If a divergence between dollar and psychological costs emerged, more significant economic incentives would be required.

As farmers increase their supplement use, pasture utilisation falls, and milk production increases because supplement is more energy-dense (DairyNZ n.d.-a). This is evident in the poor performance scenario where pasture utilisation falls 16% (table 24). The relatively higher energy density leads to greater production. However, substituting grass for supplement is not one-for-one as cows tend to graze for twelve minutes less for each kg/dm supplement (DairyNZ 2021). Additionally, pasture is the most economical feed for NZ dairy farmers (Dillon et al. 2008). Therefore, substituting grass for supplement may lead to greater production but have implications on cost and profit. Farmers may increase supplement use and production given an exceptionally high milk price, forgoing pasture utilisation in favour of higher production levels. This unique case is not covered in the sensitivity analysis. Suppose a high supplement and production scenario was included, it would lead to high supplement substitution and reduced breakeven costs, making the IPSF approach relatively more favourable.

When exploring the breakeven price with a scenario and sensitivity analysis, it was evident that exchange rates and inhibitor prices are relatively unimportant for the overall viability of IPSF relative to the cost of and quantity of supplement and the methane mitigation potential. However, input prices and their determinants are still crucial to the economic viability of IPSF. Therefore, as more information about these values emerges, the inputs should be updated. Many pricing and performance inputs are estimations grounded in recent literature where possible or personal communications when not.

Overall, this chapter and the associated model show that there is a possibility that IPSFs are a viable method for some farms to reduce methane emissions. However, the viability of this approach is contingent on the associated favourable supplement substitution and methane mitigation potential. For these factors to occur, smart-feeder and inhibitor manufacturers must revise their products to suit the characteristics required for success in a pasture-based farm system such as NZ.

3.8.1 Policy Implications

Uncertainty around how methane emissions reductions will be incentivised is why the breakeven methane price is the ultimate output of the model. Having a breakeven price as the output ensures the model is of use regardless of how policy in this space develops.

The viability of IPSF hinges on the technology's breakeven price, which is the point at which the costs of introducing IPSF into a farm system are equal to the value of mitigated methane emissions. The methane price used for this analysis is the proposed price under HWEN, a reference point of \$2.31 /kgch4. However, this price depends upon the acceptance of the HWEN proposal. In addition to accepting HWEN and the proposed maximum charge, significant incentives are required. While the HWEN proposal is explicit in a maximum charge of $0.11/kgch4, the incentives attached are not yet defined. Adoption of IPSF is unlikely if the government does not include significant incentives.

If HWEN is not accepted, methane prices will be determined according to the NZ ETS with a free allocation to farmers that decreases with time. If the market underpins methane prices, farmers will face additional uncertainty as supply and demand for carbon credits fluctuate. In this scenario, projected carbon prices scaled to reflect free allocation could be used as a breakeven reference point.

3.8.2 Limitations

The uncertainty of pricing and technological performance limits the findings of this chapter concerning the farm-level cost-effectiveness model developed. At the time of writing there was insufficient information to construct such a sub-model of methane mitigation with respect to inhibitor dose and frequency. However, its inclusion could significantly affect the economies of the approach as targeted delivery could be further investigated. Additionally, while the costs of methane inhibitors and IPSFs are based on literature/personal communications, they are still only estimates. When these technologies become commercially available and the associated mitigation and costs are apparent, updating the model would be useful.

3.8.3 Future Research

Methane mitigation is a significant factor in economic viability. In this model, it is taken exogenously due to complexities around modelling the mitigation effect of an inhibitor concerning dose quantity and frequency, which are generally the determinants of potential mitigation (Black et al. 2021; Stefenoni et al. 2021). Future improvements to the model could include a methane mitigation sub-model based on the frequency and quantity of inhibitor dose. At this time, there is no such model available, nor the data to generate such a model, but it would be a welcome improvement.

Additionally, the robustness of the cost estimations could be improved with field trials to determine the amount of supplement required and the labour required for IPSFs. However, removing ambiguity around these costs is impossible as the IPSF are not currently available in the specification needed for this approach, as discussed in chapter one.

3.9 Conclusion

This chapter sought to identify the situations in which IPSFs as inhibitor delivery vehicles were economically viable. The financial performance of IPSFs was evaluated first by developing a cost-effectiveness model and then assessing the model via scenario and sensitivity analysis. The combination of the model and analysis shows that supplement substitution is a significant determinant of whether the approach is viable on a given farm due to the additional supplement being the greatest portion of the costs associated with adopting IPSFs to deliver methane inhibitors. The model predicts Northland as the best target market for the approach in scenarios where the marginal supplement cost is low. Not only does the region experience the lowest breakeven price, but the adoption of IPSFs also has the smallest impact on profitability.

Chapter 4: Conclusion

This thesis evaluated a novel approach to delivering methane-inhibiting compounds to dairy cows in a pasture-based system using IPSFs. Potential adoption outcomes were explored using the ADOPT model in conjunction with focus groups which determined that given expected technology performance, poor adoption outcomes in terms of the time until peak adoption, and the level of peak adoption. Following the adoption modelling, a deterministic farm-level cost-effectiveness model was developed, which outlined that, given expected performance levels, the economic viability of IPSFs in this approach is unlikely. However, both modelling pieces found that if the performance of IPSFs in the delivery of methane-inhibitors could be improved, the adoption and economic outcomes would also improve.

The most significant barriers to modelled adoption were trialability, ease & convenience and environmental performance, while the largest cost in economic modelling was the cost of the additional supplement. Additionally, farmer focus groups showed that farmers viewed the additional labour as prohibitive even though economic modelling indicated that labour costs were small relative to other costs associated with adoption. Holistically this means that if the farmers can trial IPSFs on their farms and the quantity of supplement and labour can be reduced, both modelled adoption and economic outcomes may rise to the levels needed to meet the climate change commitments of NZ in regards to biogenic methane emissions.

Recommended improvements in IPSFs are the required delivery frequency of methane inhibiting compounds, the magnitude of mitigated eissions, and the precision of supplement dispensed from IPSFs.

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Appendix A – Expert Consultation Questions

1) Context related questions

- What are smart-feeders?
- What are methane-inhibitors?
- Why do we care about these things?

2) What are the characteristics you think is the most important for the success of this approach?

- Please rank the following characteristics in order of most to least important: refill frequency, ability to check machine performance via phone/computer, animal:machine ratio, device ownership structure, maintenance contract, machine manufactured in NZ or overseas, and the amount of damage to paddocks.

3) Help us answer these questions that are consistent across NZ Dairy farmers in this context (these are ADOPT inputs what are constant across the population)

4) Given scenario one presented in the slides, please answer the following nine ADOPT input questions pertaining to the technology performance.

5) Given scenario two presented in the slides, please answer the following nine ADOPT input questions pertaining to the technology performance.

6) Do you have preferences between the scenario one and two? If so, why?

Appendix B – Ethics Application Supplementary Material

Initial Contact Script

Hi <name>, my name is Ben Marmont. I am reaching out to you regarding a focus group on a subject you may wish to share your thoughts on. The focus group is part of research being undertaken at the University of Waikato as part of a wider project funded by DairyNZ and the NZ Agricultural Greenhouse Gas Centre. We are exploring the use of in-paddock smart feeders to deliver a methane-inhibiting feed-additive. We are keen to hear the opinion of farmers about how this new technology might work in a commercial farm system.

We invite you to a small focus group held at <time> and <place> to be part of this small focus group. If you would like more information, I am happy to provide it. If you are interested, please RSVP by <date> by contacting Ben.

Alternatively, if any questions arise, please contact Ben on <phone number> or <email address>

Participant Information Sheet

- The purpose of this research is to understand the likely adoption outcomes of Smart Feeders as in-paddock methane inhibitor delivery systems in the wider environment of reducing methane emissions in the dairy industry.

- The research is conducted by Ben Marmont <email address> (postgraduate Economics student at the University of Waikato) and Callum Eastwood <email address> (Senior Scientist at DairyNZ.) Callum is part of Ben's supervisory team in conjunction with Zack Dorner <email address> (Senior Lecturer in Economics at the University of Waikato) and Mark Neal (Farm Systems Specialist at DairyNZ). This research is a part of a wider project funded by DairyNZ in conjunction with the New Zealand Agricultural Greenhouse Gas Research Centre.

- We are hosting a focus group with local dairy farmers to discuss the likely adoption of in-paddock smart feeders. We are extending an invitation to you to share your thoughts on the technology and how it may be applied in farm systems. We expect these focus groups to include 7-10 people and last for 2-3 hours. During this time, we will outline the technology, capture your feedback on the potential use of the technology and work with you to quantify some input variables for adoption prediction models.

- During the focus groups we will take notes of your feedback, the discourse in the group and photograph the brainstorms, the is referred to as the data gathered in the focus group.
- The data collected from these focus groups will be stored on a password protected server where only the researcher and supervisors can access the data. We intend to use the data in publications where it will be anonymous, and any quotes will use pseudonyms rather than real names. Prior to publication participants will be sent a short summary of findings from the study.
- These focus groups will be run confidentially, so we ask that those in attendance keep the views and identities of other participants confidential.

- If you would like to be emailed a summary of the focus group results, please tick the appropriate box on the consent form.
- If you initially indicate that you would like to be part of these focus groups, but later change your mind please let Ben know by Monday 7th March (7/3/22) via email: <email address>
- For more information about the wider project, or the focus groups themselves please contact Ben or Callum (emails above).

Appendix C – Farmer Focus Group Supplementary Material

Questions

1) What have you heard?
2) What are the characteristics you think is most important for the success of this approach?
3) (After adding characteristics from the first time, and discussing the results) What are the characteristics you think is most important for the success of this approach?

Provided Information

- Summary of NZ's greenhouse gas emissions and the associated goals and legislation.
- A summary of methane mitigation options and their efficacy.
- Specific information about methane inhibitors as a way to mitigate methane such as their performance and delivery.

Appendix D – Contextualised ADOPT Questions

These were the ADOPT questions asked to the participants of the expert consultation. The questions are contextualised for IPSFs, such that ‘New Zealand dairy farmers’ replaced ‘target population’ and ‘the use of in-paddock smart feeders as a inhibitor delivery mechanism’ replaced ‘the innovation.’

1) Profit Orientation

What proportion of the New Zealand Dairy farmers have maximising profit as a strong motivation?

Almost none have maximising profit as a strong motivation
A minority have maximising profit as a strong motivation
About half have maximising profit as a strong motivation
A majority have maximising profit as a strong motivation
Almost all have maximising profit as a strong motivation

2) Environmental orientation

What proportion of New Zealand Dairy farmers have protecting the natural environment as a strong motivation?

Almost none have protection of the environment as a strong motivation
A minority have protection of the environment as a strong motivation
About half have protection of the environment as a strong motivation
A majority have protection of the environment as a strong motivation
Almost all have protection of the environment as a strong motivation

3) Risk orientation

What proportion of New Zealand Dairy farmers have risk minimisation as a strong motivation?

Almost none have risk minimisation as a strong motivation (risk takers)
A minority have risk minimisation as a strong motivation
About half have risk minimisation as a strong motivation
A majority have risk minimisation as a strong motivation
Almost all have risk minimisation as a strong motivation (risk averse)

4) Enterprise scale

On what proportion of New Zealand Dairy farms is there a major enterprise that could benefit from in-paddock smart feeders as an inhibitor delivery mechanism?

Almost none of the target farms have a major enterprise that could benefit
A minority of the target farms have a major enterprise that could benefit
About half of the target farms have a major enterprise that could benefit
A majority of the target farms have a major enterprise that could benefit
Almost all of the target farms have a major enterprise that could benefit

5) Management horizon

What proportion of New Zealand Dairy farmers have a long-term (greater than 10 years) management horizon for their farm?

Almost none have a long-term management horizon
A minority have a long-term management horizon
About half have a long-term management horizon
A majority have a long-term management horizon
Almost all have a long-term management horizon

6) Short term constraints

What proportion of New Zealand Dairy farmers are under conditions of severe short-term financial constraints?

Almost all currently have a severe short-term financial constraint
A majority currently have a severe short-term financial constraint
About half currently have a severe short-term financial constraint
A minority currently have a severe short-term financial constraint
Almost none currently have a severe short-term financial constraint

7) Trialable

How easily can in-paddock smart feeders being used as an inhibitor delivery mechanism (or significant components of it) be trialled on a limited basis before a decision is made to adopt it on a larger scale?

Not trialable at all
Difficult to trial
Moderately trialable
Easily trialable
Very easily trialable

8) Innovation complexity

Does the complexity of in-paddock smart feeders being used as an inhibitor delivery mechanism allow the effects of its use to be easily evaluated when it is used?

Very difficult to evaluate effects of use due to complexity
Difficult to evaluate effects of use due to complexity
Moderately difficult to evaluate effects of use due to complexity
Slightly difficult to evaluate effects of use due to complexity

Not at all difficult to evaluate effects of use due to complexity

9) Observability

To what extent would the use of in-paddock smart feeders as inhibitor delivery mechanisms be observable to farmers who are yet to adopt it when it is used in their district?

Not observable at all
Difficult to observe
Moderately observable
Easily observable
Very easily observable

10) Advisory support

What proportion of New Zealand Dairy farmers uses paid advisors capable of providing advice relevant to the project?

Almost none use a relevant advisor
A minority use a relevant advisor
About half use a relevant advisor
A majority use a relevant advisor
Almost all use a relevant advisor

11) Group involvement

What proportion of New Zealand Dairy farmers participates in farmer-based groups that discuss farming?

Almost none are involved with a group that discusses farming
A minority are involved with a group that discusses farming

About half are involved with a group that discusses farming
A majority are involved with a group that discusses farming
Almost all are involved with a group that discusses farming

12) Relevant existing skills & knowledge

What proportion of New Zealand Dairy farmers will need to develop substantial new skills and knowledge to use the innovation?

Almost all need new skills and knowledge
A majority will need new skills and knowledge
About half will need new skills and knowledge
A minority will need new skills and knowledge
Almost none will need new skills or knowledge

13) Innovation awareness

What proportion of New Zealand Dairy farmers would be aware of the use or trialing of the use of in-paddock smart feeders as inhibitor delivery mechanisms in their district?

It has never been used or trialed in their district(s)
A minority are aware that it has been used or trialed in their district
About half are aware that it has been used or trialed in their district
A majority are aware that it has been used or trialed in their district
Almost all are aware that it has been used or trialed in their district

14) Relative upfront cost of the innovation

What is the size of the up-front cost of the investment relative to the potential annual benefit from using in-paddock smart feeders as inhibitor delivery mechanisms?

Very large initial investment

Large initial investment
Moderate initial investment
Minor initial investment
No initial investment required

15) Reversibility of the innovation

To what extent is the adoption of the use of in-paddock smart feeders as inhibitor delivery mechanisms able to be reversed?

Not reversible at all
Difficult to reverse
Moderately difficult to reverse
Easily reversed
Very easily reversed

16) Profit benefit in years that it is used

To what extent is the use of the in-paddock smart feeders as inhibitor delivery mechanisms likely to affect the profitability of the farm business in the years that it is used?

Large profit disadvantage in years that it is used
Moderate profit disadvantage in years that it is used
Small profit disadvantage in years that it is used
No profit advantage or disadvantage in years that it is used
Small profit advantage in years that it is used
Moderate profit advantage in years that it is used
Large profit advantage in years that it is used
Very large profit advantage in years that it is used

17) Future profit benefit

To what extent is the use of the use of in-paddock smart feeders as inhibitor delivery mechanisms likely to have additional effects on the future profitability of the farm business?

Large profit disadvantage in the future
Moderate profit disadvantage in the future
Small profit disadvantage in the future
No profit advantage or disadvantage in the future
Small profit advantage in the future
Moderate profit advantage in the future
Large profit advantage in the future
Very large profit advantage in the future

18) Time until any future profit benefits are likely to be realised

How long after the use of in-paddock smart feeders as an inhibitor delivery mechanism is first adopted would it take for effects on future profitability to be realised?

More than 10 years
6 - 10 years
3 - 5 years
1 - 2 years
Immediately
Not Applicable

19) Environmental costs & benefits

To what extent would the use of in-paddock smart feeders as inhibitor delivery mechanisms have net environmental benefits or costs?

Large environmental disadvantage

Moderate environmental disadvantage
Small environmental disadvantage
No net environmental effects
Small environmental advantage
Moderate environmental advantage
Large environmental advantage
Very Large environmental advantage

20) Time to environmental benefit

How long after the use of in-paddock smart feeders as inhibitor delivery mechanisms is first adopted would it take for the expected environmental benefits or costs to be realised?

More than 10 years
6 - 10 years
3 - 5 years
1 - 2 years
Immediately
Not Applicable

21) Risk exposure

To what extent would the use of the use of in-paddock smart feeders as a inhibitor delivery mechanism affect the net exposure of the farm business to risk?

Large increase in risk
Moderate increase in risk
Small increase in risk
No increase in risk
Small reduction in risk
Moderate reduction in risk

Large reduction in risk

Very Large reduction in risk

22) Ease and convenience

To what extent would the use of in-paddock smart feeders as a inhibitor delivery mechanism affect the ease and convenience of the management of the farm in the years that it is used?

Large decrease in ease and convenience

Moderate decrease in ease and convenience

Small decrease in ease and convenience

No change in ease and convenience

Small increase in ease and convenience

Moderate increase in ease and convenience

Large increase in ease and convenience

Very large increase in ease and convenience