Using Monte Carlo Simulations to Achieve the Best Response From Nitrogen on Grazed Pasture Under a Legislated Nitrogen Cap in New Zealand: A Review

Review

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Highlights

- The benefits of split applications (or more applications at lower application rates) of N fertilizer on pasture have often been espoused without the support of statistical evidence.
- Provides some clarity on the benefits of split applications of N fertilizer.
- Explains why low application rates work in situations where accurate spreading is not required.

Abstract. *Pastoral and crop farming systems have traditionally used the application of nitrogen (N) to achieve an optimal economic production response. This nitrogen response is estimated from an exponential function that approaches an asymptote, which is typical of most fertilizer response curves. The optimal economic N response is often achieved when application rates are greater than plant utilization rates, often resulting in leaching, nitrogen run-off, and volatilization of nitrogenous compounds. These losses can have an impact on freshwater quality and contribute to greenhouse gas (GHG) emissions. In New Zealand, urine from N-fertilized pasture grazed by dairy cattle has been shown to be the most problematic source of N losses. As part of New Zealand's National Environmental Standards (NES), a synthetic N cap of 190 kgN ha^{-1}yr^{-1} on grazed pasture and crops has been implemented to reduce nutrient enrichment of fresh water. This study reviewed the use of multiple split applications of N to improve N fertilizer use efficiency and pasture response and used Monte Carlo simulations to demonstrate improved response to split N applications rather than a single optimal application based on economic response. In addition, spreading accuracy also became less important as all the low-application variation occurred along the steepest part of the response curve where this variation results in added yield.*

Keywords. *Dairy cattle, Fertilizer cap, Monte Carlo simulations, Nitrogen use efficiency, Nutrient management.*

Pastoral farming is practiced on approximately 8.6 million hectares of land, comprising nearly one-third of the land area of New Zealand (Statistics NZ, 2018). New Zealand's temperate climate and generally adequate rainfall regime (> 1000 mm per annum) are ideal for grass-based farming systems. Fertilizers have been applied to New Zealand pastures to achieve an optimum economic outcome, usually after soil testing and advice from a qualified account manager or field officer (Moir et al., 2000). Pasture grass response, assuming the nitrogen nutrient applied is a limiting factor, is an exponential function, reaching a plateau and demonstrating diminishing production returns (Cameron et al., 2013; Miller et al., 2009; Moir et al., 2000).

Nitrogen Cap

A nitrogen (N) cap of 190 kgN ha^{-1}yr^{-1} of synthetic fertilizers containing more than five percent N, which applied to grazed pasture and cropping land, was introduced in New Zealand on 1 July 2021 (New Zealand Ministry for the Environment [NZME], 2020). The cap does not apply to horticulture or non-forage arable farming systems (NZME, 2020). N application in pasture for sheep, beef, deer, and non-dairy production systems is very rarely greater than the current cap as they utilize biological N fixation from clover and lucerne (Fertiliser Association NZ). Dairy farming has increased N fertilizer use (Cameron et al., 2013; NZME., 2020; Bishop and Manning, 2011; Parfitt et al., 2012) from approximately 45,000 tons in 1990 to 320,000 tons in 2019 (NZME., 2020; Parfitt et al., 2012). Thus, the recent cap on synthetic N fertilizers affects dairy farming more so than other livestock operations.

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Nitrogen Use Efficiency

The N cap regulation aims to reduce potential adverse environmental effects of synthetic N fertilizers by increasing the N use efficiency (NUE) of pasture by reducing instances when N supply exceeds pasture and crop growth requirements. In grazed ryegrass *(Lolium perenne)* and white clover *(Trifolium repens)* pastures, 80 to 210 kgN ha^{-1} per year is supplied by rhizobial fixation, which decreases with N fertilizer application due to the suppression of clover (Castillo et al., 2000). The fertilized ryegrass tends to shade out white clover, reducing its vigor. In addition to synthetic N fertilizer application and legume fixation, pasture N is also supplied by the application of dairy effluent (Castillo et al., 2000; Ministry of Primary Industries [MPI], 2013), which is not limited by the N cap (Dexcel, 2007; Dairy NZ, 2015). Based on DM production and N uptake, Castillo's equation can then be used to estimate N return as urine and environmental impact (Castillo et al., 2000; Ledgard, 2001). The uptake of N by pasture in the presence of excess N results in high protein levels and increased urine N concentration when grazed by dairy cattle (Silva et al., 1999). This high urine N concentration contributes up to 80% of the nitrate N leached as well as 33% of nitrous oxide greenhouse gas emissions from the grazed dairy pasture (Cameron et al., 2013; Castillo et al., 2000; Ledgard, 2001).

There have been several mitigation strategies employed to improve NUE and reduce instances where applied N exceeds pasture requirements, including controlled release N fertilizer and N transformation inhibitors to reduce soil ammonium and nitrate levels (Di et al., 1998a; Di et al., 1998b). Controlled release N fertilizers, such as N-Protect (provides 75 days release) (Ravensdown, 2022) and SustaiN (provides 30 days release) (Balance Agri-Nutrients SustaiN, 2022), use polymer-coated urea (which will start to act within hours and provides a total response within 7 to 14 days) to slow the release rate of N. The reduction of the N release rate avoids excessive uptake by pasture grass, increasing the NUE (Bishop et al., 2008; Edmeades and McBride, 2017) and reducing pasture grass N content. The application of urease inhibitors slows the conversion of urea to ammonia, reducing the losses of applied fertilizer N via leaching and volatilization. However, urease inhibitors could increase pasture N uptake and require a reduction of total N applied by 30% to 50% to achieve similar levels of pasture production and pasture N content to that fertilized with urea.

The application of nitrification inhibitors, such as dicyandiamide (DCD) or 3,4-dimethylpyrazole phosphate (DMPP), slows the conversion of ammonium to nitrate. The latter is rapidly taken up by pasture grass but is also rapidly leached during heavy rainfall events. The reduction in nitrification rate thus increases NUE and lowers the risk of nitrate leaching from pasture (Smith et al., 2008).

Current mitigation options have been limited, either by cost (where controlled release N fertilizers are about twice as expensive as that of uncoated N fertilizer) or by the contamination risk associated with the residues of nitrification inhibitors. The latter was exemplified in 2012 when DCD contamination was detected in milk powder in New Zealand (MPI, 2013). The application of small, frequent applications of N fertilizer offers a potential alternative to these mitigation strategies, but this practice would significantly increase application costs, which may be offset by increased NUE. The current implementation of New Zealand's Essential Freshwater Package (MfE Discussion Document, 2021) will impose a mandatory requirement for certified freshwater farm plans for most farms in NZ. Any persistent failure of a farm to comply with the plan's requirements to reduce its impact on freshwater quality may lead to the imposition of fines on the farm operator. Accordingly, there is a financial disincentive to increase environmental impact (by decreasing the NUE).

This review discusses the economic advantage of small and frequent applications of N fertilizer using narrow spreading widths (10 m) applied by farmer-owned fertilizer spreaders, compared to broad-acre truck spreaders with a 30 m width. The analytical approach employed Monte Carlo simulation (random sampling, in this case, using a normal distribution of spreading variability and fertilizer response) to assess NUE and fertilizer responses to estimate changes in nitrate leaching and greenhouse gas emissions.

It is important to factor in spreading accuracy as much of the published work on N fertilizer response has been undertaken on trial blocks using accurate N applications on randomized block design treatments, which may not reflect field response in a farm situation due to the variation in uniformity of on-farm spreaders.

Materials and Methods

Rationale

There have been numerous studies examining pasture response to N fertilizer applications, the most famous being the continuous trial at Rothmanstead since 1843 (Cameron et al., 2013). Pasture responses to N are dependent on several factors, such as soil N status, soil temperature, pasture species, rainfall, and air temperature (Ball and Field, 1982; Walker and Ludecke, 1982; Cameron et al., 2013; Shepherd et al., 2015). For modeling purposes, a base loading of 120 kgN was used for N fixation, and the additional yield response was subsequently calculated, based on fertilizer distributions, to determine dry matter (DM) differences between the two production scenarios (the control and fertilizer treatments). Although responses above the control (no N applied) may vary from 4 kg dry matter (DM) to 33 kg DM per kg N applied, the response is non-linear and takes the form of an exponential function showing diminishing returns with increased N application (see equation 1 [Shepherd et al., 2015], and table 1 and figure 1 [Shepherd et al., 2015; DairyNZ, 2020]). The regression coefficient used to convert DM to milk solids (MS) also varies, depending on pasture quality, legume content, and species, from 7 to 23 kg DM MS^{-1}. In the more temperate regions of New Zealand, the annual average coefficient is around 15 kg DM MS^{-1} (Ball and Field, 1982; Walker and Ludecke, 1982; DairyNZ, 2020). The economic optimum is established by calculating the benefit in terms of MS payout and deducting the cost of N as urea (46% N), with a $US14 per ha commercial truck spreading charge (Ravensdown, 2021). This simulation

Table 1. Response to the application of N in kg DM per kg N applied based on equation 1.

kg N	kg DM kg N^{-1}
0	0
40	21
80	18
120	15
160	13
200	11
240	10
300	8

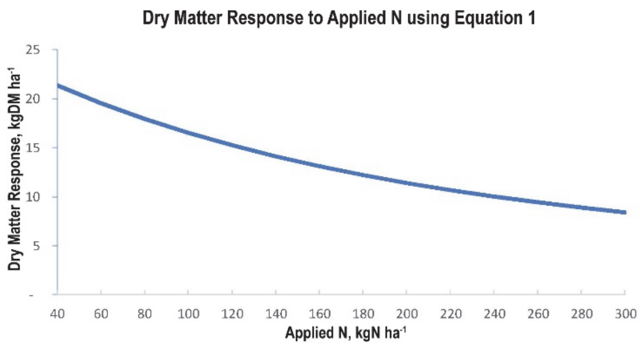

Figure 1. Diminishing returns of DM in terms of response to increased N.

used a currency conversion ratio of $NZ = $US0.70 (see table 2 and fig. 2). Urea was modeled (as N is the only nutrient contained within it) and it is the cheapest and most widely used N fertilizer in the dairy industry (Ravensdown, 2021).

Equation 1 from (Shepherd et al., 2015):

$$DM = 4297 - 4072\ x\ e^{\left(-0.8449x\left(TN + 0.01143xNapplied\right)\right)} \quad (1)$$

where

N applied = kg N applied per ha

TN = total soil N.

For tables 1 and 2 and figures 1 and 2, TN is assumed to be 0.5%.

The Cost of Uneven Nitrogen Applications

The economic optimum of applied N (US$240), which equates to 448 $kgha^{-1}$ of urea that supplies 206 $kgha^{-1}$ N, is greater than the New Zealand synthetic N cap (190 $kgha^{-1}$) when using parameters which are assumed to be in the middle of the N response ranges (see table 2 and fig. 2). Figure 2 marks the economic optimum at the maximum of the curve.

Responses to N application are also dependent on the accuracy of the spread of N fertilizer. Spreading N fertilizer at a higher than the mean desired rate results in additional cost with little benefit as the response curve is flat to the right of the economic optimum. Consequently, this results in some field areas receiving lower application rates with a reduced response unless additional fertilizer is purchased and applied (Grafton et al., 2017). This is reflected by an exponential increase in cost through inaccurate spreading, theorized in studies by Miller et al. (2009) and Søgaard and Kierkegaard (1994), and modeled based on a New Zealand dairy farm in a study by Lawrence and Yule (2007). However, at low application rates of around 50 $kgNha^{-1}$, any over-application would still provide an added benefit, almost in the same

Table 2. Economic responses from the value of N applied at $US0.54 kg^{-1} in milk solids valued at $US5.18 kg^{-1} using a conversion ratio of 1 kg MS from 15 kgDM.

Kg N	$US N	$US MS
0	0	0
30	40	195
60	80	331
90	120	422
120	160	481
150	200	514
180	240	529
210	280	529
240	320	509
270	360	492
300	400	482

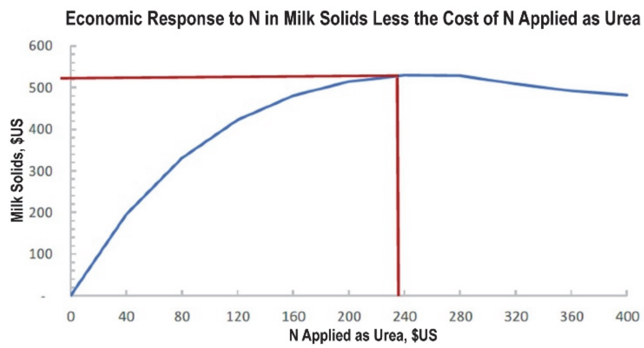

Figure 2. Net benefit of response to N in milk solids less cost of N applied as urea. Economic optimum is $529 at $240 worth of applied N.

proportion as the lost benefit from areas receiving under-application (see table 2 and fig. 2).

In addition, multiple low application rates cumulatively provide a better N response than an economic optimum of a single application (table 2, Castillo et al., 2000; Ledgard, 2001; Bishop and Manning, 2011; Cameron et al., 2013). Response measurements in the literature are generally measured from small test plots where fertilizer application is much more precise and accurate (Ball and Field, 1982; Silva et al., 1999; Ledgard, 2001; Bishop et al., 2008; Smith et al., 2008; Bishop and Manning, 2011; Cameron et al., 2013; Raveendrakumaran et al., 2020). The fertilizer responses measured in these field trials are influenced on a larger scale and are affected by the accuracy of the fertilizer application for each rate applied. Factors affecting the accuracy of spreading application, machine calibration, driving error, topography, and particle ballistic properties and systems that can mitigate and reduce these losses have been well researched (Grafton et al., 2013; Mersmann et al., 2013; Yule and Grafton, 2013).

Monte Carlo Simulations

The cost associated with sub-optimum spreading accuracy has driven the use of precision technologies (Grafton et al., 2013; Mersmann et al., 2013; Yule and Grafton, 2013). Commercial spreading operators have been adopting precision technologies in response to their clients' awareness of yield losses associated with poor spreading. This is particularly true for the application of urea, as the response is seen within days of application, and variation in application rates rapidly shows as striping in pasture or forage crops (Yule and Grafton, 2013).

Dairy farmers facing an N cap may forego the practice of applying N fertilizer as close to an economic optimum as permissible using a single application and instead consider the benefits of NUE using split applications. It is likely that if multiple split applications are undertaken, these would need to be applied by farmers or their operations staff. Therefore, spreading equipment employed for split applications would be less expensive and have lower technical specifications than typically used by commercial operators. Although the split applications would be less accurate and have a larger in-field application rate coefficient of variation (Grafton et al., 2013; Mersmann et al., 2013; Yule and Grafton, 2013), they could provide improved overall production and compliance benefits for the producer.

In this study, Monte Carlo simulations were undertaken using software "@Risk 7.6" (Palisade Company LLC, NY, USA) to compare the expected response of urea application on pasture at varying spreading accuracies using equation 1. The Monte Carlo simulations assume randomness of application – any areas that receive an application rate higher than the targeted rate are equally likely to receive a lower than the targeted rate in subsequent applications (and vice versa).

Results and Discussion

Simulation Parameters

The accuracy and uniformity of application spread was modeled for a commercial spreader (~30 m) with an in-field CV of 37% in 2006 (Lawrence and Yule, 2007). With differential GPS, an experienced driver, large regular shaped flat fields, and border and headland control, this value can be reduced to around 20% (Grafton et al., 2013; Mersmann et al., 2013; Yule and Grafton, 2013). In contrast, a farmer-owned spreader (~10 m) without the features listed above, is likely to have a CV of 50% to 70% (Lawrence and Yule, 2007).

Monte Carlo simulations were conducted using 5,000 iterations around the mean (or target) application rate and used a normal distribution pattern for the application (fig. 3). The effect on net urea response in $US, assuming CVs of 20% and 37%, and an application rate of 190 kg ha^{-1}, is shown as a net response using equation 1 (see figs. 4 and 5 respectively). Using the same methodology, this result was compared to four simulated applications at 47.5 kgNha^{-1} with a CV of 50% and 70% (see figs. 6 and 7, respectively).

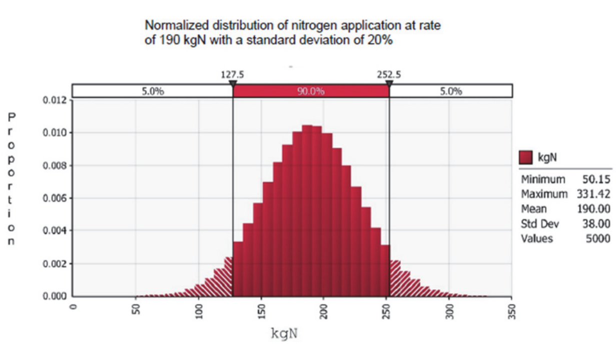

Figure 3. Monte Carlo simulation of an application of 190 kgNha^{-1} applied as urea with spreading accuracy CV of 20%.

Columns 1 to 4 in table 3 summarize the outputs from figures 4 to 7, respectively.

In column 1 of table 3, note the kurtosis of the distribution (displayed in fig. 4) compared to that of the normal distribution (fig. 3). Over-application has little benefit since the response is close to the maximum in figure 2. In column 2 of table 3, note the kurtosis of the distribution (displayed in fig. 5) compared to that observed in figure 4. Again, over-application has little impact on the reduction of the mean response shown in figure 4. Also, note that application rates below 0 kg ha^{-1} are not permitted in the model. In column 3 of table 3, the kurtosis (displayed in fig. 6) is reduced (compared to figs. 4 and 5) when N is reduced to one-quarter of the application rate. This occurs in the steep region of the response curve (fig. 2) and, accordingly, results in a greater DM response. In column 4 of table 3, the kurtosis (displayed in fig. 7) is now larger than that of figure 6 due to the imposition of a higher (70%) CV value. Note, however, that the N application rate (47.5 kgN ha^{-1}) still lies within the steep region of the response curve shown in figure 2. As a result, the poorer accuracy of spread is still less costly than the

Table 3. Effect of spreading accuracy on urea fertilizer response from pasture as modeled using equation 1.

Parameters	Column 1 190 kg N	Column 2 190 kg N	Column 3 47.5 kg N	Column 4 47.5 kg N	Column 5 (4 x47.5) kg N
CV	20%	37%	50%	70%	70%
Std Dev., $	17	73	108	160	319
Kg DM / kg N	13	13	22	22	22
$US Target	525	525	313	313	1,252
$US Model	515	490	270	270	1,080
Figure No.	4	5	6	7	-

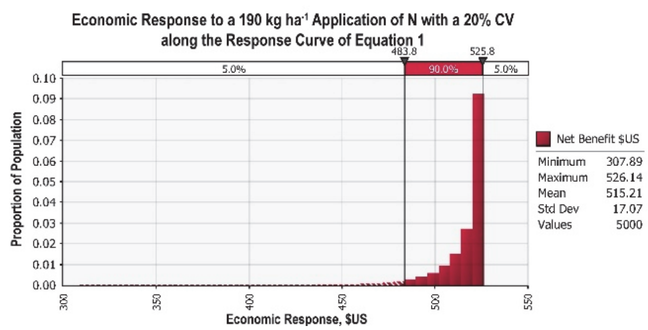

Figure 4. Monte Carlo simulation of net benefit of application of N applied as urea at 190 kgNha^{-1-} applied with CV of 20%, and assuming normal distribution application pattern (fig. 3).

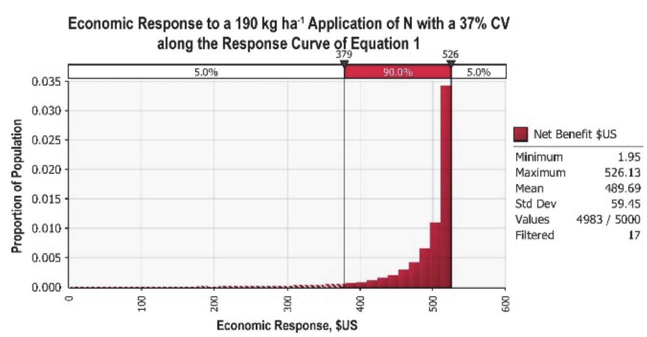

Figure 5. Monte Carlo simulation of net benefit of application of N applied as urea at 190 kgNha^{-1-} applied with CV of 37%, and assuming normal distribution application pattern (fig. 3).

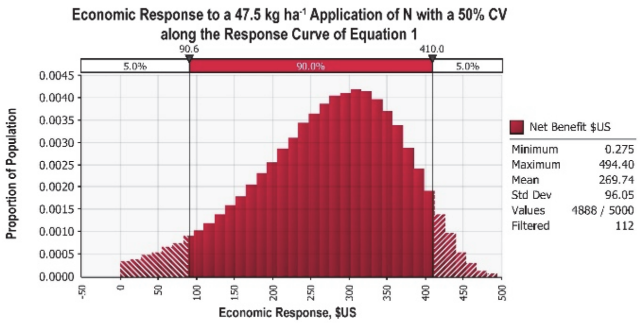

Figure 6. Monte Carlo simulation of net benefit of application of N applied as urea at 47.5 kgNha^{-1-} applied with CV of 50%, and assuming normal distribution application pattern.

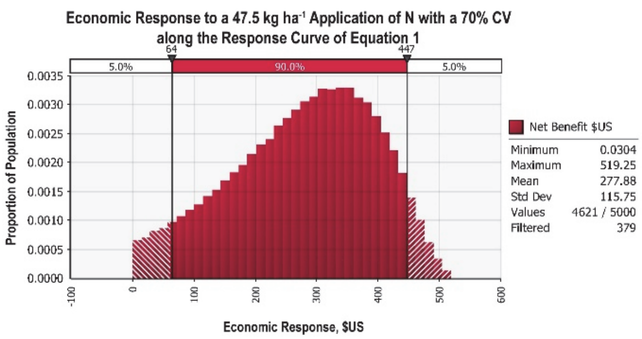

Figure 7. Monte Carlo simulation of net benefit of application of N applied as urea at 47.5 kgNha^{-1-} applied with CV of 70%, and assuming normal distribution application pattern.

maximum permissible application rate of 190 kgN ha^{-1}. Also note that the mean of the targeted N application rate is now larger than in figure 6, as there have been a larger number of values that were below 0 kg ha^{-1} and thus filtered. In column 5 of table 3, the cumulative effect of four discrete applications at 47.5 kgN ha^{-1} with a CV of 70% is shown compared with one application at 190 kgN ha^{-1}. Since the maximum allowable targeted rate (190 kgN ha^{-1}) is applied over four applications (each at 47.5 kgN ha^{-1}), the uniformity of spread will have a standard deviation of the square root of 4, compared to the case of a single application of 190 kgN ha^{-1}. So, the uniformity improves, and the kurtosis of the distribution decreases. Figure 8 (not summarized in table 3) demonstrates that, even with a 20% CV at low application rates, there is little benefit in accurate and uniform fertilizer spreading.

The modeled results demonstrate the benefits of split applications of urea using a response curve based on average total soil N levels on dairy farms in New Zealand (Shepherd et al., 2015). The response is also dependent on spreading accuracy (Grafton et al., 2017; Lawrence and Yule, 2007; Grafton et al., 2013; Mersmann et al., 2013; Yule and Grafton, 2013). This modeling approach implies that, at low application rates, the pastoral response is less dependent on application accuracy than at rates approaching the economic optimum. This supports some of the research conducted on the split application of urea in New Zealand (Cameron et al., 2013; Di et al., 1998b; Bishop et al., 2008; Shepherd et al., 2015).

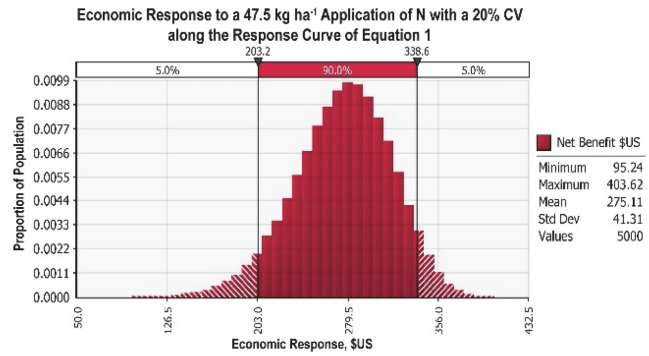

Figure 8. Monte Carlo simulation of net benefit of N applied as urea at 47.5 kgN ha^{-1} applied with CV of 20%, and assuming normal distribution application pattern. Although figure has kurtosis very similar to "Normal distribution", net benefit in improved accuracy is negligible.

Conclusions

The results from the Monte Carlo modeling simulation suggest that if urea applications are split and applied when appropriate, ideally in spring and autumn when growth responses are higher, then N use efficiency (in terms of DM per kg N applied) increases. The growth and utilization gains from split applications remain, even if spreading accuracy is poor, as all fertilizer is applied below the optimum of the response curve (fig. 2), rather than above the optimum where cost is added and there is little gain in response. This is because the application is along the steep part of the response curve where yield response in terms of income is much greater than the cost of urea applied.

Improved N efficiency reduces excess uptake of N in the pasture as pasture growth is achieved with less N. This would also reduce the N content in cattle urine, which is the major source of N leachate issues on New Zealand's dairy farms.

The modeling demonstrates that even when application accuracy is low, such as when undertaken by small wheel-driven spreaders, the economic returns are similar to those found in scientifically randomized block trials.

Implications

The implications of this study are that dairy farmers may achieve improved returns under an N cap, even by using low specification and technological equipment, instead of using contractors employing high specification equipment for fertilizer spreading. The use of smaller farmer-owned spreaders (without GPS or rate control) means that spreading widths are much smaller (~10 m) than larger commercial models used by contractors (~30 m). Therefore, farmer-applied split applications may be more expensive than using a commercial operator; however, the value of dry matter modeled is more than double that of a one-time application at the N cap (see table 3).

The cost of an application can be reduced by having a supply of urea on hand to apply when conditions most warrant application by installing a small on-site silo. This would save a bagging charge of US$17.50 for 0.5 and 1-tonne bags (Ravensdown, 2021).

At low application rates, farmer-managed fertilizer applications may have greater accuracy than those expressed here. This situation could occur if spreading is undertaken randomly, so that on average, over four applications, each area may receive a similar quantity of fertilizer. These applications may also help integrate fertilizer spreading with effluent management, which has been left outside the N cap but is controlled by New Zealand's Regional Councils (Bishop and Manning, 2011; Castillo et al., 2000; Dexcel, 2007; DairyNZ, 2015; Di et al., 1998a; Di et al., 1998b; Shepherd et al., 2015; DairyNZ, 2020).

There is a potential issue with high fertilizer rate-spreading CVs. In these situations, the application of urea to non-responsive areas (such as laneways) or environmentally sensitive areas (such as streams and wetlands) becomes more likely, and the impact of the dairy farm on the freshwater environment is increased. However, this risk could likely be reduced by the narrower spreading widths of farmer-applied fertilizer spreaders. As these units have smaller and slower rotating spinning disks, control near boundaries and sensitive areas can be more easily managed.

Additionally, the use of split applications of urea may be a cheaper option than applications of slow-release or polymer-coated N fertilizers that can be applied at higher application rates. This is due to these products being 10% (slow-release N) to 50% (polymer-coated urea) more expensive than urea, with the former losing effectiveness if not used within six months (Ravensdown 2021).

In summary, the Monte Carlo modeling approach used in this study links spreading accuracy to fertilizer response and provides a rationale for split applications of urea under a synthetic N cap in New Zealand.

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