Doing more for the environment with lower inputs in pasture-based livestock systems: does this always lead to lower outputs?

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Abstract
The rates of production growth achieved in the pasture-based livestock industries of New Zealand and Australia in the absence of environmental regulation may be curtailed as they enter a regulated future. Environmental limit-setting policy requires science that encompasses the multiple ways in which food can be produced, the multiple ensuing environmental emissions, and the long-term (50 to 100 year) relationships between these seemingly competing interests. In this paper, we use the rapid growth in food production achieved in the New Zealand dairy industry between 1990 and c. 2014 as an example of the emerging tensions between food production and environmental management. We describe an analysis, based on simulation, of the trade-offs between rates of food production and the long-term environmental impact of meat and dairy production systems which shows that it is not the change in land use from meat animals to dairy animals per se in New Zealand that has led to greater environmental impacts. Rather, it is the level of nitrogen (N) inputs associated with intensification of dairying that matters. The analysis shows that land use change from meat to dairy (with total nitrogen inputs of around 150 kg N/ha per year in the latter) can result in lower total emissions per hectare. We also show that interactions between food production and environmental emissions across the full spectrum of options cannot be represented by a single relationship, despite the attractiveness of such a simplification. The implications of this for science and policy are discussed.

Keywords
Food production, meat, dairy, pasture, environmental impacts, nitrogen.

Introduction
The quest to produce more food for a projected global population of 9 b people by 2050 raises the spectre of a conflict between food production and the consumption, or deterioration, of environmental resources (Godfray et al. 2010). Concern is deepening in many jurisdictions as the requirement for environmental resources increases from many sectors of the economy, and as the demand grows from societies that the quality and availability of environmental resources is protected for future generations. These concerns are very prevalent and topical in the context of grassland ruminant production. Much of the debate centres around a perception that any attempt to increase agricultural output (food production) is synonymous with worsening environmental impacts, and that decreasing inputs and animal numbers is the obvious, if problematic (from a food supply stand-point) solution. In this paper we revisit recent analyses that suggest reducing inputs and/or outputs is not always best: hence the question mark in the title. A deeper look at how food production from grassland (in its many forms) and its environmental impacts (also in its many forms) are inter-related may offer a better basis for society to seek better solutions. However, the conditions required to attain these 'better' solutions must be clearly understood and defined.

One previous attempt to depict a general relationship between food output and environmental 'good', in a form that suggests useful compromises are available, is shown in Figure 1 where, to the far right of the agricultural output axis, measures of environmental quality decline disproportionally to gains in production. This implies that a limited reduction in food output from near maximum levels (e.g. point C on the curve) towards some optimum, (e.g. point D) would be beneficial. Graphs of this form, plotting what are in fact two outputs (or goals) from a system against one another, are common in consumer economics and behavioural ecology, notably where the objective is to find an optimal trade-off between multiple goals. While the conceptual relationship shown in Figure 1 makes intuitive sense, it is not a causal relationship. Furthermore, it is questionable whether all forms of food production will have the same general impact on all environmental impacts such that one single line can encompass all situations. Nor is the shape of the line a certainty.

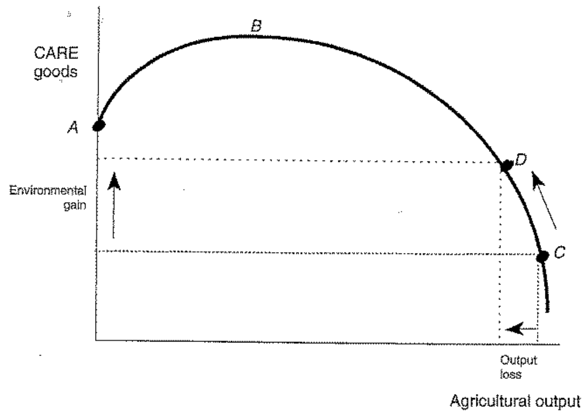

Figure 1. General relationship describing conflicts between product output (x-axis) and environmental outcomes (y-axis) in agriculture. From McInerny (2000).

Increases in food production from grasslands can be brought about in different ways and these can each result in a different balance of environmental impacts: the main ones of interest currently being nutrient losses, greenhouse gas emissions, and adverse impacts on carbon sequestration/soil organic matter. The different impacts depend on how the increase in food was created, whether it was from the use of more fertiliser, or a change from meat to dairy production, as two basic examples relevant to grasslands. Rather than seeing the food/environment conflict as captured and depicted in a single curve, we may expect multiple, separate curves. Indeed, we would hope this was the case, as it would increase the prospects for mitigation via practical farm systems solutions and effective environmental policy for sustaining food production within acceptable environmental impact limits. It is certainly important to ensure that those advocating for reduced impacts do not propose 'solutions' that make little difference (or, in fact, make the situation worse) at the expense of essential food supply and the viability of the industry that delivers it.

In this paper, we consider whether expansion and intensification is always the problem behind environmental impacts in pasture-based livestock systems, or whether it can even at times be a solution. We consider changes in the area of land used, as well as the intensification of land use, notably shifts between meat and dairy systems, using insights from a process-based model of environment-soil-plant-animal interactions (Parsons et al. 2016).

The New Zealand dairy industry provides a good case study here because both land use area change (expansion) and intensification (defined as using more inputs to increase production from the same unit of land) have both occurred during industry development over the last 2-3 decades. The individual effects of intensification and expansion are often conflated, which introduces confusion and the risk of mis-identifying the true nature of the problem.

Growth in the dairy industry in New Zealand: the past quarter century

The largest single trend in agricultural land use in New Zealand in recent decades has been the overall growth of the dairy industry, from around 1.02 m hectares and 2.40 m cows in 1990/91 to 1.75 m hectares and 5.02 m cows in 2014/15 (Table 1). Simultaneously, public concern regarding the negative environmental impacts of 'intensive' dairy farming has risen sharply, as reflected for example in Foote et al. (2015), and calls in social media for (total) dairy cow numbers to be reduced by 80% (http://www.nzherald.co.nz/the-country/news/article.cfm?c_id=16&objectid=11669052).

Table 1. Changes in cow numbers, feed eaten and N eaten in the New Zealand dairy industry, 1990/91 to 2014/15. Non-pasture feed includes crop, supplement harvested on farm, and supplement purchased from off farm. Based on Wales and Kolver (2017).

	Total cows (m)	Feed eaten per cow (t DM)			Total feed eaten (m t)			Total N eaten ('000 t) [1]		
		All feeds	Pasture	Non-pasture	All feeds	Pasture	Non-pasture	All feeds	Pasture	Non-pasture
1990/91	2.40	3.96	3.77	0.19	9.50	9.05	0.46	308	299	9
2014/15	5.02	4.93	4.04	0.89	24.75	20.28	4.47	759	669	89
Difference	2.62				15.24	11.23	4.01	451	371	80
Difference due to increased cows [2]					10.38	9.88	0.50	336	326	10
Difference due to change in feeding [3]					4.87	1.36	3.51	115	45	70

[1] Assumes mean N content of DM as follows: pasture 3.3%, non-pasture 2.0%
[2] = (total cows in 2014/15 x 1990/91 feeding levels) – (total cows in 1990/91 x 1990/91 feeding levels)
[3] = (total cows in 2014/15 x 2014/15 feeding levels) – (total cows in 2014/15 x 1990/91 feeding levels)

While calls such as that cited above can be, and are, hotly debated, there is little doubt that the overall growth of the dairy industry between 1990/91 and 2014/15 will have affected environmental outcomes. The data in Table 1 place the issues in perspective. Between 1990/91 and 2014/15, the total amount of feed dry matter consumed by the national dairy cow herd grew by a factor of 2.6. Of the additional 15.24 m t feed eaten in 2014/15 compared with 1990/91, about 10.4 m t was associated with more cows, while 4.9 m t was associated with increased feeding per cow. Increased use of non-pasture feed (including supplements imported onto the farm) accounted for 72% of the latter (3.5 m t). Over this time period, non-pasture feed increased from around 5% of total feed per cow to around 18% (Table 1). Simultaneously, the application of N fertiliser to increase grass growth increased from a national average of around 50 kg N/ha per year in 1990/91, to around 200 kg N/ha per year (MPI 2012).

Assuming the mean N content of dry matter eaten was 3.3% in pasture and 2.0% in non-pasture feed, the national herd consumed approximately 760,000 t of N in 2014/15: an increase of 450,000 t from 1990/91 (Table 1). A substantial proportion (typically >95%) of N eaten by ruminants is excreted/secreted, whether as urine, milk or in dung, though as we stress later, the partitioning between these forms is obviously very different in lactating animals (such as dairy cows) than in dry-stock. A great deal of attention has been focussed on the fate of N in urine (which accounts for about 70% of the N eaten in dry stock, but only c. 50% in lactating stock, Kebreab et al. 2001). Of the N in urine, about 20% is eventually leached (Selbie et al. 2015), noting there is a wide range in leaching among farms dependent on soil type and climate. On a simple mass balance basis, we could estimate that N leaching losses, alone, of ~ 76,000 t N per year could be expected from dairy farms in 2014/15. This is an increase of c. 45,000 t N per year (compared with 1990/91).

But seemingly straightforward calculations such as this overlook the fact that N losses will have been incurred under whatever alternative land use prevailed before conversion to dairying. They also miss the point that urine alone, and indeed animals per se, are not the original source of N losses, nor the only source of N loss, as we stress in this paper. Losses of N as nitrous oxide, a potent greenhouse gas, are widely described, and significant in the overall footprint of all food production activities. Rather, it is important to account for *all* losses/releases of N, and not just those associated with these two routes. There are considerably larger rates of N loss/release by denitrification. While a high proportion of these losses is in the form of di-nitrogen (N_2) which is environmentally benign, it follows that N inputs (e.g. as fertiliser) are required to replace the N lost by all pathways to sustain production. Thus there is a link between leaching and nitrous oxide emissions and all N outputs that are not in the form of products. In the text below we account for the fate of all N inputs to, and cycling within, the system. (A breakdown into the many different components of that loss is available from the authors).

It is also important to comment that the growth in the dairy industry over this period has contributed heavily to New Zealand's export earnings: in 2014, the value of dairy exports was $NZ16.9 b, or 46% of total primary product export value. Importantly, this growth occurred largely in the absence of environmental regulation. That era is now over, following the release (in 2014) of the NZ Government National Policy Statement for Freshwater Management (www.mfe.govt.nz) and the introduction of limits on nutrient emissions from land-based industries administered by 13 Regional Councils throughout the country. Hence, fundamental analyses of the nature of the relationship between food production and environmental impacts in pasture-based livestock systems are critically important for assisting policy and practice aimed at balancing these seemingly competing interests.

Dairy industry development in New Zealand: which way from here?

New Zealand is entering a critical phase where the implementation of policy to address environmental issues must be informed by (among other imperatives) sound science to ensure the problems are, indeed, solved and the risk of negative consequences elsewhere is avoided. Policy must address more than just nutrient concerns. As a signatory to the Paris agreement (December 2015), New Zealand must now achieve reductions in total greenhouse gas (GHG) emissions: agriculture currently contributes about 48% of the national GHG inventory, therefore the inclusion of agriculture in emissions reduction targets is politically unavoidable. The challenge for policy is to signal then regulate the practice changes required to achieve sustainable nitrogen and carbon (C) balances under different land uses. This extremely difficult task is only partially assisted by empirical science which is almost always forced to operate within time frames that are too short to allow consideration of long-term outcomes. The only certainty is that change is required.

But change to what? How can we identify, through science, the long term (50-100 year) consequences of the numerous possible ways to increase (or decrease) the amount of food produced, and/or its multiple environmental impacts, when some of the proposed changes have not yet been studied, and when robust grazing trials are expensive and typically continue for only 3 to 5 years? Here we draw on insights from a well-established, dynamic, process-based model (Hurley Pasture Model, HPM) that captures the long-term trends in C and N cycling and dynamics under grazing (Parsons et al. 2013; 2016). Later, where possible, we link those insights back to recent data from farm systems studies to join up some of the theoretical and empirical information to increase our confidence in the insights drawn. Parsons et al. (2016) describe in detail the provenance of, and the use of the model to capture the feedback loops between soil, plants and animals that govern the cycling of C and N under grazing.

One critically important feature in the analytical approach is that the model was parameterised to make optimal use of pasture for animal feeding, in all cases. This is essential to ensure that the effect of simple mismanagement of pasture feed supply does not cloud the issue. When changes are made to the farm system, for example by adding more N in fertiliser to an N-deficient system, there will be major increases in plant growth and feed supply. Without an appropriately matching adjustment in animal numbers, the effect of such a change on the pathways by which N and C move through the system and into the environment would be masked by the phenomena of under-utilisation. In the present analysis (as in Parsons et al. 2016) we apply a consistent algorithm for adjusting stock numbers to implement control of vegetation state and give a more direct line of sight on the fundamental effects of any changes being made.

In this approach, the number of animals per unit area is therefore an emergent property of the model, not a pre-fixed value, because the model adjusts animal numbers to best match feed demand to feed supply. Fundamental comparisons of the efficiencies of, for example, dairy versus beef grazing systems, are then possible, without requiring judgements about which stocking policies (animals per hectare, grazing method) to model. This simplification must always be acknowledged in the interpretation of the predictions and analysis. We note, however, that the goal of utilizing as much of the pasture grown as possible for animal production is common to high performing pasture-based livestock production farms irrespective of livestock species. It is widely advocated as being the most effective basis for livestock feeding, and that there are many combinations of strategic and tactical grazing decisions which can achieve this in practice (Chapman and Griffiths 2017).

Insights into the impacts of NZ pastoral agricultural development over the past 25 years

Previously, we noted that the overall growth of the NZ dairy industry from 1990-2015 was driven by greater intensity of farming practices (an increase in inputs and outputs per unit land area) as well as an increase in the total area under dairy farming, and that these two aspects of industry growth are often conflated. Focussing just on changes in total cow numbers is not helpful, because this measure doesn’t allow the two growth pathways to be separated, and potentially limits the search for better solutions to the conflict between food production and environmental outcomes. In the sections below we deal first with intensification (using units of per hectare for all processes), then consider the case of area expansion.

Predicted, long-term sustainable outcomes for production and environmental emissions per hectare from several example land use scenarios are presented in Figure 2. These represent a restricted cross-section of pastoral land use change in New Zealand since c. 1990, starting with relatively low input (60 kg N/ha per year) meat production (M60; beef finishing, rather than breeding cow/calf), then moving progressively left to right to dairy production (L) based on first the same low inputs (L60) then higher inputs of N (L150 and L300; 150 and 300 kg N/ha per year respectively). Finally, two further meat production scenarios are presented, each also with higher inputs of N fertiliser (M300 and M150; 300 and 150 kg N/ha per year respectively). These are included to provide a fundamental comparison of two animal systems (when comparing L and M) at the same level of N input, as well as to consider what the outcomes might be following any return from dairy production to meat production, but where meat systems perhaps retained some aspects of intensification, e.g. higher N inputs.

Supplementary feed is excluded in the examples chosen here (but is considered in detail in Parsons et al. 2016). We can also incorporate grass/legume systems into this analysis, but suffice to say the phenomena are very similar whether the N input is derived from fertiliser N or from fixed N and the relative benefits of grass/legume vs fertiliser N systems are covered elsewhere (e.g. Chapman et al. 1996). In the analysis reported here, no distinction is made between different N sources. In practice, the total N input may come from some combination of N fixation, N fertiliser, and N in imported feed. We note here that, in this practical context, from 1990/91 to

2014/15, the major change in N inputs to dairy farms has been a large increase in the amount of N fertiliser applied.

The model predicted that the production of meat using few inputs (M60) results in relatively low total emissions of N per hectare (Figure 2c). However, total food production (measured as kg protein N per hectare, Figure 2a) was also low. This low N input-low N output system also ranked poorly when assessed against the key efficiency indicator of kg N in food products per kg N lost to the environment (Figure 2e). The rate of carbon sequestration in soil organic matter was similar to the other systems simulated (Figure 2b) and, while absolute methane production was relatively low (Figure 2d), methane emission per unit of food product was high (Figure 2f: note for this measure, large values are 'worse' than small values).

Moving from this scenario to milk production (L) and increasing inputs of N to 150 kg/ha per year markedly increased food production (Figure 2a), with relatively small predicted increases in total absolute N losses and methane emissions (Figure 2c and 2d respectively). Taken together this substantially improved the efficiency of food production relative to its environmental impacts (Figures 2e and 2f). A further increase in N inputs per ha to the dairy system (L300) led to further gains in food production per ha (Figure 2a), though the marginal benefit (yield gain per unit N input) of this further increase in N input was of course reduced. The constraint in L300 is the diminishing return in C capture rate per unit N input, associated with the fundamental physiology of leaf area expansion and light interception in grazed grass-based swards, as explained by Robson et al. (1988). The model suggests that, at the higher N input level (in this case likely achieved from N fertiliser), the system has moved onto the steeper part of the exponential curve that describes the relationship between total N inputs and total N emissions from grazing systems (Carran and Clough 1996; and see Figure 5 c in Parsons et al. 2016).

The greater N input (300 v 150) led to major increases in the absolute N release to the environment (Figure 2c). But, although the N releases were increased in absolute terms, the efficiency of food production per unit N release to the environment remained far greater for this high input, high output dairy system, than for the low input-low output meat system (Figure 2e), even with 300 kg N input per ha per year. Likewise, methane production per unit of food product remained low (Figure 2f).

There are two key points we can stress from this analysis when we compare the outcomes in food production and environmental impacts from dairy with those from meat, at the same level of N input (e.g. L150 with M150; or L300 with M300). The first is that dairy systems are substantially more efficient in the use of inputs of N than are meat systems and this difference in efficiency is a direct outcome of a greater proportion of the N ingested per hectare (as well of course as per animal) being partitioned to, and removed, in food products (Kebreab et al. 2001; Dijkstra et al. 2013). Comparing L150 with M150, the former sustainably delivers over 2x the amount of food production per ha (Figure 2a), with only half of the total N emissions per ha (Figure 2c) (this is all N entering the environment in any form), hence a 4- to 5-fold increased efficiency in food production per unit N input. The increase in efficiency is sufficient to allow much greater food yields from dairy with disproportionately small absolute increases in adverse environmental impacts. This is true even when L150 is compared with M60: i.e. when higher N inputs are used for milk production than for meat production.

This suggests that dairy per se is not 'bad' for the environment, as is popularly argued. Indeed, using the same examples, conversion of land from intensive dairy production back to meat production, even lower input meat systems, would lead to a substantial reduction in the supply of food products from grassland with little benefit to, indeed in some cases a substantial worsening of, environmental outcomes (compare L300, or L150, with M60, Figure 2).

Second, looking at outcomes on a per ha basis, and so at the impacts of intensification, it is not the number of animals, or the physiology/species of animals, that determines the size of N losses. It is the amount of N input per hectare. Animals are not a source of N, despite their highly recognised and important role in altering the fate of N. The only true de novo sources of N in the farm system, whether for food production or emissions to the environment, are fertiliser N input, N fixation, atmospheric deposition, and importation in supplementary feed. Soils may substantially buffer the demand for N by plants, but the amounts of N (and C) that can be sustained in soil are also driven by the rates of inputs of N (and C).

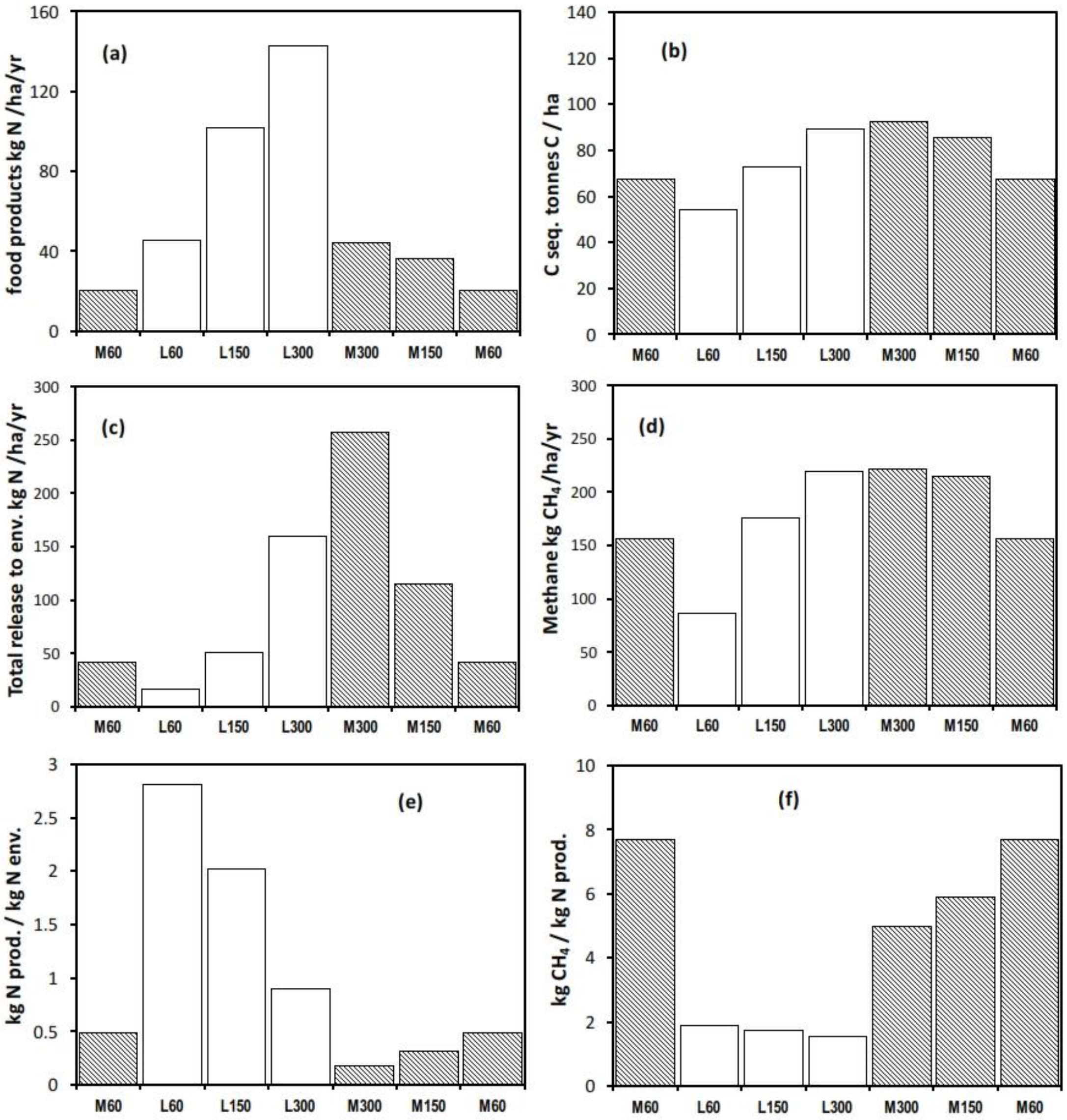

Figure 2. Predicted effects (all expressed per ha) on (a) food production (in units of meat or milk N), (b) carbon sequestration, (c) total N release to the environment and (d) methane, of simulated meat ('M'; shaded bars) or dairy ('L', lactating, open bars) systems using different N inputs (60, 150 or 300 kg N/ha/year). The associated efficiency of food production per unit N release is also shown in (e).

In all scenarios presented in Figure 2, the amount of N removed in products (Figure 2a) and the total release of N to the environment (Figure 2c) sum to the simulated rate of N input. The graphs depict the sustainable outcomes of long-term and dynamic feed-backs between plants, animals and soils in which all outputs must add up to, and balance with, N inputs. The balances depicted here can differ substantially from those derived from short-term analyses such as farm nutrient budgets. The predicted effect of management changes over 50-100 years can be counter-intuitive, sometimes opposite to the predicted short-term (3-10 year) consequences (Parsons et al. 2016). Hence the results of short-term field trials must be interpreted with caution, and over-extrapolation from static nutrient budgets to represent long-term outcomes should be avoided.

Relationships between outputs

Figure 2 shows the predicted consequences (on the y-axis) of changes in inputs or actions (bundled together in systems on the x-axis). This is conventional when plotting a causal relationship. However, as noted in the Introduction, this does not directly or immediately convey the answer to the question of how increasing food production is related to environmental impacts in the same seemingly simple way that Figure 1 does. However, given what we have just described, it is clear that the results of the simulations depicted in Figure 2 cannot be plotted using the same axes used in Figure 1.

As we proposed in the Introduction, the total environmental impact (denoted as 'care goods' on the y-axis of Figure 1) of a farm system is made up of multiple components, each of which may respond differently to different ways of increasing food production. In Figure 3, we have plotted the four key outcomes of interest (food production, C sequestration, total N release/emissions, and methane emissions, all per hectare) using the same model outputs, but in this case in relation to rates of food production on the x-axis. Hence, note, the relationship between 'food' and food' is (reassuringly) a straight line in Figure 3a.

Each curve is derived from six values representing successive increases in simulated fertiliser N inputs: 15, 30, 60, 150, 300 and 600 kg N/ha/year. The different lines in each graph depict relationships for meat (solid line) or dairy (dashed line) production. It is immediately obvious that a relationship such as that conveyed in Figure 1 would be very difficult to derive from our knowledge of the way grassland production systems function, where all carbon-related outputs (yield, C sequestration and methane) plateau with increased N inputs whereas all nitrogen-related outputs increase exponentially (Whitehead 1995; Carran and Clough 1996; Parsons et al. 2016).

Drawing a vertical line at different positions along the x-axis in Figure 3b-e to intersect (if possible) the curves reveals the predicted environmental outcomes for a given level of food supply. Simultaneously, the food production system (limited here to meat or dairy) and/or N input rate required to deliver all those outcomes is also revealed. If more than one plotted line is intersected, this means there are alternative ways of delivering the same total food output: but they could have markedly different environmental outcomes. Likewise, the intersection of a horizontal line originating from any point on the y-axis indicates whether there is more than one alternative way to deliver a chosen environmental outcome: and what the consequences of this would be for the level of food production achieved.

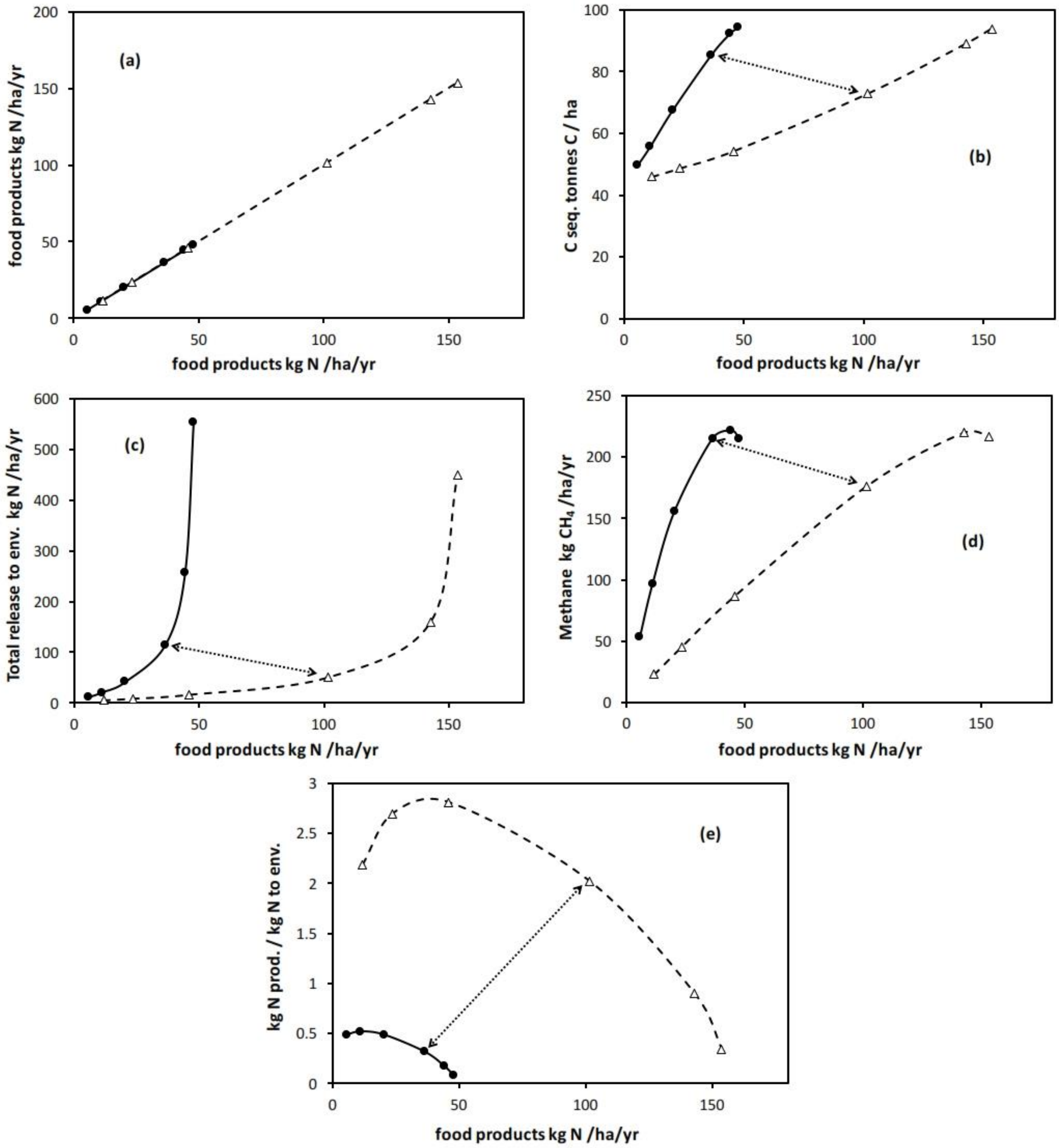

Figure 3. Predicted relationships between food production (kg N/ha per year) and its consequences for C sequestration (b), total N releases (c) and methane (d) where food is produced as meat (solid line) or dairy (dashed line). The values along each line show the impacts of where food production was increased using increasing N input (15; 30; 60; 150, 300 or 600 kg N/ha/year). Dotted lines with arrows contrast meat and dairy at the same level of N input (150 kg N/ha/year). The layout in (a) to (e) is purposely the same as in Figure 2, so in (a) food production appears on both axes (hence the 1:1 line).

Last, but not least, comparing points representing the same level of N input on the meat and dairy lines (see the dotted lines joining 'L150' with 'M150' in each case in Figure 3) reveals what is the impact of switching between meat and dairy.

While this may appear complicated, some of the conclusions are profoundly straightforward. For example, if the driving desire of society was to obtain high food output per ha from grassland, the model predicts this simply cannot be achieved using a meat production system, at least not fed grass alone. It also predicts that, in many cases the environmental consequences of certain combinations of N inputs and dairy animals are no worse than when using meat animals, while the food production rates are much higher. This is true even in absolute terms (Figure 3c and 3d), let alone true in terms of production efficiencies (Figure 3e). These diagrams offer a capacity to weigh up different expectations for food supply and/or environmental impacts and illustrate what scope there is, using what systems, to deliver different combinations and balances of these.

Expansion/contraction of land area used for dairying
The predicted consequences of expanding or contracting the area of land used for dairying (or meat production) in terms of food supply and environmental impacts are readily obtained from the graphs above of the consequences of changes expressed per hectare. To see the effect of changing the total area (alone) of the dairy industry, the outcomes can all simply be scaled linearly: i.e. halving the area at a given production intensity leads to a halving of values calculated from the y-axis (and vice-versa, for expansion). But this simple scaling detracts attention from how changes in the overall size of the dairy industry can involve both changes in the area (ha) and in the intensity (per ha) of land use. Which is better, changing area or changing intensity?

As is well recognised, the responses to nitrogen inputs per unit land area are very non-linear (e.g. Parsons et al. 2016). All components of the system involving carbon (food production, methane emissions, and carbon sequestration) plateau as inputs such as N fertiliser per ha (a component of intensification) increase. All forms of N emissions show exponential (upward) type increases following intensification. In all cases, then, as we stress in this paper, it is better to aim to sustain an overall intermediate (here say 150 kg N/ha/yr) as opposed to higher level of inputs per hectare, as higher levels of inputs reduce substantially the 'efficiency' ratio of food production to N emissions.
What this means is that, if increasing the size of the dairy industry it is better (at least, biologically) to increase the total area, rather than to increase the 'intensity' of inputs per ha; but if called upon to reduce the size of the dairy industry, it would be better to sustain the larger area, but reduce the 'intensity' (of N inputs). In short, having the current c. 2 million hectares running at 150 kg N/ha/yr would give a far more beneficial outcome than having 1 million hectares running at 300 kg N/ha/yr, even though both cases involve the same total absolute N input to the industry. The former would have greater industry wide yield, with smaller industry wide environmental impacts. Both approaches would involve some reduction in cow numbers, but focussing simply on total cow numbers does not help distinguish between the two approaches.

Some empirical evidence
Empirical research into the relationships between grassland food production and environment impacts overwhelmingly seeks solutions *within* livestock systems (e.g. meat, Mason et al. 2003, or dairy, McDowell et al. 2017), with the inevitable result that some form of single line representation, similar to Figure 1, is perpetuated. This will tend to constrain the range of solutions that emerge for catchment water quality or national GHG inventories or, worse, result in poorer outcomes if society insists on picking one livestock system (e.g. meat production) over another (e.g. milk production) based on a misleading conceptual framework for "how things work".

The analysis described here is an attempt to move beyond the restrictions of empirical research and sector-based thinking. The results are based on a process model and must of course be treated as indicative, not absolute. Confidence in simulation information is frequently sought by comparing predicted values with observed data. This is a valid and important exercise in many cases: but one beset by stiff challenges in this case. First, as noted above, different grass-based food production systems (e.g. meat versus dairy) are never compared within the same empirical study design. Even farm benchmark data sets (which have some utility, but also some inherent limitations, for this sort of analysis) are held separately by industry-good organisations, and use different physical production metrics. Environmental benchmark data sets are only now starting to accumulate. Secondly, for environmental factors such as total N emissions, very few full-scale grazing studies have directly measured all components of N losses. Where these have been measured, they are often confined to volatilisation, leaching or nitrous oxide emissions, with no account of di-nitrogen fluxes (the substantial component of denitrification) which generally dominate the atmospheric loss pathways (and are included in the model output presented here). Moreover, even within empirical experiments in GHG mitigation programmes, components such as methane, nitrous oxide, and (soil) carbon sequestration are rarely combined.

Nitrogen contained in food produced with different inputs is always measured (as milk protein yield) in dairy systems studies, so this provides one reference point for comparing simulated and observed values at that relatively basic level. Fertiliser N inputs are also well documented. For example, in the study reported by Chapman et al. (2017), a 'lower input' dairy system operated under irrigation in Canterbury, New Zealand, stocked at 3.5 cows/ha with an average (over 4 years) of 154 kg N fertiliser/ha per year and minimal imported supplement yielded 117 kg N/ha per year in milk. This aligns closely with the predicted value in Figure 3, of just over 100 kg N/ha in milk (the role of N in supplements is considered by Parsons et al. 2016). Note, in the model, the system was simulated with minimal soil-based constraints to pasture growth (akin to irrigation and adequate base levels of essential soil nutrients, as applied in the grazing study) plus optimal utilisation of pasture grown for animal production (as achieved likewise through rigorous grazing management implementation in the empirical grazing study). Estimated (using Overseer©) mean annual nitrate leaching was 32 kg N/ha per year.

In the same study (Chapman et al. 2017), a 'higher input' system (mean 309 kg N/ha per year as fertiliser, stocked at 5 cows per hectare) produced 154 kg milk N per hectare per year. Again, this is similar to the value for milk N yield predicted in Figure 3, and was clearly achieved with much lower overall N use efficiency compared with the 'lower input' system. Moreover, this level of milk production required high inputs of N and C in supplement (> 5 t DM/ha per year). For an indication of relative N losses (since leaching is only one component of N emissions), this was associated with a 44% increase in nitrate leaching (mean 46 kg N/ha per year) compared with the 'lower input' system. This order of increase in N releases to the environment aligns with the predictions from the same model as used here, but with supplements added, in Parsons et al. (2016).

The general alignment between the observed data described above (which is admittedly limited, and sometimes itself also from a model, e.g. Overseer©) and the corresponding predicted values in Figures 2 and 3 lends some confidence that the simulations reported here are capturing the critical phenomena of pasture growth, utilisation, milk production and C and N cycling in grazing systems.

Inevitably much more empirical information is needed for the full suite of environmental factors under different systems of food production from grassland to increase confidence. We note that, even starting now, new empirical studies could only measure short-term results, and not the sustainable outcomes of the food production systems we require to feed a growing global population. What matters most for any analysis is that: (i) all the inputs of C and N are accounted for; (ii) likewise, all the outputs are accounted for (and so the system 'adds up' in its entirety); (iii) we do know plants show diminishing returns in C uptake with increasing N availability; (iv) we also know that animals excrete/secrete differing proportions of the N they ingest under different conditions; and (v) all N not removed in products (or sequestered) will ultimately be released to the environment. Given that all those conditions are covered by the model, phenomena such as those depicted here are highly plausible and likely inevitable.

Conclusions

Different ways of producing food (such as dairy or meat), and different ways of increasing food production (such as using higher rates of N input), have very different effects on the relationship between food output and environmental impacts. This is true not just of the overall environmental impacts, but the balance among the different forms of impacts. For dairying in New Zealand, the analysis presented here suggests that total N inputs of around 150 kg N/ha/year combined with high levels of utilisation of pasture for animal feeding strikes an optimal balance between food production and environmental outcomes. It coincides with the point where the capacity for carbon fixation plateaus as more N is added, and beyond which (indeed as a consequence of which) additional N inputs result in exponential increases in N release to the environment. As can be seen in Figure 3, this gives neither maximum food production, nor maximum overall N use efficiency: rather, it appears to strike the optimum trade-off between the absolute amount of food produced, the N use-efficiency of that production, and its adverse impacts on the environment from a *biological* stand point.

From this perspective, therefore, we can posit that the impacts on the environment (including those on freshwater and in GHG emissions) brought about by land use change to dairy in New Zealand over the past 25 years are not a fundamental problem caused by farming dairy cows versus other animal species per se. Far from it. It is much more likely that they are consequences of a substantial increase, and in some cases an over-use, of total N inputs. The way forward for the NZ dairy industry must include 'dialling back' where possible on the rate of N inputs. It must also involve improvements in the efficiency of N use achieved at any given level of N input (Pinxterhuis et al. 2015). However, we cannot aim for maximum efficiency alone because the greatest N use-efficiency is obtained when the absolute level of food production is very low.

It remains for society to decide what balance between food production and any consequences of it is acceptable, *sociologically*. The best efforts of science should then be directed to understanding how the system 'works' to identify how different actions will affect the balance of consequences for food production and different components of environmental impact. This should then form the basis of policy.

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