Front. Agr. Sci. Eng. 2021, 8(1): 148–158 https://doi.org/10.15302/J-FASE-2020372

REVIEW

NEW ZEALAND DAIRY FARM SYSTEMS AND KEY ENVIRONMENTAL EFFECTS

Jiafa LUO (✉), Stewart LEDGARD

AgResearch Ruakura, Private Bag 3123, Hamilton, New Zealand.

KEYWORDS

dairy farms, environmental impacts, grazing systems, intensification, mitigation,

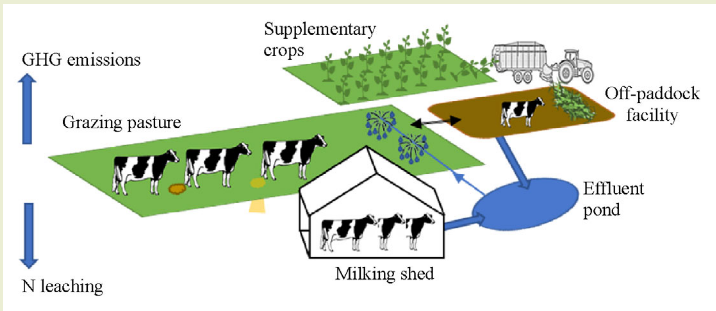
HIGHLIGHTS

- New Zealand dairy farming systems are based on year-round grazing of perennial pasture (ryegrass/white clover).
- Milk production per hectare has increased by about 29% with increased use of externally-sourced feeds over the last two decades.
- Externally-sourced feeds with a low protein concentration can potentially reduce N_2O emissions and N leaching per unit of production.
- Systems analysis is important for evaluating mitigations to minimize trade-offs between environmental impacts.

Received July 24, 2020;
Accepted November 16, 2020.

Correspondence: jiafa.luo@agresearch.co.nz

GRAPHICAL ABSTRACT



ABSTRACT

This paper provides an overview of the range of dairy pasture grazing systems used in New Zealand (NZ), the changes with increased inputs over time and associated key environmental effects including nitrogen (N) leaching and greenhouse gas (GHG) emissions. NZ dairy farming systems are based on year-round grazing and seasonal milk production on perennial ryegrass/clover pasture where cows are rotationally grazed in paddocks. There was an increase in stocking rate on NZ dairy farms from 2.62 cows ha^{-1} in 2000/2001 to 2.85 cows ha^{-1} in 2015/2016. During the same period annual milk solids production increased from 315 to 378 $kg \cdot yr^{-1}$ per cow. This performance has coincided with an increase in N fertilizer use (by ~ 30%) and a twofold increase in externally-sourced feeds. Externally-sourced feeds with a low protein concentration (e.g., maize silage) can increase the efficiency of N utilization and potentially reduce N losses per unit of production. Off-paddock facilities (such as standoff or feed pads) are often used to restrict grazing during very wet winter conditions. A systems analysis of contrasting dairy farms in Waikato (largest NZ dairying region) indicates that the increased input would result in an increase in per-cow milk production but little change in efficiency of milk production from a total land use perspective. This analysis also shows that the increased inputs caused an 11% decrease in N footprint (i.e., N emissions per unit of milk production) and a 2% increase in C footprint (i.e., greenhouse gas (GHG) emissions per unit of milk production).

1 INTRODUCTION

Dairy farming systems based on year-round grazing of perennial pasture by dairy cattle are common in the southern hemisphere in temperate climates such as in New Zealand (NZ) and Australia. These are fully coupled crop-livestock production systems with relatively low cost of production. Cost of production is low because the animals are grazing year-round and hence no costly animal housing, indoor feeding and manure collection systems are needed. Stocking rate is generally determined by production of perennial pastures[1,2] and currently varies regionally from 2.3 to 3.4 milking cows ha^{-1}[3], with dairy replacements usually grazed off-farm. On the average NZ dairy farm, intake of pasture represents over 80% of total feed intake by dairy cattle[4]. Commonly, cows are rotationally grazed through non-irrigated paddocks with swards dominated by a sward of perennial ryegrass and white clover. Pasture productivity can be maintained without the need for inputs of fertilizer N due to fixation of atmospheric N_2 by clover[5]. Annual N_2 fixation levels from white clover in grazed pastures are about 100–150 $kg \cdot ha^{-1} \cdot yr^{-1}$ N[6]. Cows have free access to water (in stationary troughs) and pasture herbage in each paddock. On most dairy farms, pasture silage or hay is cut during the peak pasture growth periods in spring and then stored and fed out to fill feed gaps during winter and early spring when growth of pasture is slower.

In the past, livestock were rarely moved from pastures when soil was wet in winter, but over the last two decades there has been an increased use of specialist areas or 'sacrifice paddocks' by standing cows off to protect pastures, soils and cows during very wet periods[7,8]. Wintering cows in paddocks can cause compaction of soil which reduces soil porosity and hydraulic conductivity and increases bulk density, particularly on fine-textured soils which have become water-saturated[9]. This soil compaction also leads to a reduction in pasture production and N_2 fixation levels from white clover in grazed pastures[10].

Milking is generally done twice per day, early morning and late afternoon, requiring cows to walk down laneways to the milking shed and spend about 45 min a day in the milking shed and associated concrete yards[11]. Travel through farm gates and down laneways may create areas of localized compaction and lead to areas with more urine and dung deposition. The amount of excreta deposited in laneways and the milking shed is roughly proportional to the amount of time spent in that area and, therefore, it is estimated that about 5%–10% of excreta is deposited in the milking sheds and associated yards[11,12]. Effluent from the milking sheds and holding yards is washed into an effluent management system, typically a contained pond system, stored, then spread over land when conditions are appropriate[13,14]. Effluent is applied to land to capture its nutrient and water value[15,16].

An early-spring calving strategy is commonly used which aims to synchronize the herd feed-demand with peak pasture growth. This subsequently results in the entire herd being non-lactating for about three months during the late-autumn to winter period[17].

The purpose of this paper is to review the agronomic and environmental performance of grassland-based dairy farms in NZ. Specifically, we examine the effects of the intensification of dairy production during the last two decades.

2 FARM SYSTEM INTENSIFICATION

2.1 Stocking rate and supplementary feed

Increased stocking pressure, resulting from a desire to increase dairy production, increases the risk of soil compaction and hoof damage to pastures[9,18] and also increases urine and dung deposition to the pastures[19,20]. As an example, Table 1 shows that between 2000/2001 and 2015/2016 the average annual stocking rate of NZ dairy farms increased from 2.62 to 2.85 cows ha^{-1}[3]. The average fertilizer N application rate increased from 115 $kg \cdot ha^{-1}$ N in 2004/2005 to about 140 $kg \cdot ha^{-1}$ N in 2018/2019 (Fig. 1). Over the same time the average fertilizer P application rate decreased from about 50 to 25 $kg \cdot ha^{-1} \cdot yr^{-1}$ P, based on soil testing showing elevated soil P status and nutrient budgeting to account for other inputs.

The increased use of externally-sourced feeds on dairy farms in NZ has been an important factor for intensification and increased productivity[16] with annual milk solids production increasing from 315 to 373 kg per cow[3]. The amount of externally-sourced feed utilized per hectare showed a clear temporal trend, increasing from around 1300 to 2500 $kg \cdot ha^{-1} \cdot yr^{-1}$ DM (dry matter) from 2004/2005 to 2018/2019, where use of palm kernel expeller (PKE) was a major component of the total externally-sourced feed intake (averaging 1000 $kg \cdot ha^{-1} \cdot yr^{-1}$ DM in recent years; Fig. 2). PKE (11–11.5 MJ metabolizable energy kg^{-1} DM and 14% crude protein) is a by-product of the palm oil extraction process from the fruit of the palm and is sourced from Malaysia and Indonesia.

Dairy farms can be categorized according to the externally-sourced feeds used[16]. NZ dairy farms are categorized into five production systems (Table 1), with System 1 farms being all pasture and self-contained through to System 5 farms using 25%–40% externally-sourced feed[16]. Many NZ dairy farmers have moved away from the low external-feed input systems (i.e., Systems 1 and 2 with lower externally-sourced feed) over the last 15–20 years. This trend is highlighted in Table 1 and shows that the proportion of System 1 and 2 farms halved between 2000/2001 and 2015/2016. Conversely, the proportion of medium System 3 farms increased from 17% to 43% during the same period. There was also a small increase in the proportion of the System 4 and 5 farms from 12% to 21%. Average herd size also increased from 251 to 419 cows from 2000/2001 to 2015/2016 (Table 1). Correspondingly, the number of herds in NZ decreased from 13,892 to 11,918.

Growing of externally-sourced feed as annual crops, such as maize, generally involves cultivation, which results in mineralization of soil N and can lead to N losses through leaching[24], although no-till techniques can also be used to minimize the losses. Nutrients (including N) are imported in feed brought in from outside the farm, which subsequently increases the amount

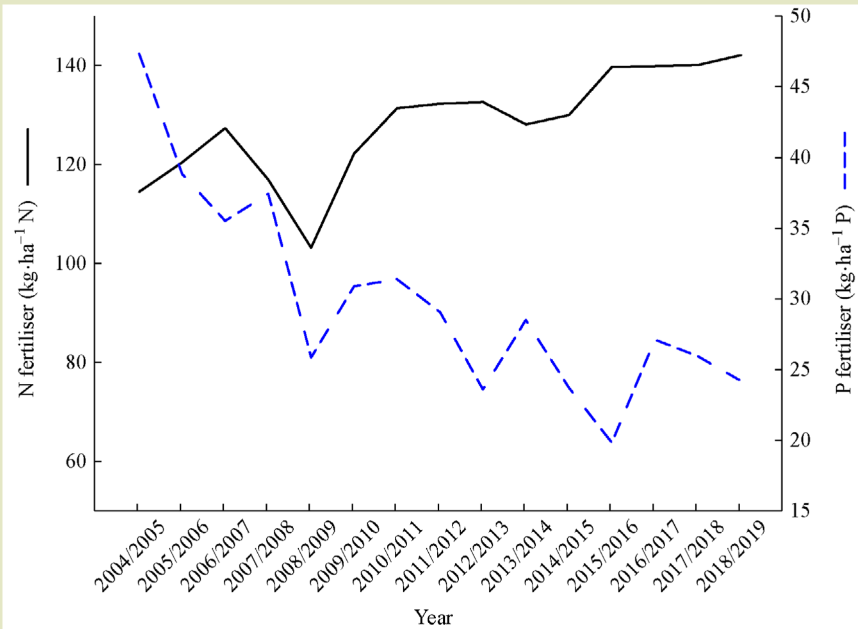


Fig. 1 Temporal changes in rate of fertilizer N and P use on New Zealand average dairy farms. Based on farm survey data from DairyNZ DairyBase.

Table 1 Trends in New Zealand dairy farming[3,21–23]

Item	2000/2001	2005/2006	2009/2010	2015/2016
Dairy statistics				
Dairy herds (no.)	13,892	11,883	11,691	11,918
Average herd size (no. cows)	251	322	376	419
Average stocking rate (cows ha^{-1})	2.62	2.74	2.81	2.85
Average milksolids production ($kg \cdot ha^{-1}$)	825	907	912	1063
*DairyNZ farm systems**				
Low (Systems 1 and 2) (%)	72	51	42	36
Medium (System 3) (%)	17	32	36	43
High (Systems 4 and 5) (%)	12	17	22	21

Note: * System 1, all pasture, self-contained, all stock on the milking platform; System 2, feed imported (4%–14%), fed to dry cows; System 3, feed imported (10%–20%) to extend lactation (typically autumn feed) and for dry cows; System 4, feed imported (20%–30%) and used at both ends of lactation and for dry cows; and System 5, feed imported (25%–40%) and used all year, throughout lactation and for dry cows.

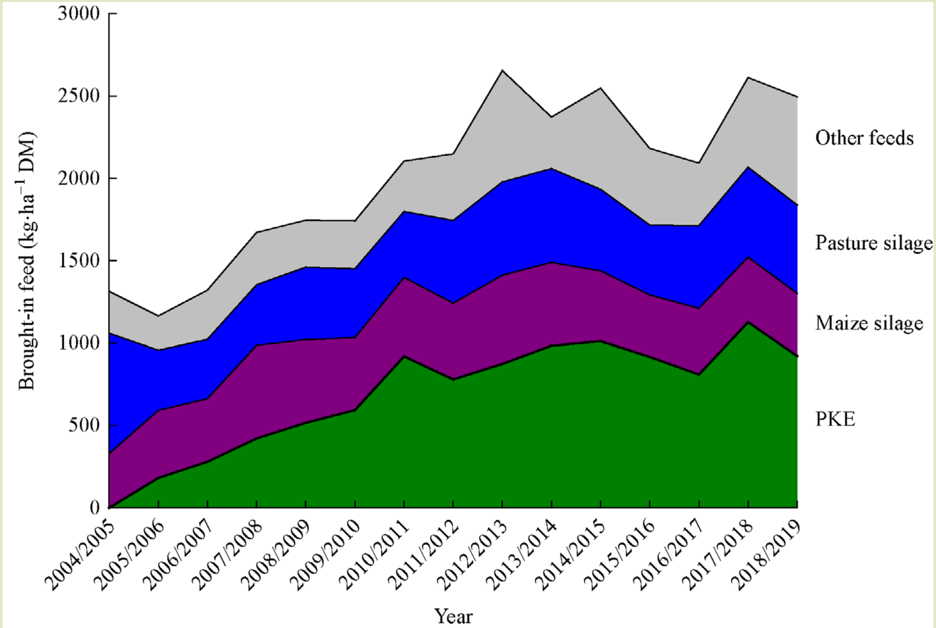


Fig. 2 Temporal changes in annual amount of feed consumption from externally-sourced feeds on New Zealand average dairy farms. Data are expressed on a per-hectare on-farm basis. PKE, palm kernel expeller. Based on farm survey data from DairyNZ DairyBase.

of N excreted onto farm systems with potential for increased losses to the environment.

To improve feed utilization and reduce labor costs, concreted feeding pads near the milking shed are often used (Table 2), with cows fed externally-sourced feeds on these platforms for short periods of time before milking[14,25]. Excreta deposited on feed pads are collected and directed to the contained dairy farm effluent (DFE) pond system.

2.2 Animal confinement facilities

With the increase in dairy intensification there now exists a variety of off-paddock structures (standoff pads, feed pads and animal shelters) that farmers can employ strategically, sometimes for a few months of the year, to decrease treading damage, increase feed use efficiency and/or protect pastures[25] (Table 2). In NZ, standoff pads are estimated to be used by 25% of dairy farming operations[11,14] (Table 2). Standoff pads are an area for holding cows when off pasture. Carbon-rich materials such as wood chips, bark or sawdust are used as bedding material[25,26]. The top 5–10 cm of material, which includes manure, is regularly scraped and stockpiled without cover for subsequent field application to maintain pads in optimum condition for animal health[27]. A similar amount of new bedding material would be generally added annually to replace the scraped materials. A lining and drainage system is installed below the bedding material for collection of effluent. Animal shelters can be covered standoff pads, although fewer than 5% of animal shelters have a hard surface such as concrete, which is slatted to allow collection of effluent and manure beneath[7]. Feed and standoff pads can be combined in one facility[14] and drainage from it is collected and directed to the DFE system.

A result of the use of off-paddock systems is an increase in the proportion of animal excreta entering the DFE system. Furthermore, these systems are leading to an increase in the pond storage requirements to accommodate the increased amounts of effluent before it can be safely applied to land. Effluent is commonly stored in leak-tight but uncovered ponds before land application. The volume and concentration of stock excreta from a standoff or feed pad will vary depending on how it is collected, stored and treated[14]. A study of farms with high feed inputs showed that these farmers have increased their DFE collection facilities, compared with the low feed-input farms, while also increasing the proportion of the land area over which the DFE is applied to an average of 66% (up to 100% on some farms) of the farm paddock area. This is greater than the 21% of the land area for low feed-input farms when the effluent application rate is the same[5]. DFE is generally applied to pastures from late spring to autumn.

Table 2 Trends in the estimated use of off-paddock structures and effluent management systems on New Zealand dairy farms since 2000 (adapted from Rollo et al.[11])

Item	2000	2005	2010	2017
Structures used (% of all dairy farms)				
Feed pads (%)	< 1	7	27	30
Standoff pads (%)	0	1	22	25
Loose housed barns (%)	0	< 1	2	3
Free-stall barns (%)	0	0	< 1	1
Effluent management				
Two ponds and discharge to water (%)	50	20	12*	12*
Land application				
Sump (%)	20	20	15	10
Storage pond (%)	30	60	75	88
Solid separation				
Mechanica (%)	0	< 1	1	2
Passive (Weeping wall) (%)	0	< 1	7	10

Note: *Some are hybrids with a component to land application.

2.3 Annual forage crops

A range of additional forage crops can be grown, on or off dairy farms, to provide forage to cover periods of perennial pasture (ryegrass/white clover) feed deficit. These arable annual crops are often grown in paddocks before pasture renewal (every 5–10 years) and can include maize silage, annual ryegrass, fodder beet, summer/winter brassicas (e.g., kale, rape, swedes and turnips) or cereal crops (e.g., barley, oats and triticale), and with dairy farm intensification their use has been increasing in recent years to provide extra feed from summer through to the next spring[28]. When grown on-farm, these annual forage crops normally only occupy about 5% of the on-farm area, with the rest in pasture[4]. These crops can be grazed, baled or ensiled. Most farms use commercial contractors to plant and harvest forage crops. In addition, the use of a crop rotation helps to break the cycles of pasture pests and weeds in continuous pastures. Grazing of forage crops generally occurs over a short-term period with break-feeding on a daily basis at a very high stocking density, e.g., 1000 to 1400 cows ha^{-1}[29]. The high stocking density is due to the higher yield of forage crops relative to pasture. The high stocking rates can result in a high concentration of dung and urine patches[24,29].

3 ENVIRONMENTAL IMPACTS AS AFFECTED BY DAIRY FARM PRACTICES AND INTENSIFICATION

Intensification of dairy production, through increasing use of N fertilizers, off-paddock facilities and supplementary feeds, will potentially impact the environment. The possible impacts are described below.

3.1 Application of N fertilizers and dairy farm effluent

Increasing fertilizer N inputs to the farm may result in increasing N surpluses (i.e., Σ (N inputs) – Σ (N outputs in products)). Some of this farm surplus N will temporally remain in the soil which can subsequently be lost through leaching and gaseous emissions, causing economic and environmental impacts[2,30]. As N losses, including leaching and N_2O emissions from grazed pastures, are highest from wet soils[31,32], NZ farmers generally avoid application of fertilizer N during late-autumn to winter when pasture growth is slow and soils are wet. Studies also show that strategic application of DFE to pastures under low soil-moisture status could potentially reduce emissions of N_2O by up to 96%[32].

3.2 Externally-sourced feeds

Externally-sourced feeds have GHG emissions and N leaching associated with their production and use due to soil cultivation and inputs of fertilizers[5]. In addition, the use of fossil fuels for planting, harvest and transport of externally-sourced feeds leads to GHG emissions (e.g., Ledgard et al.[33]). Externally-sourced feeds therefore have the potential to increase the environmental footprint of farm systems compared to farms based only on grazed pastures (System 1) (Table 1). However, these higher intensity production systems may also provide opportunities for achieving improved environmental efficiency (e.g., Ledgard et al.[34] and Luo et al.[35]). Grass/clover pasture generally contains an excess of protein relative to animal requirements[36], and therefore feeds with low protein and high metabolizable energy contents (e.g., maize silage) can increase the efficiency of N utilization by dairy cows[37] and potentially reduce all N losses including N_2O emissions and N leaching per unit of milk production[19,38]. By reducing the protein content of the whole ration, externally-sourced feeds reduce the N excretion to urine from dairy cows and proportionally more N excretion in dung can be achieved (e.g., Selbie et al.[36]). Urine N is rapidly converted to leachable N[37], as the majority of N in urine is in the form of urea and other readily transformable organic N species. Dung-N is in complex organic forms which will be only slowly mineralized to mineral N.

The effects of feeding an extra 5 $t \cdot ha^{-1} \cdot yr^{-1}$ DM of externally-sourced maize silage were evaluated over five years in a small farm system trial with 3.8 cows ha^{-1} compared to a no-maize pasture-only system at 3.0 cows ha^{-1}. Average total dietary crude protein content was approximately 18% and 22%, respectively. At an on-farm per-hectare basis, this showed a 34% increase in milk production, a small increase in N leaching (c. 10%) and only 4% higher N_2O emissions[19,38]. However, when land used to grow the maize silage was accounted for, the whole-system leached-N per kg milk solids was 7% higher but could have been decreased with reduced tillage and optimized fertilizer-N practices. In contrast, N_2O emissions were low in the maize crop and whole-system N_2O-N per kg milk solids was 22% lower than in the no-maize system. These results indicate that in terms of N leaching and N_2O loss intensity (i.e., kg^{-1} milk production), integration of low-protein and high-energy forages in grassland-based dairy production systems can potentially be an effective management practice to mitigate N losses.

3.3 Restricting grazing

The use of standoff or feed pads or housing systems provides an opportunity for controlling N_2O emissions and N leaching[38,39], as the animal excreta are collected and applied to the pasture at optimum rates and times when the risk of N losses is minimal and the pasture response is maximized. On a farm area basis, studies have found that N_2O emissions and N leaching can be reduced by 25%–60% when animals were on standoff or feed pads or in animal shelters (e.g., 6 $h \cdot d^{-1}$ grazing and 18 $h \cdot d^{-1}$ standoff) for 3–4 months during late autumn to winter compared with year-round grazing[32,38,40]. However, in these restricted grazing systems the optimum collection, storage and application of large quantities of farm effluent and manure become critical for nutrient use efficiency, as there are many opportunities for nutrients to escape from animal manure management systems such as emissions from animal confinement and manure storage and application[14,27]. Manure management techniques are increasingly important with these practices to avoid N pollution swapping (e.g., reducing N leaching from paddocks but increasing NH_3 loss from animal shelters)[4].

3.4 Forage crop grazing

Soil moisture content is usually elevated in winter in NZ, and forage crops grazed during winter are therefore especially vulnerable to compaction and consequently to high N_2O emissions and N leaching losses, as well as sediment and P runoff[29,41]. Grazing practices that reduce the total time spent on the forage crop in winter can reduce these impacts. Some forage crops (such as forage brassica rape cv. Titan) may also have potential to inhibit nitrification in the soil and consequently reduce N_2O emissions[42,43].

4 SYSTEMS APPROACH TO EVALUATE DAIRY FARM INTENSIFICATION — A CASE ATUDY

A whole-system approach is required to evaluate the total resource use and environmental impacts associated with dairy production on farms[4,5]. This should account for all contributing sources including land for production of all off-farm inputs (e.g., for production of the externally-sourced feeds), land for rearing dairy replacements where this is different to the farm area used for milk production, and the production, transportation and use of fertilizers, lime, and agrochemicals used on all these land areas. This typically involves application of a life cycle assessment (LCA) approach and considers a suite of resource use and environmental impact indicators[44]. A benefit of the LCA approach is that it can indicate if environmental trade-offs occur when a mitigation focuses on only one impact indicator such as eutrophication.

The following example is an analysis of dairy farms in Waikato, the major dairy region in NZ, with various intensification levels using a systems approach. In the average low, medium and high feed-input system farms in Waikato based on farm survey data (Table 3), the increased inputs were associated with an increase in per-cow milk production by 36% and per-hectare production by 60% on low- to high-input farms. However, the increased externally-sourced feed use would be associated with greater use of land off-farm for the production of these supplementary crop feeds, equating to increases of about 8%, 20% and 61% relative to on-farm areas for the low, medium and high-input farms, respectively. No land area was assigned to fruit/vegetable wastes, while PKE area accounted for allocation between co-products. A similar increase in milk production and land-area requirement for the high-input farms relative to the low-input farms illustrates that there would be little change in the efficiency of milk production on a total land use perspective. Maize silage yields per hectare are higher than pasture yields but the yields of other cereals and crops are lower, thereby conferring no benefit in terms of total land use efficiency.

Nitrogen budgets for the Waikato dairy farm systems show that increased feed inputs on high-input farms relative to low-input farms would represent an increased on-farm feed-N input of over 150 $kg \cdot ha^{-1} \cdot yr^{-1}$ N and an increase in farm gate N surplus of nearly 100 $kg \cdot ha^{-1} \cdot yr^{-1}$ N (Table 4). Increased on-farm N cycling would also lead to higher per-hectare N losses to the atmosphere and leaching losses to water. A major determinant of on-farm N leaching is the amount of urine-N deposited on pastures which would increase by 58% due to increasing stocking rate on the high-input farms relative to the low-input farms. Leaching of N would also occur on the land used to produce the externally-sourced feeds and this would equate to increases of 6% and 29% (relative to an on-farm equivalent basis; crop leaching data were from published data or modeling of the crops) on low- and high-feed input farms, respectively. The estimated difference in on-farm ammonia N emissions with feed-input level is smaller, being 25% higher for high-input farms than low-input farms (Table 4). This can be attributed to all externally-sourced feeds (except for soybean meal) having a lower N concentration (e.g., 1.2% N in maize silage to 2.7% N in PKE; from NZ feed database) relative to pasture (c. 3.7% N; recognizing low use of soybean meal on high-input farms at 8.8% N). Consequently, there is greater relative utilization of N by animals and proportionately more N excretion occurring in dung than in urine[34]. Ammonia emissions kg^{-1} N are much lower from dung than from urine[46].

Data were also analyzed to account for all land uses and input-related emissions using an LCA approach, with allocation of emissions between milk and live-weight sold for meat of 85%–90% to milk based on biophysical allocation (see Ledgard et al.[4] and IDF[47] for description of other LCA methodology used). For all externally-sourced feeds this accounted for all sources of inputs, processing and transport of crops according to published data for production of NZ crops or using the AgriFootprint database for imported crops of PKE and soybean (recognizing land use change effects and allocation between co-products in those crops). Nitrogen leaching estimation in externally-sourced feed crops was based on published country-specific values or for some NZ crops it was based on the use of published crop yield and N input data and the OVERSEER model[48]. This system analysis (Table 5) predicted an increase in N to water with increased feed input, but a decrease in NH_3 and N_2O kg^{-1} FPCM. There would be an increase in NO_x emissions associated with greater fuel use for the production, transport and feeding of externally-sourced feeds. The net effect would be a small

Table 3 Average animal, farm and resource use parameters in dairy farm systems in Waikato, New Zealand in 2015/2016 according to level of externally-sourced feeds (farm survey data from DairyNZ DairyBase)

Item	Low	Medium	High
Farm area (ha)	151	145	184
Cows ha^{-1}	3.11	2.95	3.78
Milk (L per cow)	3753	4154	5112
Milk (kg FPCM ha^{-1})	14,405	14,726	23,066
Feed externally-sourced ($kg \cdot yr^{-1}$DM per cow)			
Maize silage	67	192	339
Concentrate/wheat grain	21	56	38
Palm kernel expeller	152	377	734
Pasture silage	36	98	159
Soybean meal	0	0	170
Other externally-sourced feeds*	16	38	272
Fertilizer use on-farm (per year)			
Fertilizer-N ($kg \cdot ha^{-1}$)	123	122	156
Fertilizer-P ($kg \cdot ha^{-1}$)	22	18	21

Note: *Wide mix of different minor feeds such as vegetable and fruit wastes, specialist cereal blends, broll and molasses.

Table 4 Average N budget (kg·ha^{-1}·yr^{-1} N) on dairy farms in Waikato, New Zealand in 2015/2016 according to level of externally-sourced feeds (Based on average farm survey data from DairyNZ DairyBase and N flows analyzed using the OVERSEER model [45])

Item	Low	Medium	High
Farm Inputs			
Externally-sourced feeds	22	48	179
Fertilizer	123	122	156
Atmosphere (N_2 fixation, rainfall)	134	105	93
Farm Outputs			
Milk and meat	93	95	147
Ammonia volatilization	59	55	74
Denitrification	4	5	8
Leaching	31	31	49
Farm gate N surplus (N inputs minus product-N)	186	180	281
N use efficiency on-farm (%)	34	35	35
N use efficiency on- and off-farm (%)	30	30	28
Off-farm (units of on-farm area equivalent)			
Inputs			
Fertilizer N input to externally-sourced feed crops	5	14	43
Other atmospheric N inputs (externally-sourced feed crops)	2	2	31
Outputs			
Leaching from externally-sourced feed crops	2	5	14

decrease in the N footprint (i.e., sum of reactive N emissions per kg FPCM) driven mainly by the large decrease from the dominant NH_3 contribution.

The analysis also predicted a small increase in the carbon footprint (i.e., total GHG emission kg^{-1} FPCM) with increased feed input (Table 5). This would be associated with a large increase in CO_2 emissions determined by the greater fuel use for feed production and the higher N fertilizer usage with its associated production-related emissions. The large increase in CO_2 emissions (from fuel, fertilizers, lime etc.) more than countered the lower CO_2-equivalent emissions from N_2O as well as the lower CH_4 intensity associated with higher per-cow milk production. In a meta-analysis of a wide range of dairy system studies, Lorenz et al.[49] found variation in the carbon footprint of milk across different production systems but concluded that when controlled for milk yield the pasture-based systems had a lower carbon footprint than other production systems. They also found a significant decrease in the carbon footprint of milk in mixed and pasture-based systems with increasing proportion of the diet from pasture intake.

An earlier LCA study of low- and high-intensity Waikato dairy farm systems (based on the same source of farm survey data as in Table 5 but from five years earlier) covered a wider range of environmental impact categories[50]. That study had a greater difference between the high- and low-intensity systems (with high intensity having 30%–40% higher stocking rate and milk production per hectare and 4-fold higher N fertilizer and externally-sourced feed use), and also predicted a higher carbon footprint of milk from the high intensity system (an increase of 18%). Additionally, it predicted higher impacts kg^{-1} FPCM across a range of other indicators including ozone depletion, particulate matter (relating to human respiratory health), photochemical ozone formation, acidification, eutrophication and freshwater ecotoxicity (by 20%–35%). The authors noted that the main drivers of these increased impacts were from production of externally-sourced feeds, agrochemical manufacturing and the transportation of off-farm inputs.

The results presented in Table 5 include a scenario analysis for the high feed input farms, whereby strategic off-pasture housing was used for four months in late-autumn to winter (during the late- and non-lactating period). It was assumed that during the four months the cows grazed for 6 h·d^{-1} and then spent 18 h·d^{-1} standing-off in a housing facility. It was also assumed that

Table 5 Average N and C footprints of milk in dairy farm systems in Waikato, New Zealand in 2015/2016 according to level of externally-sourced feeds

Item	Low	Medium	High	High + housing
N footprint (g N kg^{-1} FPCM)				
NO*x*	0.12	0.14	0.19	0.19
N_2O	0.25	0.23	0.19	0.21
NH_3	3.30	3.01	2.41	4.10
N to water	2.63	2.76	2.83	2.16
Sum of reactive N	6.31	6.14	5.62	6.66
C footprint (g CO_2-equivalent kg^{-1} FPCM)				
CO_2	0.079	0.086	0.221	0.221
N_2O	0.122	0.109	0.089	0.111
CH_4	0.538	0.512	0.441	0.450
SUM	0.739	0.707	0.751	0.782

Note: High + housing refers to a scenario where cows were strategically housed for 18 h·d^{-1} in late autumn to winter and grazed on pasture at all other times.

manure was collected and stored before application to pasture. Such standoff practices are sometimes being used as a mitigation practice to decrease N leaching from the farm by decreasing urinary-N deposition during the important period determining N leaching losses. This analysis reveals that while N loss to water could be decreased by 24%, there was a proportionately larger increase in the ammonia contribution (70%), resulting in an 18% higher N footprint with strategic off-pasture housing. The carbon footprint was similarly estimated to increase by 4% due to higher N_2O and CH_4 emissions associated with manure management. In practice, such effects could be decreased by alternative improved manure management practices. Thus, this scenario analysis reveals that a mitigation practice to decrease one environmental impact (e.g., eutrophication due to N losses to water) may result in pollution swapping with an increase in climate change impact. Some other studies have also shown such trade-offs[51].

5 CONCLUSIONS

Over the past 20 years the drive to increase production in NZ has led to a move from low-input perennial pasture grazing systems toward to an increased proportion of high-input dairy farm systems. This has been reflected by an increase in stocking rate and increased use of N fertilizers, externally-sourced feeds and off-paddock facilities, although the increases have plateaued over the last five years due to regulatory environmental constraints. Compared with low-input systems, high-input systems can lead to more adverse environmental impacts, including water quality deterioration and higher GHG emissions. However, the use of off-paddock facilities and externally-sourced feeds with lower protein levels can potentially provide opportunities for mitigating these impacts through increased feed use efficiency and decreased direct deposition of dung and urine onto soils. A systems analysis based on surveyed Waikato dairy farms indicates that the increased externally-sourced feed inputs would result in an increase in per-cow milk production but lead to little estimated change in the efficiency of milk production from a total land use perspective. The analysis also reveals that a mitigation practice to decrease one environmental impact can potentially result in pollution swapping and trade-offs with other environmental impacts.

Acknowledgements

We thank DairyNZ for supplying farm data from DairyBase for use and the NZ Ministry of Business Innovation and Employment's Catalyst—Strategic Fund for supporting this research (Contract C10X1918).

Compliance with ethics guidelines

Jiafa Luo and Stewart Ledgard declare that they have no conflicts of interest or financial conflicts to disclose. This article is a review and does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Crush J R, Woodward S L, Eerens J P J, Macdonald K A. Growth and milk solids production in pastures of older and more recent ryegrass and white clover cultivars under dairy grazing. *New Zealand Journal of Agricultural Research*, 2006, **49**(2): 119–135
2. Ledgard S F, Luo J, Monaghan R M. Managing mineral N leaching in grassland systems. In: Lemaire G, Hodgson J, Chabbi A, eds. Grassland Productivity and Ecosystem Services. Wallingford, UK: *CAB International*, 2011, 83–91
3. DairyNZ. DairyNZ Economic Survey 2015–2016. Hamilton: *DairyNZ Limited*, 2017, 67
4. Ledgard S F, Falconer S J, Abercrombie R, Philip G, Hill J P. Temporal, spatial, and management variability in the carbon footprint of New Zealand milk. *Dairy Science*, 2020, **103**(1): 1031–1046
5. Ledgard S F, Bartlett N L, Van Boheemen P J, Wilton B R, Allen S B, Muggeridge D P. Implications of increased use of brought-in feeds on potential environmental effects of dairy farms in Waikato. *Journal of New Zealand Grasslands*, 2017, **79**: 139–145
6. Chapman D, Pinxterhuis I, Ledgard S, Parsons T. White clover or nitrogen fertiliser for dairying under nitrate leaching limits? *Animal Production Science*, 2020, **60**(1): 78–83
7. Longhurst R, Luo J. On-off farm winter management practices: potential environmental benefits and issues. In: Currie L D, Yates L J, eds. *Designing sustainable farms: Critical Aspects of Soil and Water Management, Massey University. Occasional Report No. 20: 403–410. Palmerston North, New Zealand: Fertilizer and Lime Research Centre*, 2007
8. Luo J, Wyatt J, van der Weerden T J, Thomas S M, de Klein C A M, Li Y, Rollo M, Lindsey S, Ledgard S F, Li J, Ding W, Qin S, Zhang N, Bolan N, Kirkham M B, Bai Z, Ma L, Zhang X, Wang H, Liu H, Rys G. Potential hotspot areas of nitrous oxide emissions from grazed pastoral dairy farm systems. *Advances in Agronomy*, 2017, **145**: 205–268
9. Laurenson S, van der Weerden T J, Beukes P C, Vogeler I. Evaluating the economic and production benefit of removing dairy cows from pastures in response to wet soil conditions. *New Zealand Journal of Agricultural Research*, 2017, **60**(3): 223–244
10. Menneer J C, Ledgard S F, McLay C, Silvester W B. The impact of grazing animal on N_2 fixation in legume-based pastures and management options for improvement. *Advances in Agronomy*, 2004, **83**: 181–241
11. Rollo M, Ledgard S, Longhurst B. Final Report: Trends in dairy effluent management. *Report for the Ministry of Primary Industries (MPI)*, 2017, 30
12. Bolan N S, Laurenson S, Luo J, Sukias J. Integrated treatment of farm effluents in New Zealand's dairy operations. *Bioresource Technology*, 2009, **100**(22): 5490–5497
13. Luo J, Donnison A, Ross C, Bolan N, Ledgard S, Clark D, Qiu W. Sawdust and bark to treat nitrogen and faecal bacteria in winter stand-off pads on a dairy farm. *New Zealand Journal of Agricultural Research*, 2008, **51**(3): 331–340
14. DairyNZ. A guide to using the dairy effluent storage calculator (DESC): Step by step instructions on how to calculate storage requirements. Hamilton: DairyNZ limited, 2015, 37
15. DairyNZ. A farmer's guide to managing farm dairy effluent: a good practice guide for land application systems. Hamilton: DairyNZ Limited, 2015, 55
16. DairyNZ. Dairy cow housing—a good practice guide for dairy housing in New Zealand. Hamilton: DairyNZ Limited, 2019, 65
17. Clark D A, Caradus J R, Monaghan R M, Sharp P, Thorrold B S. Issues and options for future dairy farming in New Zealand. *New Zealand Journal of Agricultural Research*, 2007, **50**(2): 203–221
18. Pow T, Longhurst B, Pow Z. The future of NZ dairy farming systems: Self managing cows with access to partial housing. In: Currie L D, Christensen C L, eds. *Nutrient Management for the Farm, Massey University. Palmerston North, New Zealand: Fertilizer and Lime Research Centre*, 2014
19. Luo J, Ledgard S F, de Klein C A M, Lindsey S B, Kear M. Effects of dairy farming intensification on nitrous oxide emissions. *Plant and Soil*, 2008, **309**(1–2): 227–237
20. Moir J L, Cameron K C, Di H J, Fertsak U. The spatial coverage of dairy cattle urine patches in an intensively grazed pasture system. *Journal of Agricultural Science*, 2011, **149**(4): 473–485
21. DairyNZ. Reviewing your wintering system Tour, a practical tool to find out what works best for you: Hamilton: *DairyNZ Limited*, 2013, 13
22. Greig B J. Changing New Zealand dairy farm systems. In: *Proceedings of the SIDE Conference*, 2012, **14**: 217–228
23. Mounsey Z. Analysis of Production Systems in the New Zealand Dairy Industry. *Report for Kellogg Organisation*, 2015, 42
24. Smith L C, Monaghan R M. Nitrogen leaching losses from fodder beet and kale crops grazed by dairy cows in southern Southland. *Journal of New Zealand Grasslands*, 2020, **82**: 61–71
25. Longhurst R, Lambourne A. What options are there for wintering cows off pasture. In: *Proceedings of the 4th Dairy3 Conference*, 2006, **4**: 3–10
26. DairyNZ. Stand-off pads—your essential guide to planning, design and management. Hamilton: *DairyNZ Limited*, 2017: 36
27. Luo J F, Saggar S. Nitrous oxide and methane emissions from a dairy farm stand-off pad. *Australian Journal of Experimental Agriculture*, 2008, **48**(2): 179–182
28. DairyNZ. Facts & figures, a quick reference guide for New Zealand dairy farmers. Hamilton: *DairyNZ Limited*, 2019: 163
29. Monaghan R M, Smith L C, de Klein C A M. The effectiveness of the nitrification inhibitor dicyandiamide (DCD) in reducing nitrate leaching and nitrous oxide emissions from a grazed winter forage crop in southern New Zealand. *Agriculture, Ecosystems & Environment*, 2013, **175**: 29–38

30. Ledgard S F, Penno J W, Sprosen M S. Nitrogen inputs and losses from clover/grass pastures grazed by dairy cows, as affected by nitrogen fertilizer application. *Journal of Agricultural Science,* 1999, **132**(2): 215–225
31. Ledgard S F, Steele K W, Feyter C. Influence of time of application on the fate of ^{15}N-labelled urea applied to dairy pasture. *New Zealand Journal of Agricultural Research,* 1988, **31** (1): 87–91
32. Luo J, Ledgard S F, Lindsey S B. A test of a winter farm management option for mitigating nitrous oxide emissions from a dairy farm. *Soil Use and Management,* 2008, **24**(2): 121–130
33. Ledgard S F, Basset-Mens C, McLaren S, Boyes M. Energy use, "food miles" and greenhouse gas emissions from New Zealand dairying-how efficient are we? In: Proceedings of the New Zealand Grassland Association. *Taupo, New Zealand,* 2007, **69**: 223–228
34. Ledgard S F, Schils R, Eriksen J, Luo J F. Environmental impacts of grazed clover/grass pastures. *Irish Journal of Agricultural and Food Research,* 2009, **48**(2): 209–226
35. Luo J, de Klein C, Ledgard S, Saggar S. Management options to reduce nitrous oxide emissions from intensively grazed pastures: a review. *Agriculture, Ecosystems & Environment,* 2010, **136**(3–4): 282–291
36. Selbie D R, Buckthought L E, Shepherd M A. The challenge of the urine patch for managing nitrogen in grazed pasture systems. *Advances in Agronomy,* 2015, **129**: 229–292
37. Kebreab E, France J, Beever D E, Castillo A R. Nitrogen pollution by dairy cows and its mitigation by dietary manipulation. *Nutrient Cycling in Agroecosystems,* 2001, **60**(1–3): 275–285
38. Ledgard S, Sprosen M, Judge A, Lindsey S, Jensen R, Clark D, Luo J. Nitrogen leaching as affected by dairy intensification and mitigation practices in the resource efficient dairying (RED) trial. In: Currie L D, Hanly J A, eds. Proceedings of the workshop on Implementing sustainable nutrient management strategies in agriculture, Massey University. Palmerston North: *Fertilizer and Lime Research Centre*, 2006, **19**: 263–268
39. Luo J, Donnison A, Ross C, Ledgard S, Longhurst B. Control of pollutants using stand-off pads containing different natural materials. In: Proceedings of the conference-New Zealand Grassland association, 2006, **68**: 315–320
40. de Klein C A M, Smith L C, Monaghan R M. Restricted autumn grazing to reduce nitrous oxide emissions from dairy pastures in Southland, New Zealand. *Agriculture, Ecosystems & Environment,* 2006, **112**(2–3): 192–199
41. Monaghan R M, Laurenson S, Dalley D E, Orchiston T S. Grazing strategies for reducing contaminant losses to water from forage crop fields grazed by cattle during winter. *New Zealand Journal of Agricultural Research,* 2017, **60**(3): 333–348
42. Luo J, Sun X Z, Pacheco D, Ledgard S F, Lindsey S B, Hoogendoorn C J, Wise B, Watkins N L. Nitrous oxide emission factors for urine and dung from sheep fed either fresh forage rape (*Brassica napus* L.) or fresh perennial ryegrass (*Lolium perenne* L.). *Animal,* 2015, **9**(3): 534–543
43. Balvert S F, Luo J, Schipper L A. Do glucosinolate hydrolysis products reduce nitrous oxide emissions from urine affected soil? *Science of the Total Environment,* 2017, **603**–**604**: 370–380
44. Finnveden G, Hauschild M Z, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S. Recent developments in life cycle assessment. *Journal of Environmental Management,* 2009, **91**(1): 1–21
45. Wheeler D, Cichota R, Snow V, Shepherd M. A revised leaching model for OVERSEER® nutrient budgets. In: Currie L D, Christensen C L, eds. Adding to the knowledge base for the nutrient manager Massey University. Palmerston North, New Zealand: *Fertilizer and Lime Research Centre*, 2011, 24
46. Bolan N S, Saggar S, Luo J F, Bhandral R, Singh J. Gaseous emissions of nitrogen from grazed pastures: Processes, measurements and modelling, environmental implications, and mitigation. *Advances in Agronomy,* 2004, **84**: 37–120
47. IDF. A common carbon footprint approach for the dairy sector. The IDF guide to standard life cycle assessment methodology. *International Dairy Federation,* 2015, **7**: 283
48. Wheeler D, Ledgard S, De Klein C, Monaghan R, Carey P, McDowell R, Johns K. OVERSEER® nutrient budgets—moving towards on-farm resource accounting. *Proceedings of the New Zealand Grassland Association,* 2003, **65**: 191–194
49. Lorenz H, Reinsch T, Hess S, Taube F. Is low-input dairy farming more climate friendly? A meta-analysis of the carbon footprints of different production systems. *Journal of Cleaner Production,* 2019, **211**: 161–170
50. Chobtang J, Ledgard S F, McLaren S J, Donaghy D J. Life cycle environmental impacts of high and low intensification pasture-based milk production systems: a case study of the Waikato region, New Zealand. *Journal of Cleaner Production,* 2017, **140** (2): 664–674
51. Chobtang J, McLaren S J, Ledgard S F, Donaghy D J. Environmental trade-offs associated with intensification methods in a pasture-based dairy system using prospective attributional Life Cycle Assessment. *Journal of Cleaner Production,* 2017, **143**: 1302–1312