Exploring potential dairy and arable farm system integration to enhance nutrient circularity: A case study analysis from the Oamaru coastal plains

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Abstract

The evolving challenges facing New Zealand's agricultural sector include rising costs, increasing regulations, and achieving environmental sustainability goals. This study evaluated the potential benefits of enhancing nutrient circularity in a North Otago dairy and arable farming system, aiming to reduce synthetic fertiliser use, nitrogen (N) leaching and carbon (C) footprint. Using an "Innovation Systems" approach that included Farmax Dairy and OverseerFM modelling, current practices were compared with two scenarios optimising manure use for arable production. Current practices involved limited nutrient circularity, with dry cows wintered on the arable farm and some barley grain and ryegrass seed straw supplied to the dairy farm. Scenario 1 introduced a barn on the milking platform for restricted autumn grazing and wintering, with collected manure applied to crops on the arable farm. Scenario 2 incorporated a pasture phase in the arable farm's crop rotation for dairy grazing; and arable crops on the dairy milking platform, fertilised with effluent. For arable crops receiving manures, both scenarios significantly reduced synthetic fertiliser inputs by 16-41% N, 5-55% P and 100% K. Whole system N leaching decreased by 8-17% due to reduced N fertiliser use and lower excreta returns to the dairy platform. Agricultural GHG emissions changed slightly (a 1.8% increase in Scenario 1 and a 0.8% decrease in Scenario 2) partly due to pollution swapping (reduced N_2O and increased CH_4). A 'cradle-to-farm-gate' life cycle assessment showed generally lower C footprints per kg of product in Scenario 2. These results highlight the potential benefits of nutrient-focused circular practices in NZ's dairy and arable farming systems, improving resource-use efficiency and mitigating environmental impacts through optimised nutrient supply and manure management.

Keywords: carbon footprint, LCA, leaching, manure management, nitrogen, synthetic fertiliser

Introduction

While the pastoral and arable sectors are significant contributors to New Zealand (NZ) land use and export earnings, each face growing challenges. These challenges are both domestic and global, e.g., increasing input costs, greater regulation, customer requirements to meet targets for sustainability, and continuous improvement in business efficiency. These pressures are an ongoing reality for the NZ agricultural sector, which has continued to adapt and evolve through time, particularly since removal of Government agricultural subsidies in the 1980s. These changes have resulted in grassland production in NZ undergoing a notable transformation towards intensified agricultural practices, marked by increased mechanisation, fertiliser use, and irrigation technology to enhance productivity (MacLeod and Moller 2006).

There is a need to be cognisant of overseas trends, which currently include new reporting requirements for climate and sustainable development measures. These are increasingly part of trade negotiations - over 80% of NZ exports (by value) are to countries with (or proposed) climate-related disclosures (The Aotearoa Circle 2024). In the near future, all products sold in Europe (including imports) will need to validate circular business practices and efficient use of materials (European Commission 2022).

Currently, NZ dairy farms are highly specialised, growing and utilising large quantities of pasture for milk production. In contrast, mixed cropping farms have a complex mix of crops and livestock within and between years. Dairy farms have significant greenhouse gas (GHG) emissions per unit area (Adler et al. 2015) and often generate large nitrogen (N) surpluses, while cropping systems have lower GHG emissions and high demand for nutrients.

Dairy and arable farm systems stand to gain significant benefits through synergistic interaction, fostering a more integrated approach that optimises the link between nutrient surplus and demand through better use of livestock manures, such as farmyard

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manure (FYM) and effluent. This optimisation promotes nutrient circularity between the systems, potentially increasing resource efficiency and reducing N leaching, GHG emissions and C footprints. Reduced losses to the environment represent increased efficiencies in farm systems: these enhancements align with a robust circularity narrative for NZ's food production systems. Strategies such as maximising the value of manure in the farming business, reducing mineral fertiliser use and N losses N to water and the atmosphere, were previously identified as some of the key principles to improve circularity of pastoral dairy farms (Burggraaf et al, 2022). Additionally, integrating circularity principles into agricultural systems brings other potential benefits such as improvements in soil fertility, structure, and C through the application of organic amendments (Chen et al, 2018).

The primary objective of this study was to evaluate the potential benefits of adopting a circular nutrient approach between dairy and arable farm systems. A modelling approach based on an existing case study was used to explore strategies for optimising the allocation of livestock manures as a nutrient source for arable production. The strategies aimed to decrease synthetic fertiliser use, lower whole system agricultural GHG emissions and C footprints per product, and reduce whole system N leaching, thereby enhancing nutrient circularity within these combined farming operations. The GHG analysis included farm-scale agricultural methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) emissions, while the C footprint included agricultural GHG plus embodied CO_2 emissions associated with inputs (fuel, electricity, supplements, fertilisers, chemicals). The financial analysis of the farm system was beyond the scope of this study.

Materials and Methods

The study modelled and evaluated a collective business with both a dairy and arable farm, comparing current practices (Baseline) to two integrated circular scenarios (Scenario 1 and 2). Using elements of an "Innovation systems" approach (Zydenbos et al. 2019, Taylor et al. 2022), diverse information sources were integrated. Farm data from existing records, staff interviews, various software tools, and external climate and soil data were used for modelling (details in "Modelling process" section). In-person discussions between the farm owners and researchers from the Foundation for Arable Research (FAR) and AgResearch enhanced the system dynamics representation.

Site location, soil type and climate

The case study involved adjacent dairy (210 ha) and arable (210 ha) farms, owned by the same business entity and located 14 km northeast of Oamaru, North Otago, NZ. Their ownership and proximity offered strong potential for integration of circular practices between the two farms.

The dominant soil type across the two farms is the Ngapara soil (S-Map reference 11a.1 Manaaki Whenua Landcare Research; smap.landcareresearch.co.nz), characterised by its deep silt loam texture. These soils have 'moderately well drained' and 'low' to 'medium' potential for N leaching classifications in S-Map.

The site has a temperate coastal climate with monthly precipitation evenly distributed throughout the year. Dry conditions induced by high evapotranspiration over summer are balanced with irrigation across both farms. The average annual climate data over 30 years were used for this modelling exercise: mean temperature was 10.8°C, total rainfall was 521 mm, and total PET was 740 mm (provided by the Virtual Climate Station Network - NIWA, niwa.co.nz).

Baseline dairy and arable farm platforms

The Baseline system represents 30+ years of standard operations and practices within the case study business, serving as the starting point of the modelling exercise. The business comprises an 810-cow dairy platform and an adjacent separately managed arable platform, primarily dedicated to wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), grass seed (perennial ryegrass *Lolium perenne)* and oilseed rape (*Brassica napus*) production.

The dairy milking platform has Kiwi-cross cows (F10-J6), milked twice a day, with an annual milk production of 434 kg milk solids (MS; fat plus protein) per cow and 1,666 kg MS per ha and a stocking rate of 3.8 cows/ha. All feed provided to the cows originates from either the milking platform or arable farm. Throughout lactation (August-May), cows graze on perennial ryegrass and white clover (*Trifolium repens*) pastures within the milking platform, supplemented with 338 t barley grain from the arable farm fed in the milking shed. A 4.5 ha fodder beet (*Beta vulgaris*) crop within the dairy farm, supplemented with ryegrass straw from the arable farm, is used for transitioning cows onto a winter fodder beet diet. During the winter months, non-lactating cows are moved to the arable farm to graze on fodder beet and Italian ryegrass (*Lolium multiflorum*), supplemented with ryegrass straw and silage from the perennial ryegrass seed crop and silage from the Italian ryegrass, also from the arable farm. The farm operates a replacement rate of 24%, with heifers transported to a nearby support block (50 km distance).

Effluent from the dairy shed is managed through a two-pond system, ensuring over 60 days of liquid retention, and then applied to the 70-ha effluent block on the dairy platform from September to March. Pond sludge is applied to the non-effluent block, typically in March, using shallow injection connected to an umbilical system (Smith and Williams, 2016). Pasture renewal of all paddocks is undertaken approximately every ten years, utilising fodder beet as a break crop or a grass-to-grass renewal using herbicide spray and direct drilling.

On the arable farm, a typical six-year rotation cycle involves two distinct crop rotations. The first rotation covers 72 ha in the following sequence: oilseed rape, wheat, barley, barley, Italian ryegrass, and wheat. Meanwhile, the second rotation, spanning 138 ha, includes oilseed rape, wheat, barley, perennial ryegrass, fodder beet, and barley. Soil management practices aim to minimise bare ground (i.e., green feed oats (*Avena sativa L.*) grown between barley crops). All crops are irrigated with *ca* 30 mm per month from November to January, with adjustments based on a soil moisture visual assessment.

Crop residues, such as wheat straw, are sold outside the business, while ryegrass straw and silage serve as dairy cow supplement during winter. Some of the barley straw is used as bedding for the calf shed, with the balance being sold. Crop nutrients are mainly supplied as synthetic fertilisers, aside from some excreta returns during winter grazing for the Italian ryegrass and fodder beet.

Both the dairy and arable synthetic fertiliser programmes consider paddock-level annual soil fertility measurements, pasture and crop requirements and removals, and N and potassium (K) inputs from effluent on the dairy farm.

System changes with respect to the Baseline

Scenario 1: Farmyard manure (FYM) to the arable platform

Scenario 1 ('FYM') comprised the inclusion of an off–paddock feeding facility (barn) on the dairy milking platform, with the stored FYM used as a nutrient supply on the arable farm. The objectives of this scenario were to manage manure nutrients more efficiently, minimise N leaching, provide a more efficient feeding strategy to the dairy herd, and minimise soil damage during grazing.

The barn served the need for both autumn on-off grazing and continuous winter usage. During autumn, lactating cows grazed on paddocks for 8 hours daily, sufficient to meet their daily feed intake requirements (D. Dalley, DairyNZ, pers. comm.) and spent 14 hours in the barn and 2 hours in the milking shed. Dry cows were wintered in the barn from June to August. Wheat and barley straw from the arable farm served as bedding material, facilitating the transformation of manure and straw into FYM, which was then stockpiled on the concrete floor of the barn after the autumn and winter periods. Manure management included its incorporation into soil prior to establishment of spring barley and maize (*Zea mays L.*) on the arable farm, while liquid effluent from the dairy shed continued to be applied on the dairy farm.

With the change in cow diets in this Scenario, fodder beet in the arable farm was replaced with maize silage crop, while Italian ryegrass was replaced with an additional perennial ryegrass seed crop. So, the first rotation had the following sequence: oilseed rape, wheat, barley, barley, perennial ryegrass, and wheat. Meanwhile, the second rotation was: oilseed rape, wheat, barley, barley, perennial ryegrass, and maize silage. Feeding maize, pasture silage and hay in a wintering barn allowed targeted use of manures for crop production. Additionally, in the dairy farm, fodder beet was removed and replaced by pasture, with any surplus allocated for silage production.

Scenario 2: Crops on the dairy farm and pasture on the arable farm

Scenario 2 ('crop swap') involved including two years of pasture (and therefore grazing lactating cows) in the arable farm crop rotation as well as receiving cow manure inputs; and including crops such as maize and autumn wheat on the dairy milking platform, leveraging their demand for nutrients from a nutrient-rich pastoral soil. The objectives of this scenario were to optimise nutrient utilisation by reducing synthetic fertiliser use, reduce N leaching and ensure a sustainable feed supply.

The feed strategy remained unchanged from the Baseline, except that the cows spent 22% of their lactation period grazing pasture on the arable farm. Internal farm roads facilitate efficient movement of livestock, and for this modelling study moving cows was considered without restrictions. Fodder beet was still grown on the dairy platform for transitioning to wintering on fodder beet on the arable farm. Dairy shed effluent management involved targeted application to maize and wheat crops, and post-wheat pasture renewal on the dairy platform. Maize was established in October via conventional cultivation, followed by autumn wheat, direct drilled in March after maize harvest. Wheat was harvested in February, before re-establishing pasture. Pond sludge was applied to the non-effluent block via shallow injection.

Under this scenario the arable farm rotation was increased to nine years, with some further subdivision of blocks required to include the 2-year pasture phase following perennial ryegrass seed and hay/straw harvest. The pasture was established by over-sowing white clover. Maize was established after pasture, while fodder beet remained for winter fodder. Rotation schedules were adjusted accordingly where 45 ha had the following sequence: oilseed rape, wheat, barley, barley, perennial ryegrass, pasture, pasture, maize and wheat. The remaining 165 ha had oilseed rape, wheat, barley, barley, perennial

Table 1 Total production of crops (t/ha and total tonnes) for the Baseline and two integration Scenarios.

Product	Units	Yield (t/ha)	Total yield Baseline (t)	Total yield Scenario 1: FYM (t)	Total yield Scenario 2: Crop swap (t)
Rape seed	t seed weight	4.5	158	158	105
Ryegrass seed	t seed weight	1.6	37	56	37
Wheat	t grain	12.0^A, 13.0^D	564	564	644
Barley	t grain	9.2	644	644	600
Fodder Beet	t DM	22.5^D, 28.0^A	745	-	616
Maize silage	t DM	20.0^A, 22.0^D	-	460	613

^{A}Arable Farm, ^{D}Dairy Farm

ryegrass, pasture, pasture, fodder beet and barley.

Modelling process

Collated farm data was used to model a single year's operation for the baseline and two scenarios (from 1 June 2021 to 31 May 2022). The area of the combined farm system represented the boundary of the modelling exercise and Ngapara soil was the sole soil type assumed for both farms.

The modelling process involved utilising the Farmax Dairy model (v8.3.1.13, farmax.co.nz) to represent a feasible long term dairy farm system, ensuring a balanced diet, cow health and milk production based on data from the Baseline. Baseline and Scenario diets were first assessed in FeedChecker tool (DairyNZ, dairynz.co.nz/tools/feed-checker), then modelled using the Cornell Net Carbohydrate and Protein System model (CNCPS, v6.5, Fox et al. 2004) to determine N excretion and evaluate proposed diets to ensure nutrient requirements of dairy cows were met. When modelling the two Scenarios, the feed supply was optimized to maintain the same milk production as the Baseline, with any surplus feed sold off-farm. The whole approach was chosen to generate farm-specific data, subsequently used as inputs for OverseerFM (v6.5.6, fm.overseer.org.nz) to model nutrient budgets and losses (i.e. N leaching, farm-scale agricultural GHG emissions and a partial LCA 'cradle-to-farm-gate' C footprint).

The GHG emissions boundary was limited to agricultural CH_4 and N_2O emissions, and CO_2 emissions from urea fertiliser dissolution following application to soil, aligning with the boundaries of NZ's agricultural GHG inventory (Ministry for the Environment, 2023). The C footprint included these agricultural GHG emissions plus embodied CO_2 emissions associated with fertiliser production, seeds, chemicals, supplements, electricity and diesel fuel used for agricultural machinery engaged in tillage, planting, and harvesting, FYM spreading, feed and animal transport, and were modelled by OverseerFM (Wheeler et al. 2013). Capital goods such as buildings and machinery were not included (March et al. 2021), nor were changes in soil C under constant land uses, due to the high uncertainties. All CH_4 and N_2O emissions were converted to CO_2 equivalents (CO_2e) using the 100-year time horizon global warming potentials of 25 kg CO_2e/kg CH_4 and 298 kg CO_2e/kg N_2O (IPCC, 2007). Allocation of dairy cow co-products (milk and meat) were based on a physical allocation method (IDF, 2015; Mazzetto et al. 2023), where fat and protein corrected milk (FPCM) was 4827 t/yr and dairy beef liveweight (LW) was 80.5 t LW/yr. Similarly, allocation of crop co-products (grain/seed and straw/silage) that are sold were based on N use and metabolisable energy (ME) for N_2O emissions and production area and ME for CO_2 emissions (Jeswani et al. 2018). Table 1 shows milk solids (MS), FPCM production and crop yields used in OverseerFM.

It was noted that nutrient flows and GHG emissions associated with manure management systems within OverseerFM may require updating to align with the NZ Agricultural Inventory Methodology (AIM; Ministry for the Environment, 2023; Tavernet et al. 2024). Therefore, emissions from FYM storage and land application were estimated using calculations based on AIM and the IPCC 2019 refinement (IPCC, 2019).

Substitution of synthetic fertilisers by manure considered the N, phosphorus (P) and K fertiliser replacement value of manure whilst also factoring in their slow release via mineralisation to ensure production levels were maintained. Nutrients available from manure was estimated using a UK software tool (MANNER-NPK, Nicholson et al. 2013), where the appropriate soil texture and climate were selected to reflect that of our case study. 'Fresh cattle FYM' was selected to represent the FYM applied to the spring barley and maize crops in Scenario 1. This software tool uses climate and soil data to estimate manure mineralisation rates and the supply of available nutrients. In Scenario 2, effluent on the dairy platform was targeted at maize, autumn wheat and pasture immediately following wheat, where total NPK inputs were estimated from the Baseline effluent data. As for

Table 2 Plant available N, P and K applied as farmyard manure (FYM) to spring barley and maize crops on the arable farm (Scenario 1).

	Spring barley			Maize		
	Total N (kg/ha)	Total P (kg/ha)	Total K (kg/ha)	Total N (kg/ha)	Total P (kg/ha)	Total K (kg/ha)
Crop nutrient supply as fertiliser without FYM use	207	40	75	147	40	100
Plant available nutrient added as FYM	33	22	160	33	22	160

Table 3 Plant available N, P and K applied as effluent to maize and autumn wheat crops on the dairy farm (Scenario 2).

	Maize			Autumn wheat		
	Total N (kg/ha)	Total P (kg/ha)	Total K (kg/ha)	Total N (kg/ha)	Total P (kg/ha)	Total K (kg/ha)
Crop nutrient supply as fertiliser without effluent	97	40	75	200	40	75
Plant available nutrient added as effluent	40	2	105	40	2	105

FYM, organic forms require mineralisation to become plant available; the supply of available forms was estimated using the MANNER software in addition to NZ research on the use of effluent for crop production (Norris et al. 2019).

Results

Synthetic fertiliser use

Both scenarios demonstrated reductions in synthetic fertiliser inputs for crops receiving manure. Scenario 1 was designed to improve the utilisation of excreta-derived nutrients for spring barley and maize production. Table 2 illustrates the recommended synthetic fertiliser inputs. A volume of 2500 t FYM could be generated from the barn when used for controlled duration grazing in autumn (March-May) and wintering cows 24 hours per day from June to August. The NPK content of the FYM, estimated using the MANNER software, was 2.4% N, 0.5% P and 2.7% K, with 20% of the total N being available for crop uptake in the first two years, of which 85% is available in year 1. To simplify annual nutrient accounting, it was assumed all the mineralised N was available in this first year (Table 2). The MANNER software estimated that 60% and 90% of the total P and K content of FYM, respectively, would be available for plant uptake in year 1. Application of FYM amounted 27 t FYM/ha to both spring barley and maize, with sufficient volume for 93 ha annually. Based on the plant available nutrient supply from FYM, the application of K fertiliser could be omitted entirely, while N and P fertiliser were reduced by 33 kg and 22 kg/ha, respectively.

Similarly, in Scenario 2, effluent application was targeted at maize and autumn wheat production on the dairy milking platform, where both crops have large N and K requirements (Table 3). The recommended fertiliser inputs were formulated considering the supply of available N following a long-term pasture. For this Scenario, the same total volume of effluent (160 m^3/ha) was assumed to be applied to each crop, as well as to pasture following wheat, supplying a total of 80 kg N, 4 kg P and 105 kg K/ha. For each crop type, the total volume of effluent was split into 2-4 applications to minimise the risk of nutrient loss below the rooting depth. It was assumed that 50% of total N and P, and 100% of K, in effluent was plant-available (MANNER software and Norris et al. 2019). Based on the plant available nutrient supply from effluent, it was calculated that all the fertiliser K could be omitted, while N and P fertiliser were reduced by 40 and 2 kg/ha, respectively (Table 3).

Spring barley and maize production in Scenario 1 represents 44% of the rotation on the arable farm. Synthetic N fertiliser use increased 5% across the entire arable farm, while P and K fertiliser use decreased by 7% and 10%, respectively (Table 4). Total nutrients applied as FYM to the spring barley and maize crops represented an arable farm-average application rate (per ha) of 71 kg N, 15 kg P and 80 kg K (Table 4). As noted above, the plant available fraction of FYM will be lower than the values shown here due to slow mineralisation of organic forms, with synthetic fertiliser replacing plant available nutrients from FYM at equivalent rates. Crop yields should therefore remain unchanged relative to a fertiliser programme based

Table 4 Inputs of N, P and K per effective area (kg nutrient/ha/yr) of the dairy and arable farms, supplied as synthetic and organic fertiliser, for the Baseline and Scenarios 1 and 2. 'Organic fertiliser' includes both effluent and FYM applied to pasture and crops.

	Baseline		**Scenario 1 (FYM)**		**Scenario 2 (Crop swap)**	
	Dairy	Arable	Dairy	Arable	Dairy	Arable
Nutrients applied as synthetic fertiliser (kg/ha)						
Total N	176	229	177	240	141	230
Total P	36	42	36	39	36	44
Total K	42	79	43	71	46	81
Nutrients applied as organic fertiliser (FYM and effluent) (kg/ha)						
Total N	41	0	41	71	41	0
Total P	5	0	5	15	5	0
Total K	38	0	38	80	38	0
Total nutrient application (kg/ha)						
Total N	217	229	218	312	182	230
Total P	41	42	41	54	41	44
Total K	81	79	82	151	85	81

Table 5 Annual N leaching per effective area (kg N/ha/yr) of the dairy milking platform and arable farm for the Baseline and Scenarios 1 and 2. 'Coll. avg' (= Collective average) relates to the average per hectare results of the envisaged dairy and arable farm collective.

	Baseline			**Scenario 1 (FYM)**			**Scenario 2 (Crop swap)**		
	Dairy	Arable	Coll.avg	Dairy	Arable	Coll. avg	Dairy	Arable	Coll.avg
N leaching (kg N/ha)	97.1	8.9	53.0	88.2	9.4	48.8	75.1	13.2	44.1
% change relative to Baseline				-9	+6	-8	-23	+48	-17

solely on synthetic fertiliser inputs.

Scenario 2 provided the largest change in synthetic fertiliser use on the dairy milking platform, with N fertiliser inputs decreasing by 20%. The amount of N fertiliser on the arable farm remained unchanged, as did fertiliser P and K inputs to both the dairy and arable farms. While the use of effluent was optimised for crop production in Scenario 2, the total nutrient input as effluent remained unchanged relative to the Baseline. This translated into no change in average 'organic fertiliser' inputs for the dairy milking platform (Table 4).

N leaching

The results suggest that both scenarios have the potential to reduce N leaching compared to the Baseline, with Scenario 2 showing the greater reductions (Table 5).

Scenario 1 showed an 8% reduction in total N leaching compared to the Baseline, mainly due to changes on the milking platform. This reduction can be attributed to the on-off grazing management implemented during autumn, where a portion of the cows' excreta was collected rather than directly deposited onto pasture. Whereas for the arable farm, the strategy of removing wintering cows did not have a significant effect on N leaching, as N leaching was initially low (at 4 kg N/ha; results not shown). In contrast, N leaching loss was 66 kg N/ha when fodder beet was grazed within a 6-year pasture rotation.

Scenario 2 exhibited greater reductions in N leaching compared to both the Baseline and Scenario 1 (Table 5). The collective average N leaching was 17% lower than the Baseline, driven by large reductions on the dairy milking platform because of cows spending less time there.

Agricultural GHG emissions

Total collective GHG emissions from Scenario 1 were 1.8% higher than the Baseline (Table 6). Examining each farm separately, the dairy farm emissions increased 9%, from 16.7 to 18.2 t CO_2e/ha/yr, mainly due to increased emissions from enteric fermentation and manure management. For the Baseline, emissions

Table 6 Annual farm-scale GHG emissions per effective area (kg CO2e/ha/yr) of the dairy milking platform and arable farm for the Baseline and Scenarios 1 and 2. ‘Coll. avg’ (= Collective average) relates to the average per hectare results of the envisaged dairy and arable farm collective.

	Baseline			Scenario 1 (FYM)			Scenario 2 (Crop swap)		
	Dairy	Arable	Coll. avg	Dairy	Arable	Coll. avg	Dairy	Arable	Coll. avg
Methane (kg CO_2e/ha/yr)									
Enteric fermentation	9838	0	4919	11010	0	5505	9068	721	4894
Manure management	1146	0	573	1467	0	734	1127	9	568
Wintering on crop	0	1146	573	0	0	0	0	1146	573
Young stock	1634	0	817	1634	0	817	1634	0	817
Nitrous oxide (kg CO_2e/ha/yr)									
Manure management	2159	0	1080	2107	198	1152	1599	560	1080
Synthetic fertiliser	487	547	517	491	777	634	462	539	501
Crop residues	9	213	111	0	125	63	64	176	120
Indirect[1]	704	47	376	736	57	396	600	127	364
Wintering on crop	0	335	167	0	0	0	0	330	165
Young stock	521	0	260	521	0	260	521	0	260
Carbon dioxide (kg CO_2e/ha/yr)									
Urea dissolution in soil	251	339	295	253	358	306	189	348	269
Total GHG emissions (kg CO_2e/ha/yr)	16749	2627	9688	18218	1515	9867	15263	3957	9610
% change in total GHG emissions relative to Baseline				+9	-42	+1.8	-9	+51	-0.8

[1]‘Indirect’ relates to indirect N2O (via ammonia volatilisation and N leaching) from following categories: storage and subsequent land application of manures and effluent; fertiliser application; excreta deposition and crop residues.

associated with cows wintering on fodder beet were attributed to the arable farm. In contrast, in Scenario 1, cows were wintered in a barn on the dairy platform, with emissions therefore captured in the accounting of dairy farm emissions. Removing wintering cows from the arable farm reduced emissions for that farm by 42%, from 2.6 to 1.5 t CO_2e/ha/yr.

Scenario 2 reduced total collective GHG by 0.8%, with emissions being transferred from the dairy milking platform to the arable farm (Table 6) due to the strategy implemented of expanding the pastoral grazing beyond the dairy milking platform boundary. The dairy farm GHG emissions were reduced by 1.5 t CO_2e/ha/yr, whereas the arable farm emissions increased by 1.3 t CO_2e/ha/yr, resulting in an average GHG emission of 9.6 t CO_2e/ha/yr across the collective.

C footprint

The C footprint for the majority of saleable products in Scenario 1 was slightly reduced compared to the Baseline products (Table 7). The C footprint for milk (0.77 kg CO_2e/kg FPCM) was similar to the Baseline (0.78 kg CO_2e/kg FPCM), while meat was also similar (5.23 vs. 5.16 kg CO_2e/kg LW for Baseline and Scenario 1, respectively). Seeds and wheat grain also showed small C footprint decreases, by 1-4%. In contrast, the C footprint for barley grain increased by 89%, while crop straw and hay increased by 22%, compared to the Baseline. Scenario 2 milk and meat C footprints were 0.75 kg CO_2e/kg FPCM and 5.01 kg CO_2e/kg LW respectively, both of which were 4.3% lower than the Baseline (Table 7). Most arable products decreased up to 9% but wheat grain increased by 25% compared to the Baseline.

Discussion

Scenario 1 (FYM)

The implementation of the barn in Scenario 1 simulated more effective use of cattle manure as a nutrient for crop production. Additionally, reducing grazing hours during autumn decreased excreta deposited on soils, thereby lowering N leaching and both direct and indirect N_2O emissions (Buckthought et al. 2015; de Klein and Ledgard, 2001; Luo et al. 2013). It is likely that this would also reduce the potential for soil damage from animal treading (Houlbrooke et al. 2009).

Application of FYM to spring crops presented an opportunity to transfer nutrient loading pressures from

Table 7 Cradle-to-farm-gate C footprint per kg product (milk, meat, seed, grain, silage and straw/hay) for the Baseline and Scenarios 1 and 2.

Product	Unit	Baseline	Scenario 1 (FYM)	Scenario 2 (Crop swap)
Milk	kg CO_2e/kg FPCM[1]	0.78	0.77	0.75
Dairy beef	kg CO_2e/kg liveweight	5.23	5.16	5.01
Rape seed	kg CO_2e/kg seed weight	0.49	0.48	0.48
Ryegrass seed	kg CO_2e/kg seed weight	0.63	0.61	0.61
Wheat grain	kg CO_2e/kg grain	0.17	0.16	0.20
Barley grain	kg CO_2e/kg grain	0.17	0.32	0.17
Maize silage	kg CO_2e/kg DM	N/A	0.20	0.18
Straw & hay[2]	kg CO_2e/kg DM	0.11	0.14	0.10

[1] FPCM = fat and protein corrected milk. [2] From wheat, barley and ryegrass.

nutrient-rich pasture blocks to nutrient-demanding arable blocks. By strategically collecting and redistributing FYM, substantial reductions in N, P and K fertiliser applications in spring barley and maize could be achieved, despite lower nutrient use efficiency. The objective was not to entirely replace synthetic fertiliser usage, as this could potentially diminish crop yields due to the slower release of nutrients (Chen et al, 2018, Zhang et al, 2020). The FYM was 'applied' to soils prior to planting high-demand barley and maize crops in spring, capitalising on the gradual rise in temperatures conducive to organic N mineralisation, thereby providing a consistent, slow-release supply of N for plant growth.

The proportion of autumn-deposited excreta was reduced, and winter grazing of fodder beet avoided. Autumn grazed pastures are recognised as high-risk N leaching practices due to the limited uptake of excreted N followed by soil drainage over the winter/spring period (Buckthought et al. 2015; Shepherd et al. 2017). Standing cows off-paddock in autumn markedly reduced N leaching potential, as observed in field studies (de Klein and Ledgard, 2001). Winter grazing of fodder beet, a high yielding low N forage, within a pasture rotation can lead to losses of *ca* 80 kg N/ha (Smith and Monaghan, 2020), although losses from fodder beet within a cropping rotation are less well understood. In this case study, N leaching losses from the arable farm were relatively low even when including winter grazing of fodder beet, presumably due to smaller pools of available N in the soil profile at times of drainage when compared to the dairy farm.

This study highlights the challenges in attempting to reduce agricultural GHG emissions from typical NZ dairy systems, due to the potential for pollution swapping. While the barn assisted with reducing N leaching and N_2O emissions from soils (de Klein and Ledgard, 2001; Luo et al. 2013), it increased CH_4 emissions from manure management. Previous dairy studies exploring the potential for off-paddock facilities as a farm-scale mitigation tool have predicted that total GHG emissions can increase (e.g., van der Weerden et al. 2018; Smith et al. 2023). In the current study, the farm boundary was extended to include the neighbouring arable platform, to ensure stored manures could be effectively utilised as a nutrient source for crop production rather than returned to pasture. This strategy may create opportunities for reduced GHG emissions from manure management, through practices such as manure incorporation into soils prior to sowing of crops. However, the net GHG emissions from the envisaged collective increased slightly by 1.8% relative to the Baseline. This increase is mainly due to higher emissions associated with storage and application of FYM, which offset the reductions from lower N fertiliser use and decrease urine-N leaching.

When considering the cradle-to-farm-gate C footprint for the different farm products, using a barn as an off-paddock facility and applying the resulting FYM to the arable farm had little impact on emissions per unit of milk and meat. Compared to studies using the same GWP, the C footprints for milk reported here are similar to those reported elsewhere for NZ dairy systems (0.73 – 0.77 kg CO_2e/kg FPCM) but are at the low end of the 0.8 – 1.3 kg of CO_2e/kg of FPCM reported from overseas dairy studies (Ledgard et al. 2020). Similarly, the dairy beef C footprints reported for the Baseline and Scenario 1 are consistent with emissions reported elsewhere for NZ and other dairy-producing countries such as Sweden, Denmark, and Norway (Mazzetto et al., 2023). The C footprints for the crops in the Baseline and Scenario 1 (seed, grain, silage and straw/hay) are comparable to those published by others (e.g. Barber et al. 2011; Jeswani et al. 2018). While the C footprints for most arable products were similar between the Baseline and Scenario 1, the latter resulted in increased emission footprints for barley grain and straw/hay. This was driven by the use of FYM for barley production because GHG emissions associated with FYM, including its storage and land application, are allocated to the barley grain and straw. The same applies to the maize crop receiving FYM, however this crop was not grown in the Baseline and therefore cannot be compared.

Scenario 2 (Crop swap)

In Scenario 2, having lactating dairy cows grazing pasture on the arable farm and arable crops grown on the dairy farm, arguably produced a more favourable environmental outcome than Scenario 1. Total synthetic N application was reduced compared with both the Baseline and Scenario 1, while reductions in N leaching were twice those in Scenario 1.

Targeting dairy farm effluent application to crops with substantial requirement for N+K resulted in reduced synthetic fertiliser use. Here, maize and autumn wheat crops were grown on the dairy farm, rather than limiting effluent application to pasture, suggesting that utilisation of supplied nutrients was optimised. This optimisation capitalised on the crops' substantial requirement for N and K, increased particularly in paddocks with a history of long-term pasture.

Despite the total amount of N excreta deposition across the dairy and arable farms being the same as the Baseline, N leaching was effectively reduced in Scenario 2. This was driven by a decrease in N leaching of 22 kg N/ha/yr in the dairy farm, attributable to cows spending less time on the dairy milking platform and the integration of maize and wheat into the pasture rotation. In turn, there was a slight increase in N leaching (4 kg N/ha/yr) from the arable farm. This overall reduction demonstrates nutrient circularity, where transferring nutrients from nutrient-rich dairy pastures to nutrient-demanding crops helps mitigate losses.

GHG emissions in Scenario 2 were changed even less (0.8% reduction) than Scenario 1 relative to the Baseline. This minor reduction was a consequence of reduced N fertiliser use on the dairy farm. Emissions directly associated with livestock (enteric CH_4, N_2O and CH_4 emissions from excreta deposition) were similar to the Baseline because the type and amount of feed was not altered. Cows grazing pasture on the arable farm will result in similar emissions to those produced when grazing pasture on the dairy platform, with milk production kept constant.

Swapping crop production with grazed pasture and applying dairy effluent to crops grown on the dairy farm in Scenario 2 led to a 4% decrease in the C footprint per unit of milk and meat produced. Besides, most arable products showed a reduction in their C footprints, ranging from 2% to 9%, except for wheat grain, which experienced a 21% increase. This increase in the wheat footprint is mainly due to the allocation of GHG from effluent storage and land application to wheat. This increase outweighs the emissions reduction from decreased reliance on synthetic fertilizers, leading to a net rise in the C footprint for wheat. However, the allocation of effluent emissions to wheat contributes to the reduction in the C footprint of milk and meat, demonstrating the impact of redistributing emission allocations across farm products.

Limitations and future work

An "Innovation systems" approach provides an opportunity to use a combination of collected and modelled data, inputs from research, and lived knowledge from farmers, for assessing farm systems scenarios (Taylor et al. 2022). However, such studies are resource demanding, limiting the number of farms that can be evaluated. The current study focused on a single case study, limiting any analysis of uncertainty associated with the results. In addition, Scenario 2 assumes adjacent dairy and arable farms, which is critical for its practical implementation, where cows graze on the arable farm during lactation. The feasibility and benefits observed for Scenario 2 may not be fully transferable to non-adjacent farms.

There is currently no single decision support tool in NZ that is specifically designed to predict nutrient inputs, flows and losses in combined livestock and cropping systems. Following considerable discussion, OverseerFM was adopted to attempt the integration of these two distinct farm systems. Stand-alone spreadsheets were used for specific components of the farm system (e.g., FYM management) and for integration of results across OverseerFM files. Using an empirical model such as OverseerFM limits opportunities for exploring the effect of nutrient supply on crop production. Therefore, for the purposes of this modelling, milk production was kept constant across the Baseline and Scenarios, while crop yields reflected what was considered as typical for this farm. Furthermore, we recognise that the tools used in this study (OverseerFM, Farmax Dairy, AIM and IPCC equations, MANNER-NPK, Feed Checker, and CNCPS) have inherent uncertainties. Therefore, the combination of these models introduces varying degrees of uncertainty that were not quantified; we acknowledge this is a limitation when interpreting our findings.

The next step to advance this case study involves integrating Scenarios 1 and 2 to explore the potential for enhanced benefits. Following this integration, evaluating the farm-scale financial implications of the proposed scenarios will be critical to supporting a more complete systems analysis.

Conclusions

The findings of this study shed light on the potential benefits of enhanced nutrient circularity within dairy and arable farming systems in New Zealand. The two modelled scenarios have demonstrated potential opportunities for a) improving nutrient-use efficiency via partial replacement of synthetic fertiliser through better utilisation of manures and b) reducing N leaching across the two farm systems by between 8 and 17%, primarily through reduced grazing pressure on the dairy milking platform.

However, the study also highlighted the challenges in reducing farm-scale GHG emissions and C footprints, with agricultural GHG emissions being either slightly increased (by 1.8% in Scenario 1) or slightly decreased (by 0.8% in Scenario 2) relative to the baseline, as a result of reduced N_2O emissions and greater CH_4 emissions. Conversely, avoiding a substantial increase in total GHG emissions on a per area and per unit of product basis when other benefits (such as reduced N leaching and decreased reliance on external inputs) are realized should still be regarded as a positive outcome.

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