Winter crop choice and body condition loss change the ecoefficiency of sheep flocks

Anna TAYLOR[1*], David R. STEVENS[2], and Sue A. MCCOARD[3]
[1]*Lincoln Research Centre, AgResearch, Private Bag 4749, Christchurch.*
[2]*Invermay Research Centre, AgResearch, Private Bag 50034 Mosgiel, New Zealand.*
[3]*Grasslands Research Centre, AgResearch, Private Bag 11008, Palmerston North.*
[*]Corresponding author: anna.taylor@agresearch.co.nz

Abstract

Research has highlighted reproduction losses when feeding low protein winter crops, such as fodder beet. The following study compared the impact of body condition score (BCS) change (0 or -0.5) with a winter feed choice of brassicas (adequate protein) or fodder beet (low protein) on sheep production, greenhouse gas emissions and N and P losses in two environments in the South Island of New Zealand. Eight farms were chosen from an existing database, with high (1090 mm/annum) or low (590 mm/annum) rainfall. Farm estimates of BCS were modified to fit the change scenarios and ewe and lamb survival at lambing, and lamb liveweight gain to weaning were altered to reflect the impacts of BCS when fed either adequate or low protein diets in mid-to-late pregnancy. Meat and fibre production, greenhouse gas emissions and N and P losses were calculated for the four scenarios using Farmax and Overseer models. Loss of BCS in winter led to greater ecoefficiency per hectare as less lambs were produced. Feeding fodder beet without additional protein reduced overall production and ecoefficiency per unit of product to a greater extent than just lower BCS. N and P losses were low and were reduced when feeding fodder beet.

Keywords: Winter crops, feed supply, climatic variation, profit, farming enterprise.

Introduction

Winter crops are an integral part of many cool temperate sheep and beef farm systems in New Zealand. Often between 3 and 5% of the farm may be as a winter crop (Stevens *et al*., 2021). Fodder beet (*Beta vulgaris*) has become a greater part of the winter crop portfolio in recent times, with over 15,000 ha planted annually (Gibbs 2014). Fodder beet has high yields, averaging approximately 19 t DM/ha (Judson *et al*., 2016). Swedes (*Brassica napus*) are a winter crop with major storage of carbohydrates in the bulb, but its yields are lower than fodder beet, often being between 10-15 t DM/ha (Chakwizira *et al*., 2011; Gowers *et al*., 2006). However, recent advances in plant breeding have provided cultivar and management systems that can increase yield by up to 30%, (Dumbleton *et al*., 2012), providing the potential for swedes to attain the yields of fodder beet.

Yields of high yielding root crops principally comprise approximately 80-85% bulb which has a high sugar content (Judson *et al*., 2016). This provides a high energy concentration, but is moderated by a low protein concentration, typically 7-9% (Chakwizira *et al*., 2013). This protein concentration varies depending on cultivar, (Prendergast and Gibbs 2015), but is generally low and may not meet the demand of the animal in some physiological states (Pacheco *et al*., 2016).

High yielding forage is used to meet animal demands in winter, while minimising the area required to be sown with winter crops (Milne *et al*., 2014). However, new research has highlighted reproduction losses when feeding winter crops which are low in protein, such as fodder beet (Hammond *et al*., 2021). When fed fodder beet in mid to late pregnancy, twin-bearing ewes lost body condition (BCS) and showed signs of under-nutrition due to protein deficiency. This led to lambs being born smaller and poorer lamb survival and growth to weaning than those from ewes fed pasture diets. Supplementing a fodder beet diet to provide adequate protein has been shown to prevent the loss in BCS and the reduction in lamb birth weight (Knol *et al*., 2019).

The BCS loss in late pregnancy has been linked to reductions in lamb survival (Everett-Hincks *et al*. 2004; McCoard *et al*., 2020) and liveweight gain from birth to weaning (Corner-Thomas *et al*., 2015) and has been related to ewe death rate in commercial flocks (Morgan-Davies *et al*., 2008; Flay *et al*., 2021). Lamb survival and growth (*i.e.,* ewe reproductive performance) are key levers to changing eco-efficiency, particularly in hill country systems (MacKay *et al*., 2012). Of specific interest are changes in greenhouse emissions and nitrogen and phosphorus losses into water courses.

The following trial tested the hypothesis that winter crop choice, specifically low protein fodder beet, is involved with a mid-to-late pregnancy loss of BCS to reduce whole farm eco-efficiency, represented as greenhouse gas (GHG) emissions and nitrogen (N) and phosphorus (P) losses from soil. To test the robustness of this hypothesis, two farm classes, South Island hill country and South Island breeding/finishing, were used, representing high and low rainfall zones.

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Materials and Methods

The impact of feeding winter crops on the reproductive performance of a ewe flock and its subsequent effects on the eco-efficiency of mixed livestock farms was investigated. The experimental design was a two-by-two factorial with four replicates and farm environment as a blocking factor. The two factors were BCS change in mid-to-late pregnancy (0 or -0.5) and adequate or low protein diets (Control or Fodder beet). BCS was determined using the industry 1-5 scale (Jefferies 1961).

Farm selection and base modelling

Eight farms (replicates) were anonymously selected from an existing database to represent two environments, ‘high rainfall’ (four farms, 1090 mm/annum) representing Class 6 Beef + Lamb NZ (2021a) South Island Finishing Breeding farms, and ‘low rainfall’ (four farms, 590 mm/annum) representing Class 2 Beef + Lamb NZ (2021b) South Island Hill Country with a cool temperate climate in southern New Zealand (Table 1). Criteria for selection included no dairy support, a representative balance of steep, rolling and flat land, winter crop use and farm size (Beef + Lamb NZ 2021). Current production metrics were used as the base condition for each farm (Table 1 and 2) and converted into a model farm using the Farmax (Marshall *et al*., 1991) Red Meat (version 8.0.1.34 Science Edition) whole farm modelling software and OverseerSci (version 3.4.1.0) (Shepherd and Wheeler 2012) nutrient budgeting tool. These tools were used in subsequent modelling for production, GHG and N and P losses.

Table 1 Physical parameters of four high rainfall (B+LNZ farm class 6 South Island Finishing breeding) and four low rainfall (B+LNZ farm class 2 South Island Hill Country) farms chosen to test the impacts of BCS change and winter forage choice on production, greenhouse gas emissions and N and P loss.

	Rainfall (mm/yr)	Farm area (ha)		Topography (ha)			Crop yield (t DM/ha)		
Farm ID		**Total**	**Effective**	**Flat**	**Rolling**	**Steep**	**Winter feed (ha)**	**Swede/[1] Kale**	**Fodder Beet[1]**
High rainfall 1	840	640	540	0	450	190	34	8.4	21.0
High rainfall 2	1170	834	734	36	637	161	71	11.7	29.3
High rainfall 3	1250	458	290	65	343	50	11	12.5	31.3
High rainfall 4	1110	422	410	0	324	98	19	11.1	27.8
Low rainfall 1	500	871	860	400	271	200	51	5.0	12.5
Low rainfall 2	585	340	337	0	340	0	30	5.9	14.6
Low rainfall 3	600	736	490	156	32	548	9	6.0	15.0
Low rainfall 4	675	805	790	0	360	445	38	6.8	16.9

[1] Crop yields calculated from rainfall assuming 50% of the annual rainfall was utilised in growing the crop (De Ruiter *et al*., 2009; Chakwizara *et al*., 2014)

Table 2 Farm performance of four high rainfall (B+LNZ farm class 6 South Island Finishing breeding) and four low rainfall (B+LNZ farm class 2 South Island Hill Country) farms chosen to test the impacts of BCS change and winter forage choice on production, greenhouse gas emissions and N and P loss.

Farm ID	Stocking Rate (SU/Farm ha)	Sheep:cattle ratio (kg eaten/kg product)	Net pasture production (kg DM/ha[eff])	Feed Conversion efficiency	Animal Product (kg meat and wool/ha[eff])
High rainfall 1	7.3	78:22	3,831	25.0	134
High rainfall 2	13.4	70:30	7,077	22.3	289
High rainfall 3	13.6	91:9	7,259	22.5	208
High rainfall 4	9.3	93:7	4,825	26.2	187
Low rainfall 1	6.7	82:18	3,519	25.2	142
Low rainfall 2	9.1	61:39	4,783	23.4	211
Low rainfall 3	7.2	74:26	4,148	24.6	107
Low rainfall 4	6.8	83:17	3,754	22.8	161

[eff] Effective area of the farm. The BCS change for the chosen farms averaged -0.3 BCS from scanning to lambing.

Impacts of body condition score on reproductive parameters

The BCS in mid-to-late pregnancy impacts on the reproductive performance of sheep, including ewe mortality (Morgan-Davies *et al*., 2008; Flay *et al*., 2021), lamb mortality ((Everett-Hincks *et al*., 2004; McCoard *et al*., 2020), and liveweight gain to weaning (Stevens *et al*., 2012; Mathias *et al*., 2013; Everett-Hincks *et al*., 2013). While these factors have been noted, actual whole flock response to BCS change has not been well documented. McCoard *et al*., 2020) noted that avoiding BCS loss may be more important than pre-winter BCS. For this reason, data from a commercial flock, over two seasons, using 2200 recorded ewes, was used to measure reproductive performance in relation to changes in BCS, rather than any static BCS parameter. A description of this flock has been published by Johns *et al*. (2016). Using the full data set, the following equations were created to represent ewe mortality and lamb mortality, in response to BCS changes during mid-to-late pregnancy.

Ewe mortality rate (%) = = $+3.49*\Delta BCS^2-4.12*\Delta BCS+3.5$ ($r^2=0.988$) [*Equation* 1]

This provided comparable mortality rates to those previously published (Morgan-Davies *et al*., 2008; Flay *et al*., 2021).

Lamb loss (%) = $7.76*\Delta BCS^2 - 3.79\Delta BCS + 14.9$ ($r^2 = 0.943$) [*Equation* 2]

This provided comparable lamb mortality rates to those previously published (Everett-Hincks *et al*., 2013; McCoard *et al*., 2020). Changes in lamb liveweight gain from birth to weaning were calculated from the literature (Stevens *et al*., 2012; Mathias *et al*., 2013; Everett-Hincks *et al*., 2013) and resulted in the following equation:

Lamb liveweight gain change (g/d, birth to weaning) = $30 * \Delta BCS$ [*Equation* 3]

Finally, a further adjustment was made to reflect feeding the low protein diet during mid-to-late pregnancy, based on the work of Hammond *et al*., (2021).

Equation 4: Lamb loss (%, low protein diet) = 2* [*Equation* 4]

Adjustments to reproductive performance of the base models

The reproductive performance on each farm was altered to reflect the impact of changing BCS in mid-to-late pregnancy using equations 1-4. Initially, ewe BCS changes from scanning to lambing within each base farm was calculated from true liveweight difference estimates from the Farmax files, using the relationship 1 BCS =10% of true liveweight (Kenyon *et al*., 2014). To standardise the comparison between farms, live weight profiles and reproductive performance were adjusted relative to the calculated BCS changes on each farm (Table 3), using equations 1-4 to fit the 0 or -0.5 BCS change criteria.

Mid-to-late pregnancy feeding

Control scenarios used either kale (*Brassica oleracea*) or swedes (*Brassica napus*) as the winter crop. The area of crop in the Control 0 and Control -0.5 scenarios was taken from the area on the base farms (Table 1). Winter crop yields were determined using calculations from published research, as these were not available for each farm. Yields of swedes or kale were calculated using the growth relationship of 20 kg DM per mm of rainfall (Table 1), assuming that half of the annual rainfall was available during the growing period (de Ruiter *et al*., 2009).

Table 3 Ewe reproductive parameters of four high rainfall (B+LNZ farm class 6 South Island Finishing breeding) and four low rainfall (B+LNZ farm class 2 South Island Hill Country) farms chosen to test the impacts of BCS change and winter forage choice on production, greenhouse gas emissions and N and P loss.

Farm ID	Scanning %	Ewe liveweight at scanning (kg)	BCS change from scanning to lambing (kg)	Lamb Weaning weight (kg)
High rainfall 1	155	63	-0.29	28.2
High rainfall 2	186	74	-0.29	33.0
High rainfall 3	197	76	-0.32	31.6
High rainfall 4	145	61	-0.40	28.0
Low rainfall 1	146	61	-0.40	26.6
Low rainfall 2	164	65	-0.26	26.2
Low rainfall 3	191	65	-0.38	28.7
Low rainfall 4	202	74	-0.17	28.5

In the fodder beet scenarios, enough was planted to replace other forage crops to meet the final 45 days feed requirements for breeding ewes before set stocking at approximately 3 weeks before lambing. This maintained a consistent DM available from the winter crops, as per the equation:

Fodder beet area = total tonnes DM/fodder beet yield [*Equation* 5]

Fodder beet yields were calculated assuming growth rates of 50 kg DM per mm of rainfall and that half of the annual rainfall was available over the growing period (Chakwizara *et al*., 2014).

Supplementing a fodder beet diet with adequate protein has been shown to prevent BCS loss and return lamb birth weights to normal (Knol *et al*., 2019). Thus, in the BCS 0/Fodder beet scenario, a supplement (0.5 kg DM/d) was included to provide adequate protein. The area of fodder beet grown on farm was further reduced to offset the amount of supplement fed. The fodder beet diet for no BCS change was 30% lucerne hay/chaff, 13% soy meal, 1% urea, 56% fodder beet, to provide a low-cost feed, following Knol *et al*. (2020).

Farmax modelling criteria

General adjustments made to ensure pasture use was similar to the original farms included adjusting lamb sales date, supplement making, stocking rate and autumn nitrogen use (Table 4). As changing flock

Table 4 Decision rules used to ensure that feed supply and demand profiles of each scenario were reflective of the original base farms.

Description	Model condition	Management decisions
The model calculates that the pasture cover and/or quality in spring is not sufficient to feed animals on the farm	Spring feed deficit	Add Nitrogen fertiliser at up to 40 kg N/ha to rolling land only
For a model to represent a long-term farm system the pasture covers need to balance at the ‘start’ (1 July) and ‘end’ (30 June). This is influenced by feed requirements of the animals on-farm and the pasture growth rates.	End cover too low (greater than 50 kg DM/ha different to opening cover)	Make silage in summer and feed back in autumn For every 1kg of DM deficient, shift the sale of 3 lambs from the end of year to one week after weaning Move all lamb sales after end April to a week after weaning as store sales If new sale after weaning carcass weight exceeds the actual weight of the next sale then make a prime, rather than a store sale
	End cover too high (greater than 50 kg DM/ha different to opening cover)	Make baleage, on flat land if available. Close up paddock after 1st Jan for 62 days and adjust area until closing covers match Remove any autumn nitrogen applications (not crop or DAP application) Sell surplus baleage at a price of $80/bale
Pasture cover surplus (more feed than required) reduces the quality of the pasture/feed	Summer surplus (>2,800 kg DM/ha)	Make baleage with same rules as end cover too high
Altering the ewe reproductive parameters from the baseline, determined for each scenerio if there were more or less lambs than the base file that needed to be sold.	More lambs	Sold on the 16th of each month (except in early sale in which date after weaning) proportionately to original file. No more than 10% of lamb sales after May.
	Less lambs	Sale numbers reduced each month proportionately to original file, using the sale closest to the middle of the month if possible, otherwise the biggest sale number
	Lamb deaths	Increased/deceased proportionately to original file %
	Ewe deaths	Increased number of ewe hoggets retained to balance ewe numbers

performance and area cropped resulted in variations in whole-farm feed supply, alterations were made to ensure that pasture covers at the beginning (1 July) and end (30 June) of the modelling cycle were representative of mid-winter.

The GHG model within Farmax was used and was based on algorithms from the New Zealand national inventory (Ministry for Primary Industries 2021) and limited to methane and nitrous oxide emissions from excreta from all the animals (beef and sheep), but excluding slope-based nitrous oxide emissions factors, and any applied N fertiliser. Overseer Science (version © 2018 | 3.4.1.0) was used to examine farm environmental outcomes for losses of N and P losses from soil in each of the scenarios.

Data analysis

The effect of high or low rainfall was analysed using each farm as a replicate to provide a description of the two environments representing Class 2 and 6 farm types (Beef + Lamb NZ 2021). Variables included pasture and supplement (including crop) consumed, proportion of area cropped, sheep:beef ratios and stocking rate. Ecoefficiency factors analysed included sheep and beef production (kg product/ha/annum), methane and nitrous oxide emissions (kg CO$_2$E/ha/annum and kg CO$_2$E/kg product), total GHG emissions (kg CO$_2$E/ha/annum), emissions intensity (kg CO$_2$E/kg product) and nutrient loss (N and P kg/ha/annum). Results of the two-by-two factorial with BCS change (0 or -0.5) and winter crop (brassica or fodder beet) as main factors were analysed using rainfall (high or low) as a blocking factor and individual farms as replicates. A number of covariates were explored, including stocking rate, initial productivity (kg product/ha), farm size and beef enterprise (% stock units as beef). Only the proportion of beef explained any further variation, and this was retained in all analyses. All analyses used the REML function of the statistical package Genstat (version 18, 2017).

Results

Comparing high and low rainfall environments

High or low rainfall resulted in significant differences between many of the factors analysed, including greater pasture production, more productivity, higher stocking rate and higher GHG emissions per hectare (3.0 *vs*. 2.2 t/ha respectively) in the high rainfall environments (($P<0.01$; Table 5). Sheep production was greater in the high rainfall environment, while beef production

Table 5 Production parameters, greenhouse gas emissions and nutrient loss from sheep and beef farms in high or low rainfall environments, when modelled in cool, temperate southern New Zealand.

Parameters		**High rainfall**	**Low rainfall**	**LSD**
Rainfall	(mm/annum)	1090	590	
Topography	(Flat:Rolling:Steep)	5:75:20	17:45:38	
Pasture consumed	(t/ha)	5.25 ^{a1}	3.47 ^{b}	0.38
Supplement consumed	(t/ha)	0.75 ^{a}	0.55 ^{b}	0.09
Proportion of area cropped		6.1	5.4	2
Sheep: beef ratio		83:17	74:26	
Stocking rate	(SU/ha)	10.9 ^{a}	7.3 ^{b}	0.8
Sheep	Product (kg/ha/yr)	179.4 ^{a}	103.4 ^{b}	24.3
	Methane (kg CO$_2$E/ha/yr)	1950 ^{a}	1296 ^{b}	80
	Methane (kg CO$_2$E/kg product)	10.9 ^{b}	12.5 ^{a}	1.3
	N$_2$O (kg CO$_2$E/ha/yr)	443 ^{a}	296 ^{b}	19
	N$_2$O (kg CO$_2$E/kg product)	2.47 ^{b}	2.80 ^{a}	0.28
Beef	Product (kg/ha/yr)	32.9 ^{b}	42.9 ^{a}	4.3
	Methane (kgCO$_2$E/ha/yr)	470 ^{b}	535 ^{a}	29
	Methane (kgCO$_2$E/kg product)	14.3 ^{a}	12.5 ^{b}	0.37
	N$_2$O (kg CO$_2$E/ha/yr)	100 ^{b}	112 ^{a}	7
	N$_2$O (kg CO$_2$E/kg product)	3.04 ^{a}	2.61 ^{b}	0.08
Total greenhouse gas emission^{s}1	(kg CO$_2$E/ha/yr)	2998 ^{a}	2259 ^{b}	86
Emission intensity	(kg CO$_2$E/kg product)	14.85	15.51	1.88
Nutrient loss	N (kg/ha/yr)	12.98 ^{a}	9.69 ^{b}	2.07
	P (kg/ha/yr)	0.88 ^{a}	0.10 ^{b}	0.06

[1] Means with differing superscripts within rows are significantly different ($P<0.05$); [2] All farm emissions including fertiliser use

was higher in the low rainfall environment (Table 5). Methane and nitrous oxide emissions from sheep meat production, while greater per hectare ($P<0.01$) in the high rainfall environment, were lower per kg of product ($P<0.01$) in the low rainfall environment. Beef enterprises in low rainfall environments produced more methane and nitrous oxide emissions per hectare than those in high rainfall environments ($P<0.01$) but lower emissions per kg of product. Emissions intensity (total GHG emissions per kg of product; Table 5) were not significantly different between environments, at 14.85 and 15.51 kg/kg product, respectively. Nitrogen and P losses were low in both environments, and lowest in the low rainfall scenarios ($P<0.01$; Table 5).

Comparing BCS change and winter crop choice

Changes in BCS interacted with winter crop choice when testing whole farm eco-efficiency (Table 6). The productivity of both the farm system and the sheep flock were lowest when fodder beet was fed and BCS change was -0.5 during late pregnancy. Sheep flock productivity was intermediate when BCS change was -0.5 and brassica-based crops were fed. However, if BCS loss was eliminated through improved feeding, there was no difference in production associated with winter crop choice.

These differences were reflected in all aspects of GHG emissions per hectare, being lowest for the lowest productivity treatment of fodder beet cropping with a -0.5 BCS change. Some changes in N fertiliser use were noted, though these resulted in very minor changes in GHG emissions, with the contribution being only 0.5% on the farm using the greatest amounts of fertiliser (data not presented). However, the reverse occurred when testing GHG emission intensity (per kg of product), with the maintenance of BCS providing the lowest GHG emissions per kg of product at 15.8 kg CO_2 equivalents/kg product. However, a BCS change of -0.5 when feeding fodder beet resulted in an emissions rate of 18.9 kg CO_2 equivalents/kg product.

Estimated N losses were relatively low, being approximately 10 kg/ha when fodder beet was used and 12 kg/ha when conventional brassica crops were used (Table 6). Phosphorus losses were extremely low, averaging 0.5 kg/ha, with no significant variations estimated between treatments (data not shown).

Discussion

Varying impacts of BCS change on reproductive performance have been reported by many authors and these impacts interact strongly with the nutrition available at the time (reviewed by Kenyon *et al*., 2014). However, practical investigations of the impacts of BCS on commercial farms have generally demonstrated benefits in ewe flock productivity (Morgan-Davies *et al*., 2008; Stevens *et al*., 2011; Casey *et al*., 2013; Everett-Hincks *et al*., 2013; Mathias-Davis *et al*., 2013; Johns *et al*., 2016; McCoard *et al*., 2020). This study used results from farm practice to quantify the potential impacts of changes in BCS and winter feeding practices on GHG emissions and N and P loss, as well as production of meat and fibre. The additional impact of feeding fodder beet (Hammond *et al*., 2021) on ewe BCS loss and subsequent lamb loss, and reduced liveweight gain from birth to weaning, caused a significant reduction in whole flock productivity, even when mitigating

Table 6 Interactions between ewe body condition score (BCS) change in mid-late pregnancy and winter fodder crops on the ecoefficiency of sheep flocks, expressed as production (meat and fibre), methane, nitrous oxide and total greenhouse gas per hectare and per kg of product, and nitrogen losses per hectare.

	Winter crop	**Brassica**		**Fodder Beet**		
	Change in mid-late pregnancy	**0**	**-0.5**	**0**	**-0.5**	**LSD**
Production (kg product/ha/yr)	Total	190 ^{a}	173 ^{b}	194 ^{a}	160 ^{c}	9
	Sheep	152 ^{a}	135 ^{b}	156 ^{a}	122 ^{c}	9
Total (kg CO_2E/ha/yr)	Methane	1918 ^{b}	1874 ^{c}	1983 ^{a}	1871 ^{c}	39
	Nitrous oxide	438 ^{b}	425 ^{c}	454 ^{a}	425 ^{c}	9
	Total GHG	2356 ^{b}	2299 ^{c}	2437 ^{a}	2295 ^{c}	48
Intensity (kg CO_2E/kg product)	Methane	12.9 ^{c}	14.1 ^{b}	12.9 ^{c}	15.4 ^{a}	0.3
	Nitrous oxide	2.9 ^{c}	3.2 ^{b}	2.9 ^{c}	3.5 ^{a}	0.1
	Total GHG	15.8 ^{c}	17.3 ^{b}	15.8 ^{c}	18.9 ^{a}	0.4
Nitrogen loss	(kg/ha/yr)	12.4 ^{a}	12.3 ^{a}	10.6 ^{b}	10.0 ^{b}	1.4

Means with different superscripts within rows are significantly different ($P<0.05$); LSD=Least Squares Difference of the mean ($P<0.05$)

measures, such as altering lamb finishing profiles or utilising supplements, were implemented.

A key to ensuring that BCS could be maintained was the addition of a high protein supplement to balance the low protein fodder beet diet (Knol *et al*., 2019). When BCS loss was mitigated by balancing protein requirements, the whole flock productivity was restored, as was the eco-efficiency of the flock and the farm. Fodder beet is only one example of a low protein diet that may be fed during late pregnancy. Others include high yielding swedes and low protein silages. Hence, this example may apply to a wider range of current industry feeding practices.

Understanding how ecoefficiency metrics, such as GHG emissions, farm productivity and N leaching losses, change as a consequence of a new technology or management practice is becoming increasingly important. The analysis of potential impacts of using fodder beet as a mid-to-late pregnancy feed for breeding ewes demonstrated a significant interaction with change in BCS. Increases in lambing percentage and lamb growth rates in the last 20 years have been major contributor to improvements in the ecoefficiency of sheep farms in New Zealand, mainly on hill country (MacKay *et al*., 2012). Alterations in productivity, driven by lamb survival and growth rates from birth to weaning, demonstrated that these variations remain important in driving on-farm ecoefficiency. Previously reported studies (MacKay *et al*., 2012, Dodd *et al*., 2020) have demonstrated this relationship between sheep flock performance and whole farm eco-efficiency. Changes in livestock performance reduced GHG emissions intensity from 25 to 15 kg from 1990 to 2002 (Dodd *et al*., 2020), which was similar to results reported by Dynes *et al*. (2011) of 14.1 – 17.8 in a range of farm management scenarios on North Island hill country. MacKay *et al*. (2012) noted a decrease in GHG emissions intensity from approximately 25 to 15 kg between 1990 and 2010 on hard hill country, although they reported no net change on easy hill country with an average GHG emissions intensity of approximately 15 kg/yr throughout in the same time-period. Greenhouse gas emissions in the current trial were lower than those reported by MacKay *et al*. (2012), most likely driven by lower rainfall (1500mm and 1250mm *vs*. 1090mm and 590mm). The current work provides an insight into the on-farm changes that may be achieved within similar environments and management when choosing winter forage options, and the interactions that may occur if nutritional targets vary.

Total annual GHG emissions of 2998 kg CO_2-e/ha and 2259 kg CO_2-e/ha for the high and low rainfall farms respectively (Table 5) were comparable to the findings of Hutchinson *et al*. (2019), who analysed 60 New Zealand sheep and beef farms and found 50% of the farms produced between 2,891 and 4,597 kg CO_2-e/ha.

The lack of significant differences in GHG emissions per kg of product between the low and high rainfall farms was likely due to the low rainfall farms having a higher product/ha from the beef enterprise. These farms represent Class 2 and Class 6 farm types in the Beef + Lamb NZ Economic Survey data set (Beef + Lamb NZ 2021a,b). As such, the greater amount of steep land (Table 1) resulting in more variable production conditions and often lower feed quality available, which was then managed through greater numbers of cattle, especially breeding cows. It was interesting to note relatively similar GHG intensity values from both of these types of property, regardless of rainfall. This result reinforced the results reported by MacKay *et al*. (2012), which demonstrated greater overall gains in productivity in more marginal environments (low rainfall) relative to higher producing environments (high rainfall) in recent times.

There is limited data available on the effect of brassicas on nitrous oxide (N_2O) emissions from grazing systems (Thomson *et al*., 2016). The data available regarding fodder beet on enteric methane suggested that it has a greater reducing effect than feeding brassicas (Thomson *et al*., 2016). Estimated reductions in GHG of 20-35% per kg DM eaten may be possible with both brassica and fodder beet diets (Thompson *et al*., 2016), which suggested that including brassicas in the calculations would further reduce enteric emissions by between 5 and 10% in such environments, if feed-based methane emission factors were considered.

Recent research has shown that lactating cows produce the least amount of methane on a fodder beet diet compared with a pasture diet, and low protein fodder beet can reduce urinary N excretion and, consequently, nitrate leaching and nitrous oxide (N_2O) emissions (Jonker *et al*., 2017). However, these benefits have not yet been captured in the GHG inventory. For inclusion in the NZ inventory, other variables that can influence GHG emissions, such as soil cultivation, grazing management and environmental processes of nitrate leaching, nitrification, N_2O emissions and soil carbon accumulation, need to be considered (Thompson *et al*., 2016). Further research and the application to sheep and beef farms is needed to realise the potential gains to be made in using fodder beet and brassica on the ecoefficiency of production.

Estimated nutrient losses were significantly higher under the control scenarios when compared to the fodder beet scenarios, which was most likely influenced by the smaller area of fodder beet grown compared to the swede and kale crops. Therefore, the development of a significant 'hot spot' for nutrient losses due to the high yield potential of fodder beet appears to have been offset by the reduction in total area required.

Conclusions

The role of ewe BCS in the reproductive success of sheep was highlighted in eco-efficiency calculations at a whole farm level, and was repeated in both high and low rainfall environments. Specific winter crops can change this relationship, due to the the impact of low protein fodder beet feeding in multiple-bearing ewes in mid-to-late pregnancy on lamb survival and growth to weaning, which, when represented at farm scale, further reduced eco-efficiency. However, mitigating such impacts using a balanced supplement was able to restore whole farm productivity and ecoefficiency. The use of winter crops for feeding pregnant ewes should be monitored carefully and the addition of a protein supplement to balance the diet is a worthy inclusion to maintain eco-efficiency.

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