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INVITED PAPER: Has progress been made in increasing the eco-efficiency of livestock systems?AD Mackay¹, DR Scobie², TR Rhodes³ and B Devantier¹¹AgResearch Grasslands, Private Bag 11008, Palmerston North; ²AgResearch Lincoln Research Centre, Private Bag 4749, Christchurch 8140; ³PGG Wrightson Consulting, PO Box 42, Dannevirke 4942

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Abstract

Current challenges for New Zealand livestock farming systems include soil erosion, water quality, greenhouse gases (GHG), and indigenous biodiversity. Industry data were used to quantify changes in emissions of the major livestock sectors from 1990, by examining inputs (e.g., livestock numbers, fertiliser) and outputs (e.g., GHG, nitrate leaching (N), saleable products) using Overseer. Productivity gains were significant for extensive sheep and beef farms, from 107 (meat + wool) kg/ha in 1990 up to 167 kg/ha in 2012. Gains were modest for intensive sheep and beef farms in this period (from 219 up to 238 kg/ha). Extensive sheep and beef increased from 3370 to 3997 kg/ha of GHG and N leached from 12 to 14 kg/ha. Intensive sheep and beef farm systems showed negligible change in N leached, while GHG emissions rose from 4167 to 4470 kg CO₂-e/ha. North Island dairy farms increased from 672 to 1000 kg milk solids/ha, from 11341 to over 12000 kg CO₂-e/ha of GHG and N leached increased from 44 up to 50 kg/ha. All farm systems delivered more product in proportion to GHG and N per hectare per year. Potential scenarios for the sheep and beef sector into the future were investigated, by examining the influence of ongoing increases in reproduction of ewes, lamb growth, hogget lambing and moving away from breeding cows and older cattle could have on future productivity gains and environmental impact. With the area in pasture likely to continue to decline in extensive livestock systems as outstanding environmental issues are addressed, the potential exists to offset > 20% of livestock GHG emissions. Intensive systems have fewer opportunities to make production and eco-efficiency gains, with less scope to reduce their impact.

Keywords: Sheep and beef; eco-efficiency; meat and fibre production; N leaching; hill country; C sequestration**Introduction**

Globally livestock systems have come increasingly under the microscope starting with the 2006 release of a United Nations report *Livestock's Long Shadow: Environmental Issues and Options*, (http://www.fao.org/docrep/010/a_0701e/a0701e00.HTM). That report identified land degradation, air and water pollution, and loss of biodiversity under livestock operations. The increasing expectation around the welfare and well-being of livestock (Stafford et al. 2002) and notable growth of veganism, adds further pressures on producers throughout the world. The New Zealand livestock industry is not immune to these challenges, with soil erosion and sediment losses in hill land, surface water quality, greenhouse gas (GHG) emissions and the loss of indigenous biodiversity on private land under pasture, all outstanding issues. In New Zealand these challenges are reflected in legislation to reduce the risk of soil erosion by introducing policy to limit vegetation clearing and tracking, and the transition from livestock to permanent woody vegetation on specific landscape units (<http://www.gdc.govt.nz/assets/District-plan-text/Chapters/Chapter-6-101015.pdf>). The National Policy Statement (NPS) for Freshwater Management 2014 supports improved water quality in New Zealand (Anon. 2014). This extends current policy controls to diffuse losses from agricultural land.

With livestock systems in New Zealand Agriculture contributing 49.2% of all GHG emissions in 2016, i.e., 38.7 Mt CO₂-e (MfE 2016a), and with enteric fermentation generating most of New Zealand's total CH₄ and most N₂O emissions from agricultural soils, there is pressure for the livestock sector to reduce its impact on the environment.

This has been brought into sharp focus by the Labour-led government's first steps towards a zero Carbon (C) Act (available at <https://www.beehive.govt.nz/release/first-important-step-towards-zero-carbon-act>). This will challenge the livestock sector further.

With their statutory requirements under the Resource Management Act related to biodiversity on private land, Regional and District Councils have operated in a varied manner (Maseyk & Gerbeaux 2015). This has resulted in varied practice across New Zealand and a continued decline in the extent and condition of indigenous biodiversity on a national scale (MfE 2016b). The current level of protection of indigenous biodiversity across all farmland in New Zealand at June 2016, was a total of 4,626 protected open spaces (including registered covenants, approved covenants, and formal agreements), covering 182,677 ha (QEII National Trust, 2017). Sheep and beef farmland has recently been reported to be the largest provider of habitat and biodiversity among the agricultural land use types, with 2.8 million hectares of native vegetation and half of that was estimated to be woody (Norton & Pannell 2018). Indeed, these authors suggested that much of that occurs in regions where equivalent native vegetation is not found in conservation land and are therefore valuable remnants. While a major achievement by individual landowners within the sectors, national direction mandating biodiversity protection on-farm is currently lacking in New Zealand, although the recent release of a draft strategy for indigenous biodiversity by the Biodiversity Collaborative Group as a recommendation to the government offers some future direction (<https://www.biodiversitynz.org/>).

Primary-sector groups in New Zealand have reacted to these mounting environmental pressures in a number of ways. Beef and Lamb New Zealand (B+LNZ) recently launched their Environment Strategy, which lays out a progressive long-term vision for the sector based on four priority areas – healthy productive soils, thriving biodiversity, clean water, and reducing C emissions (available at <https://beeflambnz.com/environment-strategy>). The Sustainable Dairying Water Accord launched in July 2013 (available at <https://www.dairynz.co.nz/environment/in-your-region/sustainable-dairying-water-accord/>), is a set of good management practices aimed at lifting environmental performance on dairy farms. The livestock sector is also investing in research and development to provide options for farmers to reduce emissions to the atmosphere. New Zealand is part of the global response to agricultural greenhouse gases (<https://globalresearchalliance.org/>), as it is to the wider pressure on livestock to improve the use of natural resources and reduce impact, whilst ensuring contribution to food security and livelihoods (<http://www.livestockdialogue.org/>). It is important that these initiatives are not limited to food and fibre but include the implications to all the benefits we obtain from livestock systems.

The two major livestock industries in NZ have developed along very different pathways in the last 30 years. Since 1990, the total area in sheep and beef production has decreased 28%, from an estimated 10.6 to 8.3 million hectares in 2017 (MfE-SNZ 2017). This decline includes a loss of land to dairy production, planted to forestry, viticulture, horticulture and urban encroachment, along with actively retiring land at risk of erosion or with indigenous biodiversity value. Sheep and beef numbers have fallen from 58 and 4.6 million, respectively in 1990 to 27.3 and 3.7 million, respectively, in 2018 (<https://beeflambnz.com/sites/default/files/news-docs/Stock-Number-Survey-30-June-2018.pdf>). Against a background of down-sizing in numbers and area, the sheep and beef sector has made substantive productivity gains, including increased average lambing percentage from 100 to 126% nationally since 1990, lamb carcass weight per ewe from 13 to 17 kg, and wool per head from 5 to 6 kg.

Dairying has a very different story since 1990. Total dairy cattle numbers have nearly doubled from 3.3 million in 1990 to 6.47 million in 2017, as has area under dairy farming to 2.6 million hectares (MfE-SNZ 2017). Furthermore, some sheep and beef farms take on dairy support including overwintering adult dairy cows and raising replacement heifers, which has provided another valuable income stream.

Given this backdrop, it is interesting to explore how the changes in the livestock sector over the last 30 years have changed their respective environmental footprint. Has the progress made in increasing the utilisation of land and associated inputs to control production costs, also influenced the efficient use of permissible emissions? The latter is of particular interest given the advent of limits and limit-setting processes to control emissions to air and water

to protect receiving environments, both of which have a finite capacity to cope. By looking back can we gain some insights into the future trajectory of these sectors?

This paper first quantifies the changes in the footprint of the two major livestock sectors from 1990 by examining the relationship between inputs and outputs using the MAF Monitoring models for Sheep and Beef Farms (Hard and Easy-Hill Finishing farms) and Dairy from the North Island through to 2012 when the MAF monitoring programme came to an end. Second, looking forward using the equivalent of the Hard-Hill-Country and Easy-Hill-Finishing farm systems now monitored as part of the economic service of the B+LNZ, we examined likely future changes in farm performance from the continued adoption of existing and emerging productivity technologies, whilst addressing current and outstanding environmental and animal welfare issues.

Materials and methods

Changes from 1990–2012 in the two major livestock sectors

Farm monitoring data

To obtain the historical picture of the changes that have occurred in the performance of the two sectors, farm monitoring models were used to explore the influence of changes in inputs (e.g., livestock numbers, nutrients, etc.) on outputs (e.g., saleable products, GHG, nitrate) from 1990–2012. These farm monitoring models were the MAF Sheep and Beef Hard-Hill Country and Easy-Hill Finishing, 1989/90, 1999/2000, 2011/2012, and the MAF Dairy Lower Central North Island 1989/90 and 1999/2000, MAF Taranaki 2011/2012 and MAF Waikato/BOP 1999/2000 and 2011/12.

Milk, meat and fibre production

To calculate fibre, sheep meat and beef production for the Hard Hill Country and Easy Hill Finishing farm systems, a stock reconciliation was constructed from the information provided in each Sheep and Beef Farm Monitoring model (Table 1). The following assumptions were made in calculating the numbers of livestock for sale or retention: (i) ewe lamb replacement rates of 30% for the Hard-Hill-Country system, (ii) a combination of 11% ewe lamb replacements, plus purchase of two-tooth or mixed-age ewes for the Easy Hill Finishing system, (iii) heifer replacement rates of 20% for the Hard Hill Country and (iv) death rates of 5% for sheep and cattle. Fibre production per sheep stock unit reported in the MAF Sheep and Beef Farm Monitoring models were multiplied by total sheep stock units, and added to sheep and beef meat to calculate meat and fibre production per hectare.

To calculate milk production per cow, performance was multiplied by cow stocking rate per hectare to obtain milk solids/ha. Meat production from cull cows and bobby calves are recognised as a significant contribution, even when replacement heifers are reared off the milking platform, but for the purposes of this study were not

Table 1 Input information and assumptions in populating Overseer® nutrient budget model for the two sheep and beef farm systems

	Hard Hill country			Easy Hill Finishing		
	1989-1990	1999-2000	2011-2012	1989-1990	1999-2000	2011-2012
Sheep and beef						
Soil	Brown	Brown	Brown	Brown	Brown	Brown
Rainfall (mm)	1500	1500	1500	1250	1250	1250
Pasture type	Browntop	Browntop	Browntop	Rye/WC	Rye/WC	Rye/WC
Olsen P (µg/ml)	11	18	18	17	23	23
Stocking rate (su/ha)	7.8	7.9	8.7	10.3	10.3	10.6
Sheep: Cattle ratio	72:28	55:45	54:46	69:31	53:47	60:40
Lambing (%)	75	110	126	93	123	134
Store lamb (kg)	28.6	30.9	35.0			
Prime lamb carcass (kg)	12.6	14.7	16.9	14.0	17.9	19.9
Works ewes carcass (kg)	19.1	22.6	24.5			
Steer carcass weight (kg)	210	275	285	275	272	300
Cull cow carcass (kg)	240	250	250			
Fertiliser P (kg/ha/yr)	17	21	21	19	22	23
Male cattle (%)	20	20	20	100	100	100
Finishing stock	No	No	No	Yes	Yes	Yes
Slope	Hill-Steep	Hill-Steep	Hill-Steep	Easy-Hill	Easy-Hill	Easy-Hill

Table 2 Input information and assumptions in populating Overseer® nutrient budget model for the dairy systems

	Lower North Island	Waikato/ BOP	Waikato/ BOP	Manawatu	Taranaki
Dairy	1989-1900	1999-2000	2011-2012	1999-2000	2011-2012
Soil	Brown	Brown	Brown	Brown	Allophanic
Area (ha)	49	83	118	80	96
Rainfall	1250	1250	1250	1250	1250
Pasture type	Rye/WC	Rye/WC	Rye/WC	Rye/WC	Rye/WC
Olsen P (µg/ml)	25	50	70	50	70
Cow numbers /ha	2.7	2.7	2.86	2.8	2.82
Peak cows	153	225	338	213	270
Total Milk solids (kg)	32920		117,700		100,500
Milk solids/ha	672	692	997	715	1047
Milk solids/cow	255	273	348	300	372
Fertiliser P (kg P/ha/yr)	26	31	28	38	28
N fertiliser (kg N/ha/yr)					
Supplements purchased (t DM)	0	70	117	70	150
Fodder crops					
Area in fodder (%)	0	45 t pasture silage	120 t Maize silage, 116 t PKE	55 t pasture silage	75 t Maize silage, 100 t PKE
Effluent system					
Cows wintered	0	Swedes	Swedes	Swedes	Swedes
Replacements reared	0	5	5	5	5
	Two pond	Spray from sump	Spray from sump	Spray from sump	Spray from sump
	On	On	On	On	On
	On	Off farm 9 months	Off farm 9 months	Off farm 9 months	Off farm 9 months
Slope	Flat/Rolling	Flat/Rolling	Flat/Rolling	Flat/Rolling	Flat/Rolling

included in the analysis due to the long-standing convention within the sector to exclude it.

Calculation of emissions to air and water

A nutrient budget model (OVERSEER® (Version 6.3.0) <https://www.overseer.org.nz/>, Wheeler et al. 2008), from here referred to as Overseer, was used to explore the relationship between inputs and outputs from each farm system from 1990 to 2012. Overseer Best Data Input Standards were adhered to. The GHG model within Overseer is based on algorithms similar to those used for

New Zealand's national inventory, modified to allow for on-farm management strategies, and includes methane (CH₄) from animals and nitrous oxide (N₂O) emissions from excreta and any nitrogen (N) fertiliser applied, and for completeness carbon dioxide (CO₂) emissions from the farm. The sheep and beef farms were examined as a single block, with details listed in Table 1. Dairy farms were treated as two blocks, an area receiving and another not receiving dairy-shed effluent (Table 2). Emissions calculated in Overseer were used to calculate eco-efficiency, the ratio of

Table 3 Details of the Hard Hill (Beef + Lamb farm Class 3) and Easy Hill (Beef + Lamb farm Class 5) sheep and beef farms used to explore the impact of existing and emerging technologies and practices and outstanding environmental challenges on future performance.

	Hard hill Country	Easy hill country
Total area (ha)	1000	200
Effective area (ha)	920	191
Crop area (ha)	5	5
Sheep SU	4187	1286
Lambing percentage (%)	120	132
Cattle SU ¹	3154	741
Overall SU/ha ¹	7.8	10.4
Sheep:cattle ratio	57:43	63:37
Soil type	Brown	Pallic; Brown
Rainfall	800-1400	800-1401
Fertiliser inputs (kg/ha) ¹	4 kg N/ha; 10 kg P/ha	5 kgN/ha; 13 kg P/ha
Planted forest (ha)	24	5
Spaced planted trees (ha)	24	4
Indigenous bush (ha)	56	5
Riparian margins (km)	0	0
Wetland (ha)	0	0
Land Classes	LUC 4-6, 7-8	LUC 2-4, 6
Variant: Slope	Hill/Hard (50/50)	Rolling/Easy/ Hill (20/40/ 40)
Farm Class	3¹	5²

¹Class 3: Steep hill country or low fertility soils with most farms carrying 6 -10 stock units per hectare, with a significant proportion of progeny sold store.

²Class 5: Easy contour farmland, mostly carrying between 8 - 15 stock units per hectare, with a high proportion of stock sent to slaughter and replacements often bought in.

the amount of product divided by emissions to receiving environments.

Future potential changes in sheep and beef farming systems

Future scenarios were assessed on the equivalent of the Hard Hill Country and Easy Hill Finishing farm systems now monitored as part of the economic service of the B+LNZ (Table 3). There were differences in the characteristics of the farm systems in the B+LNZ and those of the MAF farm-monitoring programme (Table 1). The impact of existing and emerging productivity technologies and practices for addressing current and outstanding environmental challenges, drawing from the compendium of potential mitigations in the UK 'User Manual' (Cuttle et al. 2016), were added sequentially. A total of 11 actions into the future, with potential to influence productivity and footprint were examined. It was assumed that regenerating bush is already protected on both farm systems, and there is some plantation forestry and wide-spaced trees planted on some of the steep land (LUC Class 7) for soil conservation in the Hard Hill Country system (**M1**). At a planting

density of 10 m by 10 m (100 stems/ha) this reduces annual pasture production to 89% of open pasture. Phosphorus fertiliser with high citric acid solubility but low water solubility is introduced to reduce the risk of P run off on easy, moderate and steep slopes (**M2**). Increasing the area of eroding steep land planted in pines and spaced, planted conservation trees to 10% to reduce the risk of soil erosion and protect infrastructure and receiving water bodies (**M3**). Through a combination of improved genotypes, feeding and husbandry, sheep reproductive performance is lifted by 20% and the weaning weight of lambs increased (**M4**). An increase of this magnitude is well within current industry practice (<http://portal.beeflambnz.com/tools/lambs/> August 2016). A shift in cattle policy (94% calving) from breeding cows and the sale of rising one-year olds and rising 2-year-old cattle, to the purchase of weaner cattle out of the dairy industry to be finished within 12 months in the Hard Hill Country system (**M5**). A conscious change in enterprise to extend plantation forestry and spaced, planted conservation trees on the Hard Hill Country farm to cover another 20% of the most erosion-prone steep land. Spaced-tree plantings on Easy hill extended to 20% of the area at a planting density of 15 m by 15 m (**M6**). A further lift in sheep reproductive performance (30% above base), through the introduction of hogget lambing and ongoing improvements in genetic merit, feeding and husbandry and associated increase in the weaning weight of lambs (**M7**). All major primary and secondary stream networks and wetlands in both farm systems fenced and reticulated water infrastructure extended (**M8**). The riparian area amounts to 0.25% (up to 25 ha) of the farm area and wetland representing 0.03% (up to 3 ha) of the farm land area. All streams protected from cattle to limit contribution from remaining critical source areas and overland flow pathways (**M9**). The area of easy hill and steep land planted in spaced trees is increased to 40% (**M10**). Further improvement of reproductive performance by 40% above base (155% lambing) and higher lamb growth rates (**M11**). An increase of this magnitude would approach the limit of current industry practice (<http://portal.beeflambnz.com/tools/lambs/August2016>).

The farm-scale simulation model Farmax® Pro (Version 6.4.6.07 AgResearch Science Edition for S&B) referred to as Farmax (www.farmax.co.nz), was used in tandem with Overseer to quantify the changes in the performance of the two sheep-and-beef farm systems with the sequential introduction of each practice change (**M1 to M11**).

The amount of carbon (C) sequestered in indigenous vegetation, plantation forestry (*Pinus radiata*), spaced planted trees for soil conservation, (including poplar *Populus* spp. and willow *Salix* spp.), riparian margin plantings and wetlands, were estimated using C sequestration rate (t CO₂ ha⁻¹ yr⁻¹) from Burrows et al. (2018). For indigenous vegetation, spaced planted trees in steep land and easy hill, riparian plantings and wetlands the assumption was made that C sequestration rates were one t CO₂ ha⁻¹ yr⁻¹ and for *P. radiata*, average C sequestration rate of 6.5 t CO₂ ha⁻¹ yr⁻¹.

Results and discussion

Changes in livestock performance 1990-2012

Sheep and Beef

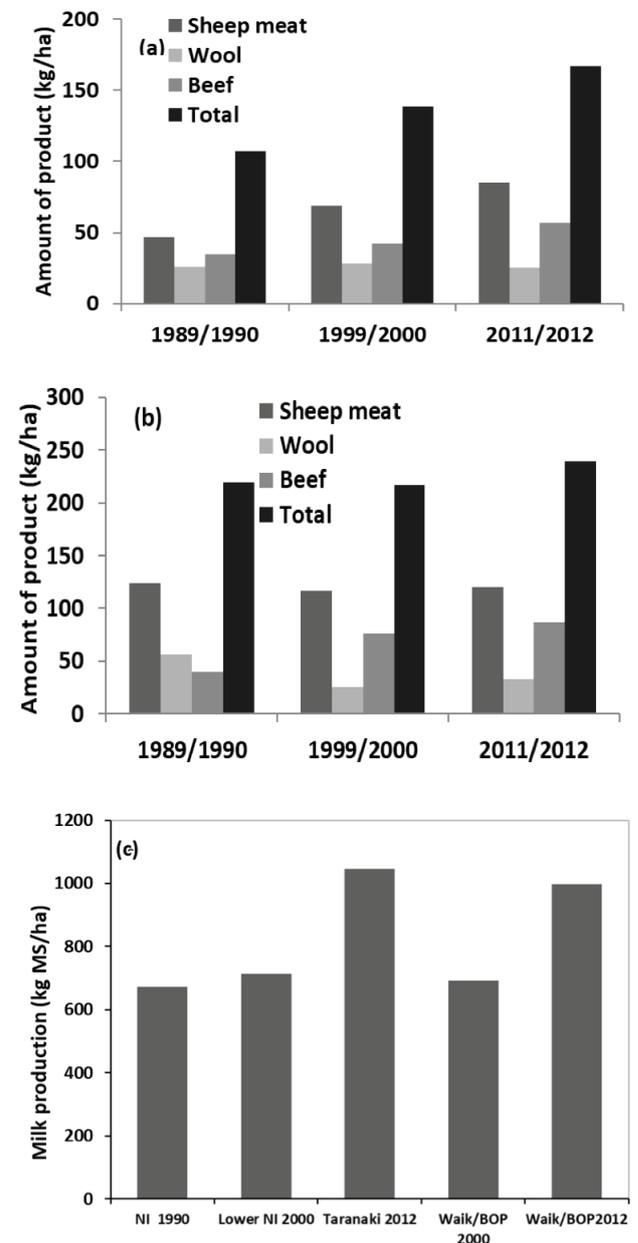
There was little change in “nominal stocking rates” in either of the MAF sheep-and-beef-farm monitoring models between 1990 -2012, with a shift from 7.8 to 8.7 stock units (su)/ha in the Hard Hill country system, while the Easy Hill Finishing systems from increased 10.3 to 10.6 su/ha over the same period (Table 1). Sheep to cattle ratios have changed very little. The shift to hogget mating is one major change since 1990. Ewe lambs have the ability to successfully breed at 7-9 months of age if they reach 35 kg live weight (Kenyon et al. 2014). Edwards et al. (2015) found that attaining puberty in the first year of life also improves reproductive performance as a two-year-old, increasing the number of lambs born by 20 lambs per hundred ewes and reducing the incidence of non-pregnant ewes. Maintenance fertiliser inputs have increased as per ha production has lifted. It is important to note that the combination of challenging climatic conditions and sub-maintenance fertiliser, as a result of the poor returns in the three to five years up to 2012, probably contribute to an understatement of the gains made by the sector since 2000 (Davison 2010).

In sharp contrast to the small changes in livestock numbers, there has been substantial change in livestock performance, with lambing percentages increasing from 75% to 126% in the Hard Hill Country and 93% to 134% on the Easy Hill Finishing operation (Table 1). In addition to increased ewe fecundity, improvements have also been achieved in lamb growth rates, with prime lamb carcass weights increased 37% from 14.5 kg to 19.9 kg over the last 20 years. This has contributed to a lift in sheep meat production in Hard Hill Country of 56% since 1990 (Figure 1a). Beef production has also increased by more than 50% over the same period, while wool production has remained static (Figure 1a). In the Easy Hill Finishing system, where average MAF Model farm size more than doubled from 173 to 368 ha from 1990 to 2012, there has been little change (<10%) in the amount of saleable product increasing from 219 to 238 kg ha⁻¹ (Figure 1b).

Dairy

Between 1990 and 2012 milk production increased from 672 kg of milk solids (MS)/ha from the lower North Island Dairy system to 1047 and 997 kg MS/ha for the Taranaki and Waikato Dairy operations, respectively (Figure 1c). This represents an increase in production approaching 2.5% per annum. A feature of dairy systems since 1990 has been increased use of fertiliser N, supplementary feeds, including maize silage and palm kernel expeller meal (PKE) from 2000, along with rearing replacement heifers off the milking platform (Table 2). All of these actions have contributed to increased production on the milking platform. This is in addition to the more than doubling of land area in dairy and total cow numbers across New Zealand.

Figure 1 Annual production of sheep meat, wool and beef per hectare from (a) Hard Hill country and (b) Easy Hill finishing sheep and beef farms and (c) annual milk production per hectare in two regions in the North Island from 1990 to 2012.



Changes in nitrate leaching and greenhouse gas emissions 1990-2012

Sheep and beef

Annual nitrate leaching losses calculated using Overseer fell within a narrow range of 12-14 kg N/ha for the sheep and beef systems (Figure 2a). There was little difference in N leaching losses between the Hard Hill Country and Easy Hill Finishing systems. This partly reflects the lower rainfall of the more-intensive operation (Table 1). Despite substantial increases in per hectare production, N leaching has changed little in either the Hard Hill or Easy Hill Finishing operation since 1990. Cameron et al. (2013) ranked temperate agro-ecosystems

based on the potential for nitrate leaching in the order: forest < cut grassland < grazed pastures < arable cropping < commercial vegetables. Nitrate leaching losses typically range for forestry from 1 to 15 kg N/ha/yr, sheep and beef from 6 to 60 kg N/ha/yr, dairying from 15 to 115 kg N/ha/yr, arable from 10 to 140 kg N/ha/yr, while for commercial vegetables it may be as high as 100-300 kg N/ha/yr. The leaching data for Hard Hill Country and Easy Hill Finishing systems fall at the lower end of the range for sheep and beef systems (12-14 kg N/ha/yr).

There was a slightly different pattern to GHG emissions with an increase from the Hard Hill Country from 3370 to 3997 kg CO₂-e/ha from 2000 to 2012, while on the Easy Hill Finishing GHG emissions increased from 4167 to 4470 kg CO₂-e/ha (Figure 2b). Methane made up 69-73% of total emissions, N₂O 22-27% and CO₂ only 2-3%. These values align with other studies of sheep and beef systems in New Zealand (Dynes et al. 2011; Vibart et al. 2011).

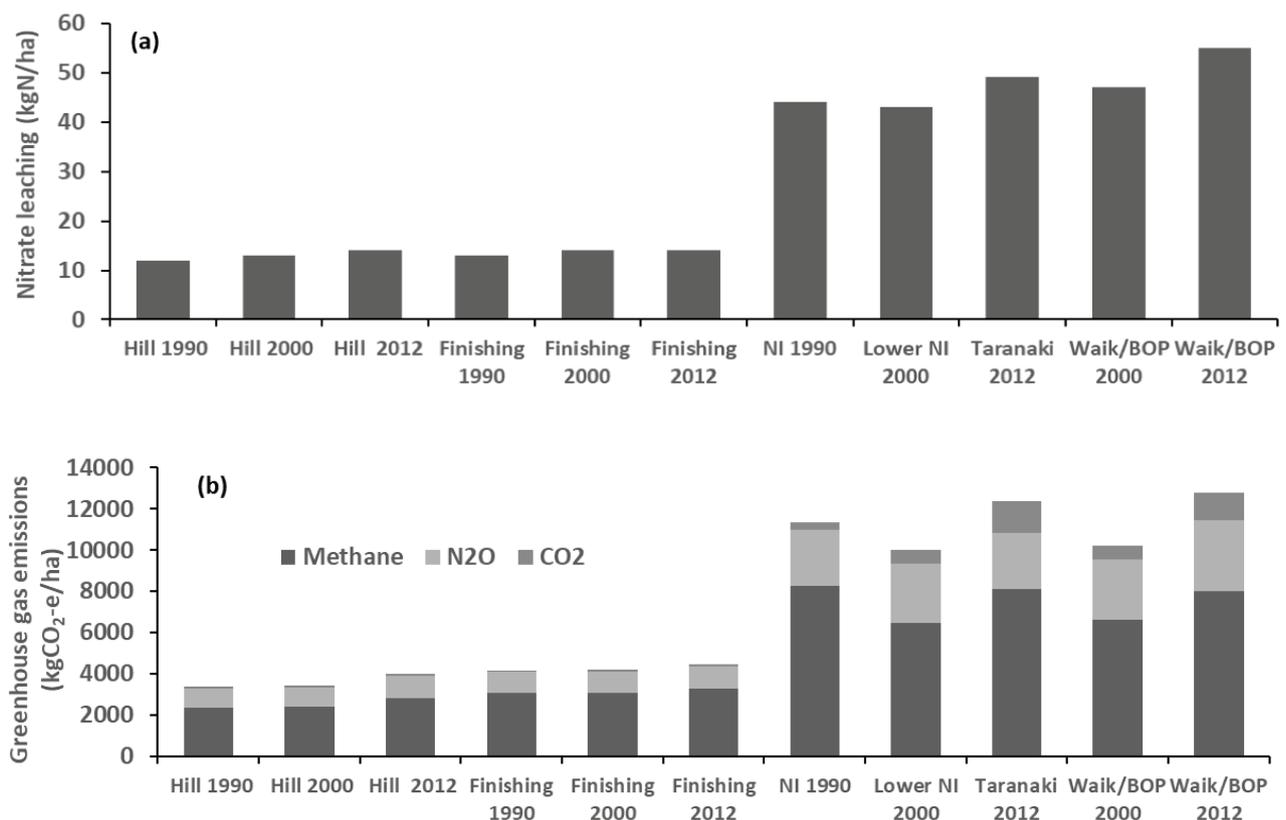
Dairy

Annual nitrate leaching losses increased from 40 kg N/ha in 1990 in the Lower Central North Island Dairy system through to 49 and 55 kg N/ha for the Waikato/BOP and Taranaki dairy operations, respectively, in 2012 (Figure 2c). The N leaching losses from both the Taranaki and Waikato/BOP are in the low to medium range reported by Di and Cameron (2002) and Cameron et al. (2013) for dairy systems, but within the range reported by Smeaton et al. (2011) and Dynes et al. (2011). These are three-fold higher

than the N losses from the sheep and beef systems (Figure 2a). The increase in nitrate leaching, aligns with increases in milk production and both are associated with the increased use of N fertiliser and imported supplementary feeds, including maize silage and PKE, along with the grazing heifer replacements off-farm for nine months. All of these serve to increase the amount of N cycling on the milking platform (Table 2) and potential for N leaching losses (Ledgard 2001). Associated with the lift in milk production with maize silage, is lower urinary N, with the higher C:N ratio of maize based feeds.

Greenhouse gas emissions from the dairy systems increased from 11341 kg CO₂-e/ha in the Lower Central North Island system in 1990 to 12350 and 12789 kg CO₂-e/ha, in the Waikato/BOP and Taranaki dairy systems in 2012, respectively (Figure 2d). Methane made up 61-73% of total emissions, N₂O 22-29% and CO₂ only 3-12%. Like N losses, these emissions are three-fold higher than those estimated for the sheep and beef systems examined in the present study (Figure 2b). In this analysis the emissions from adult cows between lactations and heifer replacements grazed off-farm are not included in the calculation but were captured in the nutrient and GHG budget of the land providing the service, in many cases a sheep and beef farm. In future, with biophysical limits placed on emissions to receiving environments becoming an integral part of considerations for livestock systems, operations providing grazing service contracts, will need to factor into the

Figure 2 Annual (a) nitrate leaching losses and (b) greenhouse gas emissions from sheep and beef farm and dairy systems from 1990 to 2012.



contract the implications of this enterprise and account for it in their overall emissions profile. Further, they will also need to understand the influence of each mitigation on all emissions. For example, Smeaton et al. (2011) analysed both dairy farms and sheep and beef farms and found a very high correlation between N leached and GHG emissions in a study based on several scenarios on a single soil-type-climate. Vibart et al. (2015), modelling GHG emission for a series of Southland dairy farms covering a range of environments, found reductions in GHG emissions to be smaller (8-14%) in comparison with the reduction possible in modelled N leaching, which ranged from 33-47%.

Measures of eco-efficiency

Sheep and beef

Meat and fibre production per ha increased (Figure 1a) while the amount of N leached per kg of animal product and CO₂-e per kg of animal product both decreased from 1990 to 2000 and again between 2000 and 2012 for the Hard Hill Country (Fig 3a and b). Total saleable product per hectare increased by 56% (from 107 to 167 kg/ha), nitrate leaching per kg of saleable product decreased by 17% (from 0.065 to 0.054 kg N/kg animal product) and GHG emissions per kg of saleable product decreased by 29% (from 27 to 19.2 kg CO₂-e/kg animal product). The GHG emissions per kg of saleable product are in line with other studies (Dynes et al. 2011, Vibart et al. 2011). The decrease in kg N leached per kg of meat and fibre produced reflects two factors. One, more of the feed grown through the spring and summer is eaten by young growing animals and turned into saleable product before the autumn and winter months. Second, less live weight per unit product sold is carried through winter, reducing the amount of urine and the potential for N losses by leaching. The reduction in the kg CO₂-e per kg animal product reflects the increased allocation of the total feed grown to saleable product and less to the maintenance of capital livestock. Reduced numbers of capital stock wintered also reduces the potential risk of P losses in run-off.

The absolute losses per hectare are the more meaningful measure of eco-efficiency as limits are set on emissions to water in catchments. The eco-efficiency gains obtained in the Hard Hill country farm system did not extend to an overall reduction in N leaching or GHG emissions per hectare, because livestock numbers remained fairly constant, but there was not a substantive increase and remained low relative to other sectors. Added to the substantive decrease in the total area in sheep and beef production across New Zealand, this helps explain why emissions from the sector have been declining since 1990.

In the Easy Hill Finishing system eco-efficiency and foot print have also changed little (Figure 3a and b), however, the system is more eco-efficient, with the amount of saleable product per hectare higher and the N leached and GHG emissions per kg of saleable product lower than the Hard Hill country operation (Figure 3a and b). This

highlights the fact that enormous scope remains to increase the amount of saleable product on Hard Hill Country through gains in per-head performance. The lambing percentage on the Easy Hill Finishing also has room to move, indicating further gains in eco-efficiency are possible. Cruickshank et al. (2009) promoted increasing lambing percentage, increasing the age at which ewes are culled and introducing hogget lambing as the most significant areas for ongoing reduction of GHG. Dakpo et al. (2017) reported that sheep farming on grasslands in France could reduce GHG emissions by 35%, but in keeping with distorted financial subsidies of European farming industries they suggest compensating farmers to achieve this! Fraser et al. (2014) found methane emissions were higher for steers grazing poor quality UK hill country pastures, suggesting lifting soil fertility and associated pasture quality is certainly a consideration for beef production in New Zealand.

The sheep industry has made much progress in terms of numbers of lambs born and weaned per ewe, and though this could be adopted more widely, there will be limits to further reproductive increase in hill country without increases in neonatal mortality (Knight et al. 1989). Hogget lambing dramatically reduces total N leaching and GHG emissions from sheep production, so wider adoption is possibly the area for greatest gains. Genetic improvement in reducing methane production from sheep certainly appears possible (Pinares-Patino et al. 2013), but the reduction in methane volume in elite flocks and dissemination throughout the industry and sustained reduction will be problematic.

Browne et al. (2015) suggested increased longevity would reduce emissions on Australian sheep and wool enterprises. Trading off longevity with the influence that has on genetic gain, would have to sit alongside the age at first mating to lamb as yearlings, as opposed to mating them at 19 months old. Hristov et al. (2013) listed cross-breeding and selection of livestock, proper nutrition, reproductive efficiency, animal health and reproductive lifespan as potential approaches to reduce emissions, but found that reduced morbidity and mortality, increased productivity and improved fecundity were the most likely to be rewarding. Animal health and reduced morbidity or mortality have not been separately considered here but are likely to be integral parts of the general improvement in productivity for all livestock systems since 1990. The focus of the sheep industry on reproductive performance, and higher growth rates in lambs and cattle provides a natural buffer to the increases in emissions generally associated with intensification of a livestock system.

Dairy

The increase in milk production was paralleled by the increase in emissions to air and water. The amount of N leached per kg milk production did decline over that period, with a drop between 2000 and 2012 in both the BOP/Waikato and Taranaki systems (Figure 3c). That might reflect the greater use of supplementary feeds, off farm grazing and the use of N fertiliser also reducing the

legume and, hence, protein content of pastures. While there was an increase in eco-efficiency, N leaching per hectare continued to increase. As limits are set on emissions to water in catchments, the absolute losses per hectare becomes the more meaningful measure of eco-efficiency. As was the case for the sheep and beef operations the gains in eco-efficiency (Figure 3a) translated into an increase in absolute losses per hectare (Figure 2c).

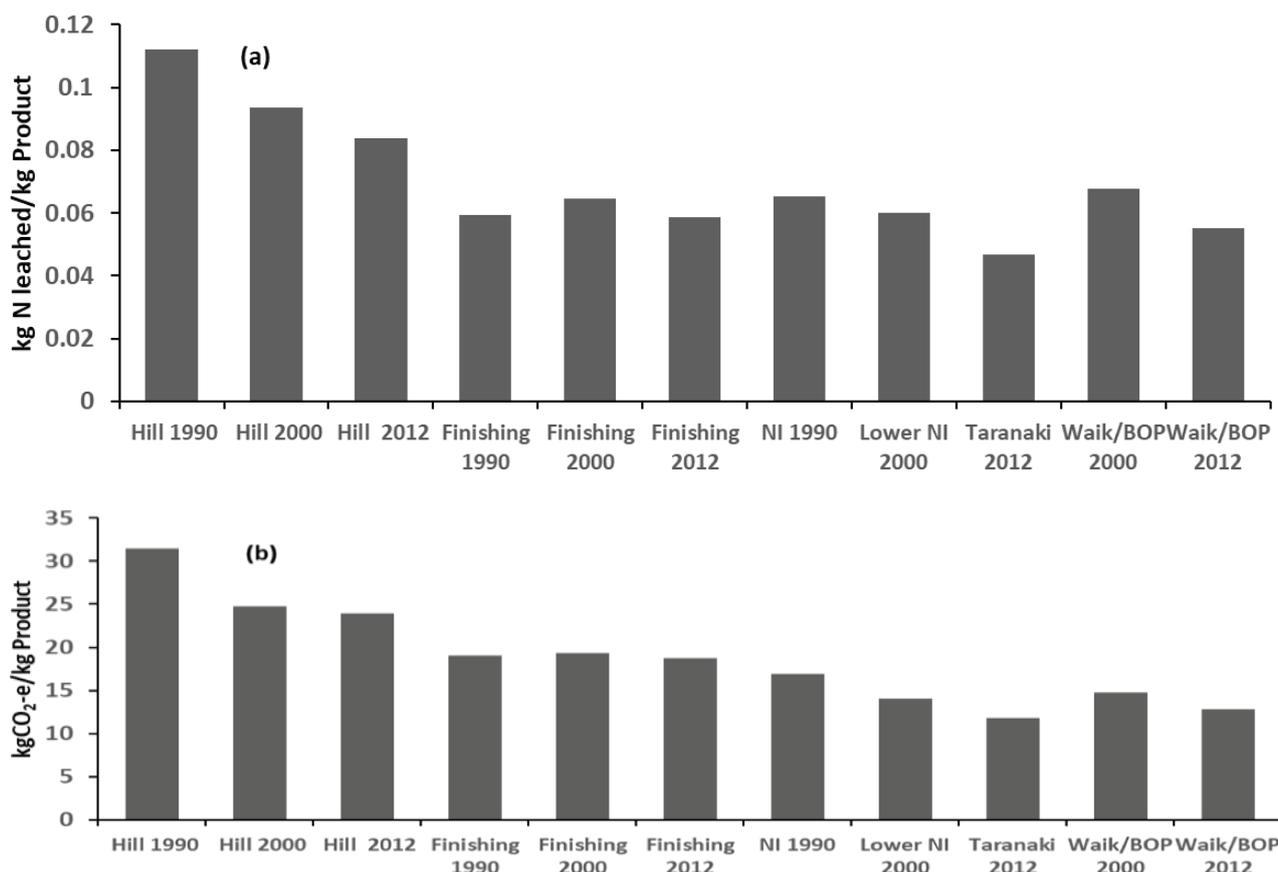
A reduction in GHG emissions per kg of milk solids from both dairy systems was also noted (Figure 3d) with emissions in 2012 (12 kg CO₂-e/kg milk solid) lower than those calculated back in 1990 (16.3 kg CO₂-e/kg milk solid). These values are in line with previous studies of Dynes *et al.* (2011), and Vibart *et al.* (2015). The options available to the dairy farm to reduce their footprint differ from that of a sheep and beef farm. Reproductive performance remains important in the dairy industry, as this creates the opportunity to reduce the percentage of replacements required and in doing so increase average cow age. Browne *et al.* (2015) suggested extended lactation to decrease GHG emissions on dairy farms was option on Australian farms, but this might not be applicable in New Zealand. Beukes *et al.* (2011) identified strategies to decrease GHG emissions including fewer animals with higher genetic merit that are milked longer, lower replacements rates, standing cows off during autumn/winter, decreased fertiliser N inputs, and incorporating low N grain in the

diet. The modelling suggested that milk production would increase by 15-20% and absolute GHG emissions would decrease by 15-20%. The changes to the system to address GHG emissions would also decrease N leaching losses. Another method to decrease CH₄ emissions, is to increase per animal production so that fewer animals are required for the same level of production (Knapp *et al.* 2014). This is based on a ‘dilution’ of the effects of animal maintenance requirements, whereby fewer efficient animals produce the same output per unit of land area (Bauman *et al.* 1985). The emergence of forages with the ability to reduce the amount of the dietary N partitioned to the urine (Cheng *et al.* 2017) show enormous promise as a low-cost alternative to standing animals off pastures for extended periods to reduce N losses and also to reduce N₂O emissions.

Future potential changes in sheep- and beef-farming systems

Future potential changes in productivity and environmental footprint from the sequential adoption of existing and emerging technologies, whilst addressing current and outstanding environmental issues (includes soil erosion, water-way health, enhancement of indigenous flora and fauna) and animal welfare (including shade and shelter) for the Hard Hill country (Figure 4a) and Easy Hill finishing operations (Figure 4b) demonstrates there is scope for future lifts in production, while continuing

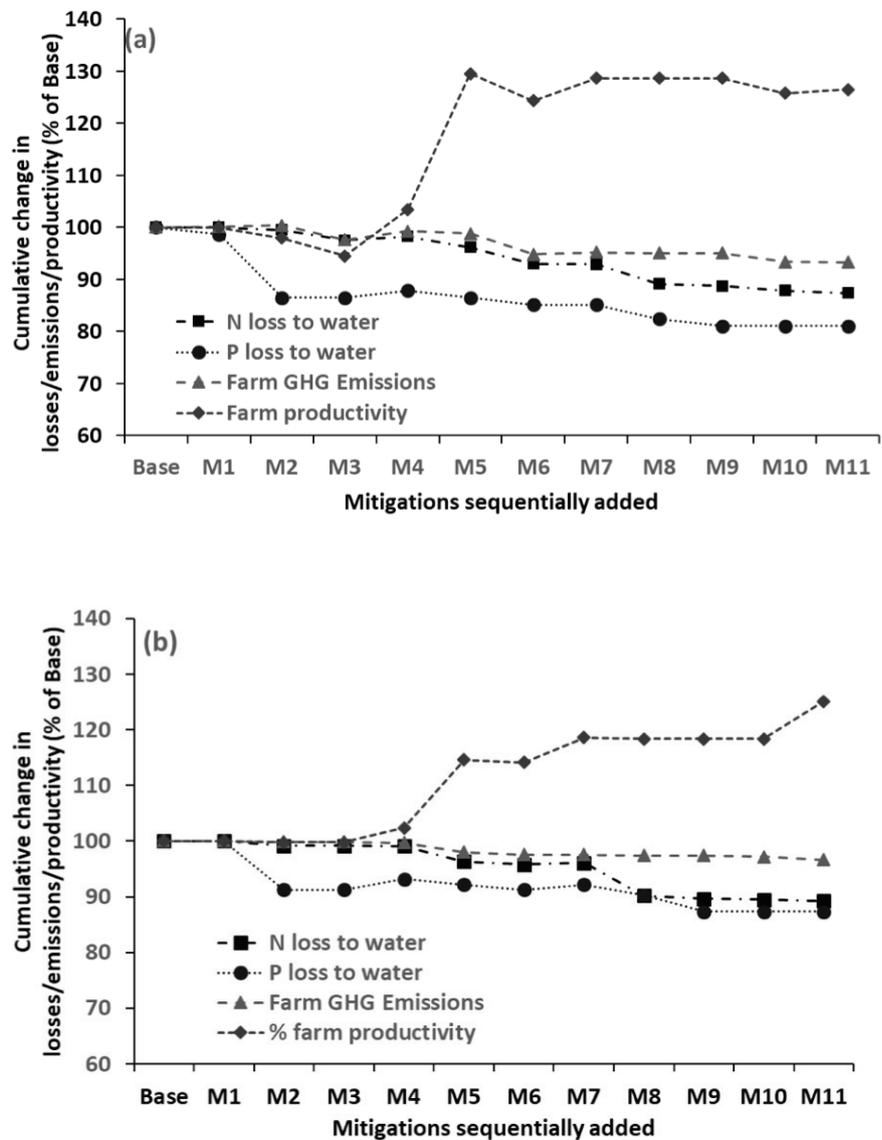
Figure 3 Annual (a) kg N leached and (b) kg CO₂-e/kg animal product (sum of the sheep meat, wool and beef) for sheep and beef and Milk solids for Dairy systems from 1990 to 2012.



to make environmental gains. There is more scope in making production gains in Hard Hill country than Easy Hill farms. The jump in per-hectare performance in the Hard Hill (Figure 4a) is the product of (a) increased reproductive performance of the ewe and higher weaning weights and (b) the shift from breeding cows to trading cattle with minimal numbers carried into a second winter. These changes in sheep performance and the shift in cattle policy both represent efficiency gains, with more forage eaten by young growing animals and fewer lighter animals wintered. To advance the change in the cattle policy will require expansion of dairy-calf-rearing infrastructure and buy-in of meat processors. The lack of ongoing productivity gains in the Hard Hill Country operation from M5-M11 reflects the fact the gains made through improving lambing percentages and farming younger cattle are offset by the decline of the area in pasture, as a consequence of protection of indigenous vegetation and wetlands, tree planting for soil erosion and planting of riparian margins. The re-allocation of existing inputs (e.g., fertiliser that would have been applied to the areas planted in forestry, redirected to the area remaining in pasture) offset some of the loss of the farm in pasture, by increasing the productive performance of the remaining pastures.

The net effect of pursuing production gains and, in parallel, addressing environmental and animal welfare challenges, is a reduction in emissions to both water and air. Modelled N leaching decreased from 14 to 12 kg N/ha/yr in the Hard Hill country (Figure 4a) and from 15 to 13 N ha/yr in the Easy Hill (Figure 4b). There was a corresponding 20% reduction in P loss. The reduction in GHG in comparison are small (Figures 4) highlighting the suite of practices to reduce emission to air contains fewer options than those available to reduce emissions to water. Vibart et al. (2015) in a study in the Southland region broadly identified mitigations as improved nutrient management (source of P fertiliser, fenced wetland, animal exclusion from streams), improved animal productivity (improved reproductive performance and live weight gain

Figure 4 Cumulative percent changes in farm productivity and emissions to air and water, with stepwise introduction of technologies and practices to lift productivity while addressing the outstanding environmental and animal welfare changes in (a) Hard Hill and (b) Easy Hill sheep and beef systems.



from adjusted animal numbers) and restricted grazing (riparian block, covered loafing and feeding pad for winter use).

Sheep and beef farms remain predominantly legume-based pasture systems. Changes in forage species and cultivars may offer future advantages that have been identified, but not formally included in the current system analysis and could potentially allow continued gains in productivity while reducing footprint into the future. Ryegrass cultivars with an elevated concentration of soluble carbohydrate (Cosgrove et al. 2015) or elevated concentrations of lipids (Cosgrove et al. 2008) might reduce GHG production. *Lotus corniculatus* or *Chicorium intybus* for grazing were also found to reduce methane emissions (Ramirez-Restrepo & Barry 2005). Using small willow trees for browsing by sheep reduced methane emissions (Ramirez-Restrepo et al. 2010), but the options of planting

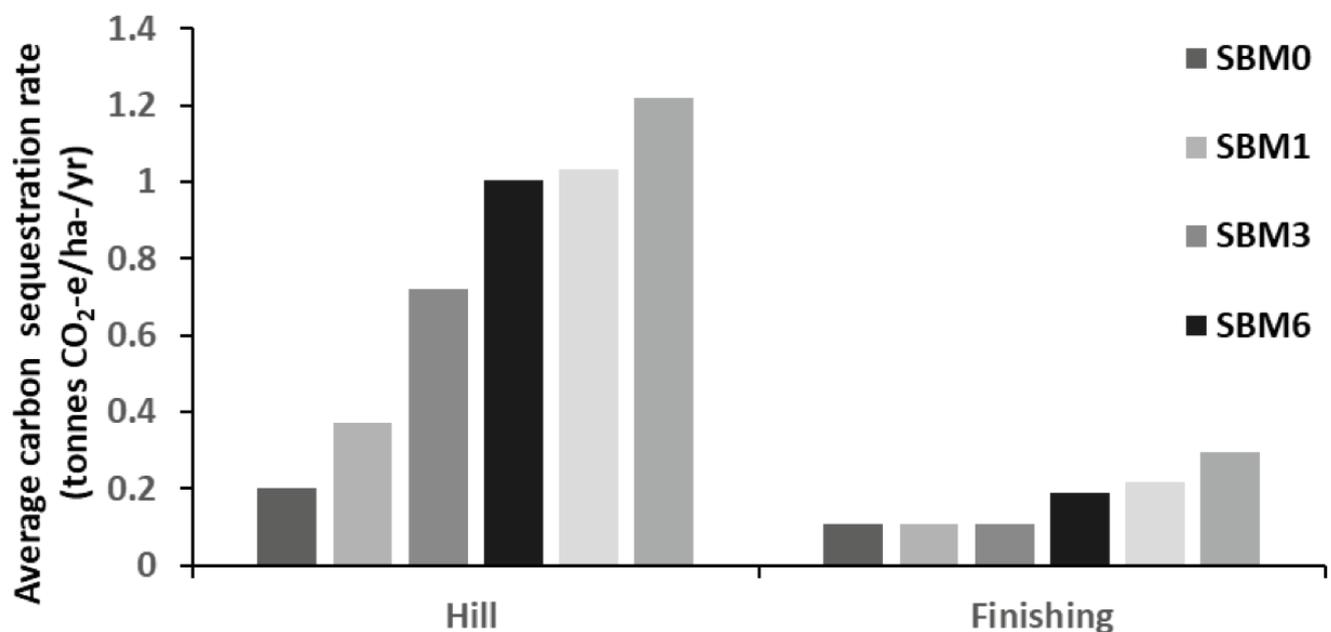
willows or poplar and riparian areas considered here were for protected trees that would not be browsed. It is also worth noting that where crops like forage brassica, fodder beet or maize silage can be grown for animals, it might be more profitable to grow vegetables for human consumption in the future! Indeed, large areas of New Zealand may revert to growing grain crops, where intensive livestock farming has recently been more profitable. However, a large proportion of the area currently farmed with sheep and beef is not suitable for cultivated crops and animal-based production will likely prevail on areas not converted to forestry or regenerating native bush. That production may tend towards other species such as goats or deer, depending on relative product values.

The planting of forestry, spaced planted trees for soil conservation and riparian margin plantings reduce emissions by (i) reducing the area in pasture (plantation forestry, riparian plantings); (ii) reducing pasture production per hectare (space planted trees); (iii) changing the living environment for the animal (e.g., shade and shelter) and (iv) offering options for increasing C sequestration for offsetting GHG emissions from livestock. Vibart et al. (2015) estimated total GHG emissions from an open pasture system in hill country of 4.8 t CO₂-e/ha compared with 4.2-4.4 t CO₂-e/ha for a farm system with spaced trees (poplar and willow) planted for soil conservation. The reduction was largely because the sheltered environment maintained or improved per-head performance despite a lower stocking rate. That study did not consider the GHG offset offered by C sequestration by indigenous vegetation, plantation forestry, spaced planted poplar and willow conservation plantings, riparian margin plantings and protection of wetland.

Plantings to sustain natural resources and provide animals with a kind living environment on the Easy Hill farm offers <10% offset for the GHG emissions from livestock and farm practices (Figure 5). Burrows et al. (2018) also found shelterbelts, hedges and small woodlots in intensive lowland sheep and beef operations offered little scope to offset livestock emissions. Hard Hill Country has the potential to offset livestock GHG emissions by more than 20%, simply by addressing outstanding sustainable land management practices (Figure 5). Into the future, a GHG budget for sheep and beef farms needs to include C sequestered by vegetation and not limited to GHG emissions from livestock and farm practices, to obtain a complete picture of the net contribution of sheep and beef operations to GHG emissions. Importantly the offset offered by vegetation has a finite life, ending when the vegetation reaches maturity at which point growth and senescence are balanced. In comparison, the on-going services and benefits provided by native bush and other plantings, include water purification, shelter, improved resilience to extreme weather events and protecting the underlying natural capital stocks (Dominati et al. 2014). Further integration of indigenous biodiversity into the farm system will likely continue as the cultural and potentially saleable benefits of such areas are recognised.

A recent report from the Productivity Commission has suggested that large tracts of hill country land should be planted to trees to balance the GHG from the livestock sector (Productivity Commission, 2018). This is a poorly informed approach, offering only a short-term GHG emission offset. Policy should be encouraging the development of long-term integrated approaches to the management of our finite land resources. For example, a wetland constructed

Figure 5 Annual cumulative carbon sequestration rates (tonnes CO₂-e/ha) based on the assumption that the remaining indigenous vegetation, spaced planted trees, riparian plantings and wetlands plantings sequester one t CO₂-e/ha/yr and pine plantings 50% of 6.5 CO₂-e/ha/yr



on a Wairarapa dairy farm to cleanse waters leaving the property (Praat et al. 2015), has the potential to reduce nitrate loss, facilitate denitrification capture phosphate, sediment and microbial contaminants in runoff and also accumulate C, while providing habitat for indigenous aquatic life that has become endangered due to widespread drainage of wetlands across the country. Returning wetland tree species like kahikatea (*Dacrydium dacrydioides*) would accumulate C through increased sequestration and add to the indigenous biodiversity in a similar manner to that achieved through remnant vegetation preserved on sheep and beef farms (Norton & Pannell, 2018). Nutrients captured in a manufactured wetland could also be salvaged and returned to farmland. This would be a buffer at the bottom of farmlands to mitigate more than just C as trees on the hills would, and more importantly, each sector would shoulder the environmental cost of their business!

This study was limited to what was possible. It did not include an analysis of the barriers to adoption, rates of adoption and changes from current livestock policy and performance on sheep and beef farms included in the study.

Conclusions

For the extensive sheep and beef farm on Hard Hill country, the productivity gains made since 1990 translate into significant eco-efficiency gains. For the more intensive sheep and beef operation in the Easy Hill country, the gains have been more modest. These eco-efficiency gains have accrued while maintaining relatively low emissions and little increase in the absolute environmental footprint of the sector. Since 1990, dairy systems have made large gains in production, some progress in eco-efficiency, but the impact on receiving environments has grown. As we move into an era where limits are set on emissions to the environment, how livestock systems affect emissions to receiving environments, shifts from an academic exercise to a key performance indicator for the business.

An important overall message emerging from this study is that extensive sheep and beef farms in Hard Hill Country have scope to continue to make production and eco-efficiency gains through increased reproductive performance of ewes and lamb growth rates and shifting from breeding cows and older cattle to buying and finishing of younger cattle. In the process of addressing outstanding environmental and animal welfare challenges, the area in pasture will decline, limiting the production gains. On the upside, in addressing outstanding sustainable land management practices, the potential exists to offset more than 20% of livestock GHG emissions in the Hard Hill Country farming system, beyond that already offset by woody vegetation on these farms. Into the future, a GHG budget for sheep and beef farms needs to include C sequestered by vegetation to obtain a complete picture of the net contribution to the GHG inventory of New Zealand. In the more intensive livestock systems there are options to make further production and eco-efficiency gains, but less scope to reduce their overall environmental footprint.

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References

- Anon 2014. National Policy Statement for Freshwater Management 2014. Issued by notice in gazette on 4 July 2014.
- Bauman DE, McCutcheon SN, Steinhour WD, Eppard PJ, Sechen SJ 1985. Sources of variation and prospects for improvement of productive efficiency in the dairy cow: A review. *Journal of Animal Science* 60: 583-592.
- Beukes PC, Gregorini P, Romera AJ, Levy G, Waghorn GC 2010. Improving production efficiency as a strategy to mitigate greenhouse gas emissions on pastoral dairy farms in New Zealand. *Agriculture, Ecosystems and Environment* 136: 358-365.
- Beukes PC, Gregorini P, Romera AJ 2011. Estimating greenhouse gas emissions from New Zealand dairy systems using a mechanistic whole farm model and inventory methodology. *Animal Feed Science and Technology* 166: 708-720.
- Browne NA, Behrendt R, Kingwell RS, Eckard RJ 2015. Does producing more product over a lifetime reduce greenhouse gas emissions and increase profitability in dairy and wool enterprises? *Animal Production Science* 55: 49-55
- Burrows L, Wakelin S, Quinn J, Graham E, Mackay A 2018. Carbon sequestration potential of non-ETS land on farms. Landcare Research Contract Report: LC3161 for Ministry Primary Industry. 85 pp.
- Cameron KC, Di HJ, Moir JL 2013. Nitrogen losses from the soil/plant system: a review. *Annals of Applied Biology* 162: 145-173.
- Cheng L, Judson HG, Bryant RH, Mowat H, Guinot L, Hague H, Taylor S, Edwards GR 2017. The effects of feeding cut plantain and perennial ryegrass-white clover pasture on dairy heifer feed and water intake, apparent nutrient digestibility and nitrogen excretion in urine. *Animal Feed Science and Technology* 229: 43-46.
- Cosgrove GP, Taylor PS, Jonker A 2015. Sheep performance on perennial cultivars differing in concentration of water-soluble carbohydrate. *Journal of New Zealand Grasslands* 77: 123-130.
- Cosgrove GP, Waghorn GC, Anderson CB, Peters JS, Smith A, Molano G, Deighton M 2008. The effect of oils fed to sheep on methane production and digestion of ryegrass pasture. *Australian Journal of Experimental Agriculture* 48: 189-192.
- Cruickshank GJ, Thomson BC, Muir PD 2009. Effect of management change on methane output within a sheep flock. *Proceedings of the New Zealand Society of Animal Production* 69: 170-173.

- Cuttle SP, Newell-Price JP, Harris D, Chadwick DR, Shepherd MA, Anthony SGA, Macleod CJA, Haygarth PM, Chambers BJ 2016. A method-centric 'User Manual' for the mitigation of diffuse water pollution from agriculture. *Soil Use and Management* 32: 162-171.
- Davison R 2010. Sheep and beef outlook drivers. Beef +Lamb New Zealand Economic Service, Wellington, N Z. Accessed: June 2011. <http://www.beeflambnz.com/Documents/Information/Sheep%20and%20beef%20outlook%20drivers.pdf>
- Dakpo KH, Jeanneaux P, Latruffe L 2017. Greenhouse gas emissions and efficiency in French sheep meat farming: a non-parametric framework of Pollution-adjusted technologies. *European Review of Agricultural Economics* 44: 33-65.
- Di HJ, Cameron KC 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutrient Cycling in Agroecosystems* 46: 237-256.
- Dominati E, Mackay A, Lynch B, Heath N, Millner I 2014. An ecosystem services approach to the quantification of shallow mass movement erosion and the value of soil conservation practices. *Ecosystem Services* 9: 204-215.
- Dynes RA, Smeaton DC, Rhodes AP, Fraser TJ, Brown MA 2011. Modelling farm management scenarios that illustrate opportunities farmers have to reduce greenhouse gas emissions while maintaining profitability. *Proceedings of the New Zealand Society of Animal Science* 71: 149-178.
- Edwards SJ, Juengel JL, O'Connell AR, Johnstone PD, Farquhar PA, Davis GH 2015. Attainment of puberty by ewes in the first year of life is associated with improved reproductive performance at 2 years of age. *Small Ruminant Research* 123: 118-123.
- Fraser MD, Fleming HR, Moorby 2014. Traditional vs modern: role of breed in determining enteric methane emissions from cattle grazing as part of contrasting grassland-based systems. *PLoS ONE*: 9
- Hristov AN, Ott T, Tricarico J, Rotz A, Waghorn G, Adesogan A, Dijkstra J, Montes F, Oh J, Kebreab E, Oosting SJ, Gerber PJ, Henderson B, Makkar HPS, Firkins JL 2013. SPECIAL TOPICS-Mitigation of methane and nitrous oxide emissions from animal operations: III. A review of animal management mitigation options. *Journal of Animal Science* 91: 5095-5113.
- Kenyon PR, Thompson AN, Morris ST 2014. Breeding ewe lambs successfully to improve lifetime performance. *Small Ruminant Research* 118: 2-15.
- Knapp JR, Laur GL, Vadas PA, Weiss WP, Tricarico JM 2014. Enteric methane in dairy cattle production: Quantifying the opportunities and impact of reducing emissions. *Journal of Dairy Science* 97: 3231-3261.
- Knight TW, McMillan WH, Hall DRH, Kilgour R, Hockey H-UP 1989. Effect of slope of lambing site on lambs slipping and lamb mortality. *New Zealand Journal Agricultural Research* 32: 199-206.
- Ledgard, S.A., 2001 Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures. *Plant and Soil* 228: 43-59.
- Maseyk F.J.F, Gerbeaux P 2015. Advances in the identification of significant habitat in two areas of contrasting biodiversity loss in New Zealand. *New Zealand Journal of Ecology* 39: 116-127.
- Ministry of Agriculture and Forestry 1990. Farm Monitoring Report: A short-term financial and physical forecast reflecting farmer, farm consultant and industry perceptions of farming trends and issues, production and financial figures. <http://www.mpi.govt.nz/news-resources/publications>
- Ministry of Agriculture and Forestry 2000. Sheep and Beef Monitoring Report: A short-term financial and physical forecast reflecting farmer, farm consultant and industry perceptions of farming trends and issues, production and financial figures. <http://www.mpi.govt.nz/news-resources/publications>
- Ministry of Agriculture and Forestry 2010. Farm monitoring Report. A short-term financial and physical forecast reflecting farmer, farm consultant and industry perceptions of farming trends and issues, production and financial figures. <http://www.mpi.govt.nz/news-resources/publications>
- Ministry for the Environment 2016a. (http://www.mfe.govt.nz/sites/default/files/media/Climate%20Change/final_greenhouse_gas_inventory_snapshot.pdf).
- Ministry for the Environment 2016b. (<http://www.mfe.govt.nz/publications/environmental-reporting/environment-new-zealand-2007-chapter-9-land-current-state>)
- Ministry for the Environment and Statistics New Zealand 2017. http://archive.stats.govt.nz/browse_for_stats/environment/environmental-reporting-series/environmental-indicators/Home/Land/land-use.aspx
- New Zealand Government 2011. National Policy Statement. Freshwater Management 2011. Accessed: 12/5/2011. <http://www.mfe.govt.nz/publications/rma/nps-freshwater-management-2011/docs/nps-freshwater-mgmt-2011.pdf>.
- Norton D, Pannell J 2018. Desk-top assessment of native vegetation on New Zealand sheep and beef farms. Report for Beef +Lamb NZ 32 pp. <https://beeflambnz.com/nortonreport>
- Pinares-Patiño CS, Hickey SM, Young EA, Dodds KG, MacLean S, Molano G, Sandoval E, Kjestrup H, Harland R, Hunt C, Pickering NK 2013. Heritability estimates of methane emissions from sheep. *Animal* 7: 316-321.

- Praat J, Sukias J, Faulkner T, Bichan A 2015. Benefits and costs of a constructed wetland on a Wairarapa dairy farm. *Journal of New Zealand Grasslands* 77: 173-176.
- QEII National Trust. 2017. Annual Statistics. http://www.openspace.org.nz/Site/Publications_resources/Annual_statistics_maps_and_graphs.aspx. Accessed 14 November 2017
- Ramirez-Restrepo CA, Barry TN 2005. Alternative temperate forages containing secondary compounds for improving sustainable productivity in grazing ruminants. *Animal Feed Science and Technology* 120: 179-201.
- Ramirez-Restrepo CA, Barry TN, Marriner A, López-Villalobos N, McWilliam EL, Lassey KR, Clark H 2010. Effects of grazing willow fodder blocks upon methane production and blood composition in young sheep. *Animal Feed Science and Technology* 155: 33-43.
- Productivity Commission 2018. Low emissions economy. <https://www.productivity.govt.nz/sites/default/files/Productivity Commission Low-emissions economy Final Report>.
- Smeaton DC, Cox T, Kerr S, Dynes R 2011. Relationships between farm productivity, profitability, N leaching and GHG emissions: a modelling approach. *Proceedings of the New Zealand Grassland Association* 73: 57-62
- Stafford KJ, Mellor DJ, Gregory NG 2002. Advances in animal welfare in New Zealand. *New Zealand Veterinary Journal* 50: 17-21.
- Wheeler DM, Ledgard SF, de Klein CAM 2008. Using the OVERSEER nutrient model to estimate on-farm greenhouse gas emissions. *Australian Journal of Experimental Agriculture* 48: 99-103.
- Vibart RE, Vogeler I, Devantier B, Dynes R, Rhodes T, Allan W 2011. Impact of carbon farming on performance, environmental, and profitability aspects of sheep and beef farming systems in Southlands. In: *Adding to the Knowledge Base for the Nutrient Manager*. Eds. Currie, L.D & Christensen, C.L., <http://flrc.massey.ac.nz/publications.html>. Occasional Report No. 24 Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 13 pp.
- Vibart R, Douglas GB, Mackay AD, Dodd MB, McIvor IR 2015. Pasture-tree systems: Modelling potential implications for animal performance and greenhouse gas emissions. *Journal of New Zealand Grasslands* 77: 153-157
- Vibart R, Vogeler I, Dennis S, Kaye-Blake W, Monaghan R, Burggraaf V, Beutrais J, Mackay A 2015. A regional assessment of the cost and effectiveness of mitigation measures for reducing nutrient losses to water and greenhouse gas emissions to air from pastoral farms. *Journal of Environmental Management* 156: 276-289.