Productivity, changes and resilience in New Zealand grassland agriculture over the last three decades

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Highlights
This paper discusses key changes in New Zealand pastoral agriculture over the last three decades at the national scale, and how these have influenced the performance of grasslands, animal productivity, and the resilience of pastoral livestock systems. It assesses the positive and negative impacts of land-use change, changes in pasture production and supplementary feeding and dry matter (DM) consumed, and the key management practices implemented by farmers to enhance farm system resilience. It also notes environmental and other policy changes and examines how sectors and Government have started to respond. The largest estimated increase in DM consumed by livestock from 1990 to 2018 was from increased supplementary feed in the dairy sector. The largest estimated decline in DM production was due to pasture-land conversion to planted forests, followed by weed and pest impacts. In 2018, the dairy sector consumed the most DM at an estimated 25.0M t/yr, followed by sheep at 16.6M t/yr and beef at 10.1M t/yr. The total consumed DM in 2018 was 51.9M t/yr which corresponds well with the independently estimated national pasture DM production of 64M t/yr. The environmental impacts of managements to enhance resilience in DM availability are becoming evident and future regulations may limit the extent to which some of these practices can expand.

Keywords: nitrogen, supplements, pasture renewal, land use

Background
The primary sector drives New Zealand's export economy. Primary sector exports (excluding seafood and forestry) made up 70 per cent of New Zealand's total goods export revenue in the year ended June 2019 (Stats NZ 2019). Pastoral-based ruminant livestock farming systems contributed $18.10B (dairy) and $10.18B (meat and wool) (Ministry for Primary Industries 2020).

New Zealand's landscape and climate are ideally suited to the maintenance of highly productive temperate grasslands. There is, however, increasing agreement that the existing pastoral systems will need to adapt significantly to meet the challenges posed by a changing climate, including mitigation of greenhouse gases, meeting national environmental standards and increased societal and consumer scrutiny of the way our food is produced and marketed.

Improved resilience of pastoral systems is important to meet current and future challenges. In its broadest sense, a resilient farm system can be defined by 'its ability to ensure the provision of system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability' (Meuwissen et al. 2019). For this review, we will adopt a narrower definition of farm systems resilience, and focus on the elements of grassland's ability to cope with variability in climate, plant and animal management within New Zealand's livestock systems. In the future, this will include adjusting farm systems to meet a number of environmental regulations.

This paper examines the temporal variability in climate, pasture and livestock production within New Zealand grassland systems over the last three decades. We also look at several management and environmental perturbations that have influenced New Zealand grassland systems and estimate the effects in terms of changes in DM production over time. Policies that may impact the future of grasslands are also discussed briefly.

Land use and its change in New Zealand: 1990 to 2018
There has been continuing change in land cover and pattern of utilisation over the last 28 years (Ministry for the Environment 2020). The New Zealand Land Cover Database (LCDB), a multi-temporal, thematic classification of the country's land cover, has been revised five times since 1996 (Land Resource Information System Portal 2020). The largest absolute change in land cover has been a reduction in grassland

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area (-592000 ha; -3.9% of total grassland area over 28 years) (Table 1). Concurrently, increases in planted forestry (517000; +5.5%), horticulture and arable (49000 ha; +11.7%) and urban settlements (27000 ha; +13.5%) have occurred. Within the grassland categories, there has been an increase in high producing grasslands of 971000 ha (+16.5%), a decline in low producing grasslands of 1432000 ha (-18.3%), and a decline in grassland with woody biomass of 130000 ha (-12.8%).

Data from the annual Stats NZ Agricultural Production Survey (1985-2019) shows there was a 32% decline in sheep and beef grasslands of 3.9M ha between 1990 and 2018 (Table 2). This was paralleled by a 70% increase in dairy land (720000 ha) and a 39% increase in forest (515000 ha) area over the same period. Over this period, the dairy cattle population increased by 2.945M animals (+86%), with a decline of 30.5M sheep (-53%) and 872000 beef cattle (-19%). There are differences between LCDB and Agricultural Production Survey values due to differences in the categorisation approaches and data collection methods. We have not been able to reconcile values between the two sources of data but consider that the lack of animal data from lifestyle blocks may be a contributor.

Estimated long-term trends in feed consumed by different livestock sectors

Feed consumed by sector

The DM consumed has been estimated for all livestock using the methodologies and energy equations adopted for the national agricultural greenhouse gas (GHG) inventory (Pickering et al. 2021), and animal numbers from the annual Agricultural Production Survey carried out by Statistics New Zealand (Stats NZ Agricultural Production Survey, 1985-2019). The total annual amount of feed consumed by New Zealand dairy cows increased by 14.21M t, a 129% increase between 1990 and 2018. Eighty-six per cent of this increase came from the national herd increase associated with land conversion to dairying, the increase in DM due to increased use of non-pasture feed supplements,

Table 1 Change in the area (1000 ha) of different land covers from 1990-2018.

	1990	2018	Difference
Grassland – high producing	5902	6873	971
Grassland – low producing	7833	6401	-1432
Grassland – with woody biomass – Operational	1022	892	-130
Grassland – with woody biomass – Non-operational	484	484	0
Sub-total – Grassland	15242	14650	*-592*
Natural Forest – Tall Forest	6592	6574	-18
Natural Forest – Regenerating	1230	1182	-48
Pre-1990 Planted Forest – Net Stocked Area	1305	1216	-89
Pre-1990 Planted Forest – Unstocked Area	160	150	-10
Pre-1990 Planted Forest – Riparian etc.	85	79	-6
Post-1989 Forest – Net Stocked Area	12	571	559
Post-1989 Planted Forest – Unstocked Area	2	82	80
Post-1989 Planted Forest – Natural Regenerating	1	49	48
Sub-total – Forest	9388	9905	517
Cropland – perennial	71	105	34
Cropland – annual	356	371	15
Sub-total – Cropland	427	476	*49*
Wetland – open water	528	535	7
Wetland – vegetative non-forest	236	227	-9
Sub-total – Wetland	764	762	-2
Settlements	209	236	27
Other land	896	896	0
Total – all New Zealand land cover	26925	26925	0

increased use of nitrogen (N) fertiliser and irrigation, and increased stocking rates. The total annual feed consumed by sheep and beef declined by 9.8M t and 0.6M t, respectively. The average feed consumed per dairy animal increased by 740 kg DM/yr (+23%) to 3.94 t DM per cow in 2018 (Table 3). Average feed consumption per sheep increased by 150 kg DM/yr (+33%), with feed consumption for the average beef animal increasing by 460 kg DM/yr (+20%).

Total DM consumed by ruminants over the last 28 years

The estimated total DM consumption by the major ruminant animal species has varied between 48.1 and 55.1M t/yr over the last 28 years. Total feed consumed increased by 3.8M t DM (7.9%) between 1990 and 2018 (Table 3, Figure 1), however, the variability within this period (7.0M t) was nearly twice this level (Figure 1). The increase in feed consumed by the dairy sector from 1990 to 2018 was nearly 40% greater than the decline in the sheep and beef feed consumed (Table 3). Variability is likely due to variable product prices and drought impacts. In a recent paper, Amies et al. (2021) estimated total national grassland DM production using satellite data to be 64.9M t/yr with a standard error of prediction of 2.2 t/ha/yr and a mean annual yield of 8.7 t/ha/yr.

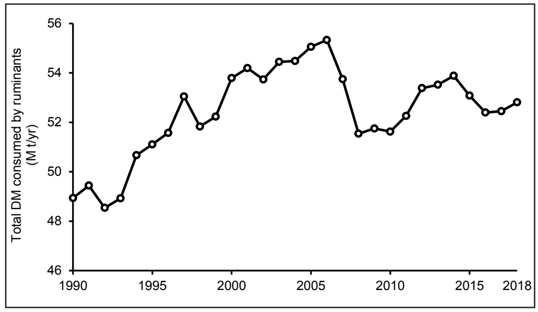

Figure 1 Changes in total feed dry matter (DM) consumption between 1990 and 2018.

Change in productivity per animal

In the following equations ‘x’ refers to years from base year 1990 (x=0) (Table 4). Milk yield has increased by an average of 4.5 kg milksolids/cow/yr over the past 28 years (y = 4.53x + 250.75; R^2 = 0.93, DairyNZ Economics Group 2019) and total feed consumed per

Table 2 Land use by the primary sector, livestock population, and changes in land use between 1990 and 2018, as recorded by the Stats NZ Agricultural Production Survey (1985-2019).

	Land use (1000 ha)				Population (1000 head)		
	Dairy	Sheep and beef	Planted forest	Total agriculture	Dairy cattle	Sheep	Beef cattle
1990	1024	12054	1318	17489	3441	57852	4593
2000	1329	10587	1782	15909	4600	43600	4600
2010	1639	9200	1820	14580	5915	32563	3949
2018	1744	8166	1833	13725	6386	27296	3722
Absolute change 1990-2018	720	-3889	515	-3765	2945	-30556	-872
Percentage change 1990-2018	70	-32	39	-22	86	-53	-19

Table 3 Summary of national feed consumed per year from 1990 to 2018 in New Zealand by the livestock sector.

		1990	2000	2010	2018
Dairy	Total feed consumed (M t DM/yr)	11.00	16.19	21.57	25.21
	Feed consumed (t DM/animal/yr)	3.20	3.52	3.64	3.94
	Pasture consumed (t DM/animal/yr)	3.08	3.29	3.08	3.21
Sheep	Total feed consumed (M t DM/yr)	26.40	23.80	18.20	16.60
	Annual feed consumed (t DM/animal/yr)	0.46	0.55	0.56	0.61
Beef	Total feed consumed (M t DM/yr)	10.70	12.10	10.70	10.10
	Annual feed consumed (t DM/animal/yr)	2.34	2.64	2.70	2.71
	Total feed consumed (M t DM/yr)	48.10	52.09	50.57	51.91

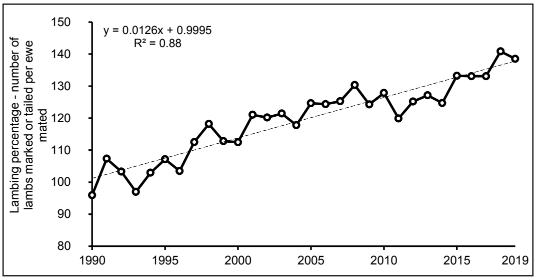

Figure 2 Average lambing percentage from 1990 to 2019.

cow by about 23% over the same period. There has been an increase in Feed Conversion Efficiency (FCE) of 0.54 kg milk solids per t DM consumed per year from 1990 to 2018 ($y = 0.54x + 64.46$; $R^2 = 0.92$, DairyNZ Economics Group 2019). This represents about a 20% increase in FCE, most likely a result of a 'dilution of maintenance' effect through increased per cow milk yield and the additional energy from supplementary feed. The level of production still only represents about 60% of that of a European Union cow fed a concentrate-based diet (Eurostat 2018), indicating there may still be potential for the New Zealand cow to eat more. However, this is less likely to be realised within New Zealand's largely grazing-based systems due to the need to balance total feed supply with meeting environmental targets.

There has been a steady increase in per animal performance in the sheep sector. The number of lambs reared per ewe has increased from 0.97 to 1.30 between 1990 and 2019 (+1.3% p.a., Figure 2), whilst average lamb carcass weight at the meat processing works increased from 13.9 kg to 19.2 kg over the same period ($y = 0.166x + 14.20$, R^2=0.94). Lamb carcass weight produced per ewe (a function of lambs per ewe and average lamb carcass weight) increased from 14.2 kg to 25.5 kg from 1990 to 2019 i.e., 80%. Feed consumed per ewe increased by only 23% (data not presented). Adult ewe carcass weight increased from 19.8 kg to 26.5 kg between 1990 and 2019 ($y = 0.193x + 20.98$, $R^2 = 0.91$).

Beef cattle carcass weights also increased slightly (2%) for adult cows, 6% for steers, and 6% for bulls during the period 1990 to 2019 with the carcass weights highly variable between years. However, beef heifer carcass weight increased by a steady average of 1.12 kg/yr ($y = 1.12x + 209.97$; $R^2 = 0.90$). There has also been an increase in more intensive bull beef systems and dairy heifer rearing away from beef cow breeding (data not presented). The drop in beef cow numbers is partly because better subdivision of pastures has allowed bulls/dairy heifer finishing cattle to be farmed on hill land.

Feed system perturbations

A range of feed system perturbations has influenced the productivity and resilience of our grassland-based livestock systems since 1990. Some are under the control of the farmer while others are not. The main practices are now covered.

Impact of the increase in carbon dioxide on pasture production in New Zealand

Few studies consider historical trends in grassland systems in relation to changes in climate. Newton et al. (2014) considered changes in pasture production of DM over the period 1960−2004 in the Winchmore irrigation pasture DM yield dataset where grazing management and fertiliser application were constant over time. They used statistical and process-based modelling approaches.

The statistical approach identified a significant

Table 4 Change in productivity per animal.

	Linear equation	R^2	Data Source
Change in annual milk solids production (kg) from 1990 to 2018	$y = 4.530x^1 + 250.75$	0.93	NZ Dairy statistics, DairyNZ Economics Group 2019
Change in kg milk solids per tonne of DM consumed by milking platform dairy animals from 1990 to 2018	$Y = 0.540x + 64.46$	0.92	NZ Dairy statistics, DairyNZ Economics Group 2019
Average adult sheep carcass weights (kg) from 1990 to 2019	$y = 0.193x + 20.98$	0.91	From MPI livestock slaughter statistics
Average lamb carcass weights (kg) from 1990 to 2019	$y = 0.166x + 14.20$	0.94	From MPI livestock slaughter statistics
Average heifer carcass weights (kg) from 1990 to 2019	$y = 1.120x + 209.97$	0.90	From MPI livestock slaughter statistics
Average Lambing %	$y = 0.0126x + 0.9995$	0.88	Agricultural Production Survey

[1] 'x' in equations refers to years from base year 1990 (x=0)

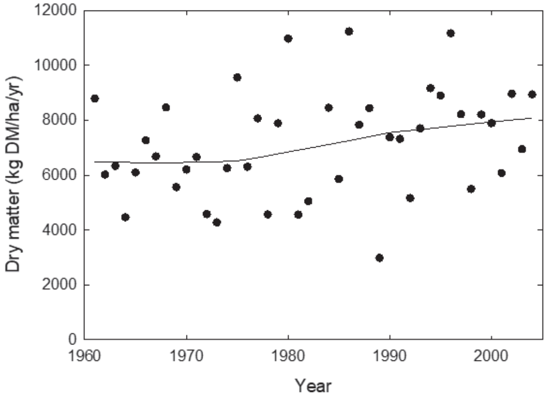

Figure 3 Trend in annual dry matter (DM) using the Winchmore irrigation and phosphate trial DM dataset.

positive trend for DM in spring but not in other seasons over the period, alongside positive temporal trends in rainfall and atmospheric carbon dioxide (CO_2) and soil N concentrations. Modelling identified atmospheric CO_2 concentration, soil properties and their interaction as the most influential variables. The impact of CO_2 was a 0.21% increase in DM per ppm CO_2; this was similar to a value of 0.19% from a FACE (Free Air Carbon Dioxide Enrichment) experiment at Bulls (Pers. comm. P Newton, AgResearch), New Zealand, with a similar type of management and pattern of pasture production. These results give confidence in experimental estimates of the CO_2 fertilisation effect, particularly at lower levels of CO_2 enrichment and provide evidence that climate change impacts are happening already.

Annual DM increased from about 6000 kg DM/ha in 1960 to just under 8000 kg DM/ha in 2004 (Figure 3; P=0.062). In spring, DM increased from about 3000 kg DM/ha in 1960 to about 4800 kg DM/ha in 2004 (P=0.007), whereas in other seasons, there were no detectable trends over time.

Between 1990 and 2018, atmospheric CO_2 concentration increased by 58 ppm, resulting in a 12.2% increase in DM based on a 0.21% increase in DM per ppm CO_2 increase derived from the Winchmore dataset. The mean area of high- and low-producing grassland covers are 7.117M ha and 6.388M ha, respectively, with forage yields of the high-producing areas estimated to have increased from 12000 kg DM/ha in 1990 (Pers. comm. DF Chapman, DairyNZ) to 13464 kg DM/ha by 2018 (+12%). Similarly, forage yields for the low-producing grassland increased from 8000 to 8896 kg DM/ha over the same period (+11%). The total estimated DM yield increase due to CO_2 fertilisation, in the absence of other limiting factors, and with the current rate of increase in CO_2, was 15.7M t DM (562000 t DM/yr) between 1990 and 2018.

The impacts of CO_2 fertilisation are supported by recent modelling of pasture (sheep and beef, dairy, Rutledge et al. 2017) using the BiomeBGC productivity model. They suggested that future increased CO_2 concentration due to increases in anthropogenic GHG emissions could induce a fertilisation effect of sufficient magnitude to counter impacts such as increased drought frequency and severity, and result in a net increase in annual productivity. This model predicted net productivity increases of 1-10%; however, these increases may not be distributed evenly across seasons or geographic locations e.g., the severity and frequency of summer feed gaps may be exacerbated, and this could present substantial management challenges for farmers. There are other impacts of climate change, notably increased temperature, that has not been accounted for here.

The estimated increase in grassland production due to irrigation

Irrigation is a key practice to address summer drought and strengthen the resilience of farming systems. Despite data collection limitations, the Stats NZ Agricultural Production Survey (1985-2019) demonstrates a steady increase in irrigated area over time (Table 5). In 1990 an estimated 1.74% (266000 ha) of farmland was irrigated (Thomas et al. 2016). By 2017 this had increased to 747000 ha, with most (86%) in the South Island and 65% in Canterbury alone (Stats NZ Agricultural Production Survey 2017).

Irrigating pasture in Canterbury has been estimated to increase average annual production by up to 5.2 t DM/ha (i.e., by 80%), mainly attributable to a summer response (McBride 1994). New Zealand's longest-running irrigation trial at the Winchmore Research Station also examined the impact of different irrigation levels and protocols. Irrigation approximately doubled pasture production, adding about 5.5 t DM/ha compared with dryland yields (Table 6).

The increase in area under irrigation of 481000 ha between 1990 and 2017, with an irrigation response of 5.5 t DM/ha, provided an additional 2.645M t DM/ha due to irrigation. However, irrigation response in areas where the base level of dryland DM production is not as low as in Canterbury and Otago, may be as low as 3.0

Table 5 Total New Zealand (NZ) irrigated area (ha).

Year	Canterbury (ha)	NZ Total Area (ha)	Percent of total grassland area
1985	Not available	230000	1.51
1990		266000	1.74
2002	241000	384000	2.52
2007	Not available	619000	4.06
2012	445000	721000	4.73
2017	478000	747000	4.90

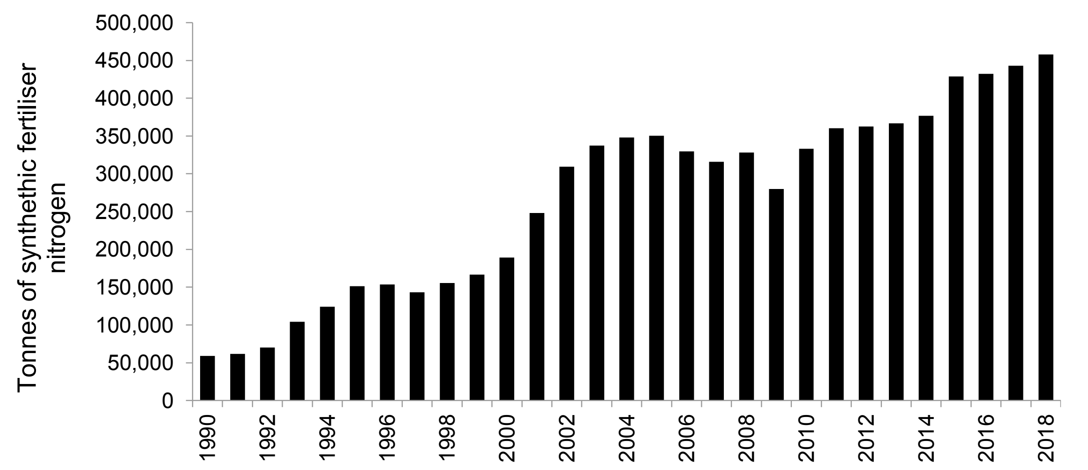

Figure 4 Total national annual nitrogen fertiliser application from1990 to 2018 (tonnes).

t DM/ha/yr greater production, and hence the national response may be lower.

Estimated national forage productivity increase due to nitrogen fertiliser application

Increased resilience in New Zealand grasslands has been facilitated by increased fertiliser N use. From 1990 to 2018, there was an 8-fold increase in synthetic N fertiliser applied, from 59265 tonnes to 457800 tonnes (Ministry for the Environment 2020, Figure 4). Currently, dairy farms are estimated to use 63% of New Zealand's total N fertiliser usage, with sheep and beef, deer, arable and horticulture estimated to use the remaining 28%, 1%, 6% and 2%, respectively (Fertiliser Association of New Zealand 2020).

The average use of 40 kg N/ha in the late 1990s has increased to an average use of 45 kg N/ha for System 1 dairy farms, and up to 156 kg N/ha for System 5 dairy farms (overall average 126 kg N/ha) in 2015/16 (Pinxterhuis et al. 2019). Feyter et al. (1985) reported an average response of 9.3 kg pasture DM/kg N fertiliser applied at a rate of 25 kg N/ha over the months of March-August. A 10 kg DM/kg N response is widely used as a guide but in practice, response rates can vary from 5 to 30 kg DM/kg N depending on the time of year, application rate, pasture species and total soil N content. Using an average response of 10 kg DM/kg N applied, it is estimated that an additional 3.985M t DM/yr was produced nationally in 2018 compared to 1990, due to additional N fertiliser application.

Nitrogen-boosted pasture is regarded as the most cost-effective supplement in the dairy industry. Any future restriction on fertiliser N use is likely to increase the supplementary feed cost to dairy farms if alternative supplements are used to fill the feed gap, assuming that farmers do not reduce stock numbers or diversify land use. Conversely, increased N fertiliser use has resulted in increased environmental impacts through additional nitrate leaching and GHG emissions.

Table 6 Comparison of mean annual pasture production (kg DM/ha) from N-irrigated plots from North Otago trial (Thomas et al. 2016).

	Cattle (kg DM/ha)	Sheep (kg DM/ha)	Mown (kg DM/ha)	Average yield (kg DM/ha)
Dryland	6010	6130	6590	6240
Irrigated	10470	14000	13650	12710
% DM increase due to irrigation	74	128	107	104

The estimated impact of phosphorus fertiliser on grassland productivity

New Zealand soils inherently have inadequate levels of soil phosphorus (P) to sustain optimum growth of grass/legume pastures. Pasture production responses to fertiliser P have been researched and documented extensively and derived response curves are used to develop fertiliser application plans (Fertiliser Association of New Zealand 2020). The largest responses occur on very P-deficient soils, with diminishing size as P fertility is increased. Applications can be regarded as either 'maintenance' i.e., maintaining current fertility, or 'capital' i.e., aimed at increasing fertility.

Total annual P application increased from 90000 t in 1990 to 220000 t in 2003 and 2004 (mostly in hill country, probably associated with favourable lamb prices), then subsequently declined to a relatively stable level of 140000 t over 2008 to 2018. The decline reflects budget constraints on sheep and beef farms, higher P prices after the 2008-09 financial crisis and a greater emphasis on nutrient budgeting. Pastoral agriculture accounts for 93% of New Zealand's P fertiliser use (Fertiliser Association of New Zealand 2020). The increased P application since 1990 has substantially increased average soil Olsen P levels for both dairy and sheep and beef farms (Wheeler et al. 2004; Pers. comm. ACH Roberts, Ravensdown). However, although a relatively large proportion of dairy industry P application rates are sufficient to maintain existing pasture production (Ministry for the Environment & Stats NZ 2018) commercial laboratory tests suggest at least 30% of dairy farm paddocks tested still have soil Olsen P levels below the biological optimum for pasture production (Pers. comm. AHC Roberts, Ravensdown). A greater proportion of hill country sheep and beef farms, however, have soil Olsen P levels well below those necessary for maximum pasture production (Ministry for the Environment & Stats NZ 2018), and commercial laboratory tests confirm at least 50% of sheep and beef farms have biologically sub-optimum soil Olsen P levels (Pers. comm. AHC Roberts, Ravensdown). This may not mean the levels are suboptimal economically. In practice, the proportion of farms below optimum soil P levels is probably higher than this, at least for sheep and beef farms where fertiliser costs are a large part of annual farm expenditure, as farmers that soil test are more likely to aim for optimum soil P levels than those who do not test. There is still a large potential for increasing pasture production nationally through remedying deficiencies in the soil available P and other limiting nutrients such as sulphur and potassium.

Estimation of the impact of P fertiliser application on current national pasture production as compared to 1990, is problematic. The pasture response per unit P applied is not well-established, and fertiliser P has a residual effect on pasture production beyond the application year (Lambert et al. 1983). Also, one-off capital dressings can be expected to stimulate additional production responses, compared to ongoing maintenance dressings which maintain current production. Response curves are expressed in relative units, whereas actual responses are highly influenced by the inherent production potential of any specific site. Lambert et al. (1983) in a multi-year grazing trial on low fertility hill country estimated a response rate of 26 kg DM/kg P applied. Phosphate application rates of up to 100 kg/ha averaged over 4 years were shown to be needed to reach optimum soil Olsen P levels in hill country (Gillingham 2016) and these resulted in an average increase in production of 1000 to 3000 kg DM/ha/yr.

Cessation of fertiliser P application was studied at three North Island research sites over periods of 4 to 7 years (Gillingham et al. 1990; Lambert et al. 1990; O'Connor et al. 1990). Pasture production was reduced by 0-7%/yr following cessation dependent on site, and the control fertiliser regime and measurement techniques used. Notwithstanding the difficulties outlined above, two approaches were used to estimate the influence of P fertiliser application on pasture production in 2018 as compared to that in 1990.

Firstly, the average maintenance P requirement for all pastures on dairy and sheep and beef farms was calculated, using numerous assumptions including the definition of a stock unit (SU, 660 kg DM/yr intake) and the annual maintenance P requirement per SU (1.7 kg) (Fertiliser Association of New Zealand 2020). In 1990 P applied (90000 t) provided 1.07 kg P/SU i.e., < maintenance of 1.7 kg P/SU. In 2018 P applied (150000 t) provided 1.77 kg P/SU i.e., > maintenance; maintenance requirement was 134000 t P, and 150000 t P was applied so 16000 t exceeded maintenance. So in 1990, national P inputs were on average below maintenance, and in 2018 were 16000 t above maintenance. If it is assumed that the responses in 2018 compared to 1990 occurred from those capital dressings, then the additional response to fertiliser P (at 26 kg DM/kg P, Lambert et al. 1983) can be estimated at 416000 t DM/yr.

Secondly, total pasture DM produced was calculated for 1990 and 2018, from pasture eaten adjusted by a utilisation factor. It was then assumed no P fertiliser was applied in 1990 or 2018, and pasture production declined as a consequence, by 3% in 2018 and 2% in 1990. The assumption of greater reduction for 2018 compared to 1990 was because P fertility was lower in 1990. Lambert et al. (1990) measured a 4.6%/yr decline for high fertility land and a 1.7%/yr decline for low fertility land at the Ballantrae Research Station. The calculated declines in pasture production were taken to reflect the ongoing response of pastures to annual P application in 2018 and 1990. For 1990 the calculated reduction from cessation was 962000 t DM, and for 2018 it was 1557300 t DM; the difference between these two is a decline of 595300 t DM.

These two contrasting approaches yield differing estimates (416000 and 595300 t DM/yr) but do suggest P fertiliser application made a significant contribution to pasture production in 2018 beyond that in 1990. For simplicity, the mean of these two values (505650 t DM/yr) is used as a guide. It was difficult to derive values for DM production responses to P application over the past 30 years because of the lack of data, in particular for the level of soil fertility on different land classes, and the historical and current level of P fertiliser application to those areas.

Changes in the use of supplementary feed to meet livestock feed demand

Another key change in New Zealand's grassland systems has been changes in the amounts and types of feed supplements used, which has varied by livestock sector.

In the dairy sector, imported supplements, including palm kernel expeller (PKE) increased by 9.0%/yr (calculated as compound annual growth rate), harvested supplement including maize silage and barley increased 5.6%/yr, and grown crops including fodder beet, kale and swedes increased 5.6%/yr between 1990-91 and 2017-18 (DairyNZ Economics Group 2019).

From 1990-91 to 2017-18 non-pasture feeds consumed by dairy cows increased from an average 0.16 (4.0% diet) to 0.89 (18.8% diet) t DM/cow (Table 7). Harvested supplements increased steadily over the 1990s and early 2000s, while imported supplements increased significantly from 2007-08. Crops consumed have increased rapidly in the last 5 years due to the adoption of fodder beet and maize silage in some regions, although the use of fodder beet has stabilised or is declining in some areas. The amount of imported PKE used has also stabilised over the last 7 years after commencing as a feed supplement in the early 2000s and rising to over 1M t DM/yr by 2012-13. The second most used supplement is maize silage, which became increasingly popular around 1990; the average national consumption is now approximately 180 kg/cow/yr. The total amount of supplements consumed reached a maximum in 2014/15 and has decreased slightly since.

Total feed DM demand for sheep between 1990-91 and 2014-15 remained relatively constant at 2.57 t DM/ha with the amount of supplements varying slightly between years but averaging about 5.5% of the diet (Table 8, Sise et al. 2017). For beef cattle the pasture feed demand increased from 0.66 t DM/ha in 1990 to 0.90 t DM/ha in 2014/15 (Sise et al. 2018), with demand from other cattle types increasing from 0.27 to 0.57 t DM/ha. Supplements for both cattle groups remained relatively stable at around 6% and 14% of the diet, respectively. Note that sheep and beef cattle are frequently grazed on the same farm, so feed consumed at the whole-farm level will be the sum of sheep and beef components. The total feed demand across all non-dairy livestock types increased from 3.58 to 4.20 t DM/ha, a 17% increase.

Table 7 Summary of national feed demand from 1990-91 to 2017-18 for New Zealand dairy cows (DairyNZ Economics Group 2019).

	Feed demand	**Pasture eaten**	**Crop consumed**	**Harvested supplement**	**Imported supplement**	**Percent supplements**
	(t DM/cow)					
1990-91	3.87	3.72	0.07	0.05	0.04	4.0
2000-01	4.37	4.09	0.11	0.12	0.04	6.4
2010-11	4.49	3.80	0.18	0.23	0.28	15.4
2017-18	4.72	3.84	0.30	0.22	0.37	18.8

Table 8 Summary of changes in estimated total feed demand and supplement usage of sheep, beef and other cattle between 1990 and 2015.

		1990-91	**1994-95**	**1998-99**	**2002-03**	**2006-07**	**2010-11**	**2014-15**
Sheep (t DM/ha)	Pasture	2.42	2.35	2.46	2.52	2.53	2.47	2.42
	Supplements	0.15	0.14	0.14	0.13	0.15	0.15	0.15
	Total	2.57	2.48	2.60	2.64	2.67	2.62	2.57
	% Supplements	5.80	5.50	5.40	4.80	5.50	5.80	5.80
Beef (t DM/ha)	Pasture	0.66	0.84	0.83	0.79	0.88	0.86	0.90
	Supplements	0.05	0.05	0.05	0.04	0.05	0.05	0.06
	Total	0.70	0.89	0.88	0.84	0.93	0.91	0.96
	% Supplements	6.40	5.70	5.50	5.30	5.70	6.00	6.70
Other cattle (t DM/ha)	Pasture	0.27	0.35	0.41	0.63	0.54	0.48	0.57
	Supplements	0.04	0.06	0.07	0.1	0.09	0.09	0.1
	Total	0.31	0.42	0.48	0.73	0.63	0.57	0.67
	% Supplements	13.70	14.60	15.30	13.30	13.90	15.70	14.40
Total All feed	(t DM/ha)	3.58	3.79	3.96	4.21	4.23	4.10	4.20

Changes in the total quantity of individual supplements used nationally by beef and other cattle enterprises

Considering all Sheep and Beef Farm Classes, supplements used totalled 2.2-2.5M t DM from 1990-91 to 2014-15 (Sise et al. 2018). Winter brassicas such as swedes and kale remained relatively constant from 1990-91 to 2014-15, accounting for approximately 65% of supplemental feed used on farm. Usage of summer brassicas such as leafy turnip increased from 10% in 1990-91 to 15% in 2014-15 whilst the use of conserved crops (baleage and barley silage) dropped from 23% to 18% over the same period. Within both the beef and other cattle enterprises, winter brassicas account for approximately 80% of total feed supplements used, with baleage accounting for the other 20%. Fodder beet usage is currently very low.

The impact of pasture renewal on forage resilience and productivity

Pasture renewal is another practice that can result in improved resilience and productivity. Having the correct species and cultivar balance to best meet individual farm climate, soil, fertility, pest and management conditions has been a major thrust of New Zealand pastoral science and practice. There is however limited long-term data to quantify the impact of pasture renewal and species/cultivar breeding on national DM production and consumption. Pastures in dairy systems are more likely to be renewed regularly than those in sheep and beef systems, with a renewal area of up to 10%/yr of total farm area on dairy farms, and 1-3%/yr for sheep and beef farms (Thomas et al. 2014). A 10-year rotation of renewal tied to winter and summer crops is often used on dairy farms.

There is a practical limit to the amount of land utilised annually for cropping within an integrated farm system, with the maximum area typically between 10% and 15% due to constraints around whole-farm feed supply/demand issues. Any more renewed land can create feed deficits while the ground is prepared, the crop is growing, and a relative oversupply once the crop is ready. There are also considerations of management effort and associated expenses that go into the crop. This suggests that while cropping has a role in New Zealand farm systems, multi-year and permanent pastures will continue to form the core of the system and are essential to long term performance and resilience.

Pasture renewal is often targeted at paddocks that have declined most in yield, have more weed species, and demonstrate a lack of persistence of originally sown species. The means of renewal also varies from over-sowing (mostly in hill country) to over-drilling into glyphosate-sprayed, short pastures or bare soil, to sowing into fully cultivated paddocks usually after a forage or grain crop. There is little research on the long-term productivity and persistence of new forage cultivars in New Zealand under grazing conditions, and associated animal performance.

A recent analysis used a 10-year longitudinal dataset (Chapman et al. 2015) from perennial ryegrass trials (Table 9). Yields per year declined over time but the analysis showed that those cultivars yielding significantly more over the first 3 years continued this trend through to the eighth year, but the advantage disappeared by Year 10. It is unknown what plant attributes are important to the overall persistence trait, which might be used by plant breeders as an important selection criterion.

Glassey et al. (2010) found a difference of 2275 kg DM/ha/yr between a 10-year-old pasture and a 1-year-old pasture measured over 2 years. This suggests it is reasonable to assume a linear decline in productivity of renewed pastures in Year 10 of 2000 kg DM/ha, or an average annual decline in production advantage over the 10 years of 1100 kg DM/ha/yr (Table 10). If this

Table 9 Mean annual dry matter (DM) yield decline of 25 ryegrass cultivars over 10 years in Hawke's Bay (Chapman et al. 2015).

	Years 1 to 3 2005/06 – 2007/08	Years 7 and 8 2011/12 – 2012/13	Year 10 2014/15
kg DM/ha/yr	10850	9025	8835
Difference from Years 1-3 (kg DM/ha/yr)		1825	2015

Table 10 Profile of renewed pasture estimated total annual DM yield change over 10 years.

Years after planting	0	1	2	3	4	5	6	7	8	9	10	Total DM Increase
Increased DM production (kg DM/ha)	2000	1800	1600	1400	1200	1000	800	600	400	200	0	11000 (1100/yr)

is applied to the total area cultivated and direct drilled (369000 ha) in 2019 (Table 11), this would provide an average extra 0.406M t DM from pasture renewal in 2019.

For 1990, a pasture renewal area of 262500 ha for dairy and sheep and beef farms was calculated by Thomas et al. (2014) for the agricultural GHG inventory (Table 11). This would provide on average an extra 0.288M t DM/yr in 1990 due to pasture renewal. This suggests the increase in potential total DM produced due to increased rates of pasture renewal between 1990 and 2019 of 0.118M t DM/yr.

Intensification of pastoral farming and the associated need to produce additional DM/ha has placed greater emphasis on the increased pasture production available through pasture renewal. However, Glassey et al. (2010) stress the need for farmers to be aware of the differing susceptibilities of cultivars to pests and disease, and regional differences and interactions with drought.

Erosion impacts on grassland productivity loss

Erosion leads to a loss of valuable grasslands and topsoil which impacts pasture productivity. Erosion also leads to fine sediment contaminating fresh water, and the coastal environment, causing problems for water and coastal ecosystems. While erosion is a natural process, it can be accelerated through human activities. In general, soil erosion in the South Island is more likely to be due to high rainfall and vulnerable, steep, mountainous terrain, while in the North Island it is due to the historical clearance of forest on steep slopes for pastoral agriculture. Of New Zealand's 269250 km² land, 14125 km² are classified as highly erodible land at risk of severe mass-movement erosion in 2012 (Ministry for the Environment & Stats NZ 2018). While mass-movement erosion continues to occur, during recent storm events, concern has been raised regarding surface erosion events as a consequence of cultivation and land/grazing management. The extent of the impact on forage production has yet to be fully determined, but it is a major concern for water quality.

In 2012, it was estimated that 192M t of eroded soil entered New Zealand's rivers each year; of this, an estimated 84M t (44%) was from introduced grasslands. There is an estimated 621500 ha of highly erodible grassland largely in North Island hill country. Assuming average hill pasture production of 8900 kg DM/ha/yr for uneroded hill country, and further assuming that eroded hill country only reaches 80% productivity of uneroded ground after 20 years (Rosser & Ross 2011), there is a potential loss of grassland DM production of 0.111-0.553M t DM/yr depending upon the extent of the erosion damage. A mean loss of 0.330M t DM/yr is assumed. Erosion control programmes such as Horizons Regional Council's Sustainable Land Use Initiative and MPI's erosion control programmes are expected to mitigate some of this loss in potential production. It has not been possible to estimate the lost DM productivity on lowland properties due to extra sediment in rivers making flooding events worse e.g., the 2004 Manawatu floods.

Impacts of invertebrate pests on forage resilience and productivity loss

The impacts of invertebrate pests on New Zealand's forage production and the cost to the economy have been reviewed (Ferguson et al. 2019). The invertebrate pests most commonly affecting pastoral-based production in 'average' years cause losses annually of between $1.7B and $2.3B (mean $2.0B) of which up to $0.9B occur on sheep and beef farms and $1.4B on dairy farms. These costs have been broken down and expressed on a DM basis assuming 12000 kg DM/ha/yr for dairy and 8000 kg DM/ha/yr for sheep and beef, and a feed value of $375/t DM (based on the cost of baleage, Table 12). This results in total production losses of 2.0M t DM in the dairy sector and 4.7M t DM in the sheep and beef sector, and a total value of $2.5B based on $375/t DM, which is very close to the $2.3B reported.

In attributing costs of "pests" to grassland systems it is important to recognise that these organisms are part of pastoral ecosystems, just as much as beneficial organisms such as rhizobia and earthworms. Attempts to eliminate organisms perceived as pests to remove their negative economic impacts may have unintended consequences for positive ecosystem function.

Table 11 Area (ha) of pasture renewal into cultivated or direct drilled in New Zealand (after Stats NZ Agricultural Production Survey 2009, 2015, 2019).

Year	Pasture renewal cultivated (ha)	Pasture renewal direct drilled (ha)	Total renewal area/yr (ha)
1990	-	-	262500[1]
2009	119979	157839	277818
2015	179080	193786	372866
2019	159466	209798	369264

[1]After Thomas et al. (2014).

The impact of pasture weeds on grassland productivity

Weeds in pasture cause economic loss by reducing edible feed production and/or quality, by directly affecting animal health through being toxic or physically injurious, by contaminating animal products, and through the cost of their control. Information on these losses and costs is needed for assessing the relative importance of individual species, for rationalising weed control strategies at all scales of analysis (e.g., field, farm, region, nation), to plan and administer weed research and extension programmes, and to reduce the market risk of developing new control measures (Auld et al. 1987). While weeds have long been a concern to pastoral farming in New Zealand, and there has been considerable expenditure (public and private) and many published reports on research into their control, and more recently their ecology, surprisingly, few data exist on their associated national production losses and economic control costs (Saunders et al. 2017).

Saunders et al. (2017) reviewed the literature on the economic costs of weeds in New Zealand pastoral agriculture and found that existing studies have little common methodology, some were based on little more than guesswork (as the authors admitted), and many were outdated. The combined cost of weeds derived from the studies reviewed was $1658M (2014 NZD) or $1778M in 2020 (Consumer Price Index-adjusted to 2020). This value was considered a conservative estimate as it only covered some weed species and was primarily focused on the loss of production, rather than the additional costs associated with weed control (Saunders et al. 2017). To calculate DM lost, we have used the monetary value of weed impacts and converted to DM using today's price for DM estimated from commercial baleage costs. The estimated loss of national DM production due to weeds, using a value of $375/t DM, was 5.296M t DM annually in 2019, approximately 77% that of pests. Due to lack of historical data, we were not able to obtain 1990 figures and have assumed they are similar to 2018. It might be expected that pest and weed control practices used in New Zealand would lead to an increase in the DM from treated pastures. As New Zealand does not collect statistics on the amount of pesticides and herbicides used, and the impact that biocontrol might be having nationally, it is not possible to estimate a net DM value for the impacts of pests and weeds and their control.

Conversion of grassland to planted forests

A total of 514841 ha has been converted from grassland to planted forestry between 1990 and 2018 (Table 2). Assuming the majority of this forestry was planted in low-fertility hill country and using an estimated annual DM yield of 8000 kg DM/ha (Pers. comm. DF Chapman, DairyNZ), grassland DM would be 4.119M t DM/yr less in 2018.

Summary of options to enhance the resilience of DM availability

The impacts, at a national level, of a range of practices that farmers have implemented to improve grassland productivity and increase the resilience of our grassland farming systems, are summarised in Table 13.

The largest increase in DM eaten from 1990 to 2018 was from supplementary feed in the dairy sector, driven by increased maize silage and PKE. The largest estimated decline in DM production between 1990 and 2018 was the conversion of pasture to forestry. The positive impacts of livestock feed supplements (recently driven by PKE), P application particularly on hill country sheep and beef farms, N fertiliser application, irrigation (largely in Canterbury), CO_2 fertilisation and pasture renewal are counteracted by the negative effects of soil erosion, invertebrate pests and weeds and forestry conversion on grassland production.

In terms of change in DM production between 1990 and 2018, supplements in the dairy sector provided the largest increase, followed closely by N fertiliser, irrigation and P fertiliser application. Finally, CO_2 fertilisation and pasture renewal provided more limited increases. It has not been possible to determine the change in DM loss due to invertebrate pests and weeds between 1990 and 2018 and so we have assumed that they are similar at both dates and so there is no

Table 12 Summary of the mean annual cost and DM loss due to invertebrate pests in New Zealand agricultural production land (after Ferguson et al. 2019).

		Affected land area (ha)			Estimated losses (t DM)		
	Production impact (%)	Dairy	Sheep and beef	Total	Dairy	Sheep and beef	Total
Grass grub	-15	385000	2046000	2431000	693000	2455200	3148200
Black beetle	-12	464000	621000	1085000	668160	596160	1264320
Porina	-9	139000	67000	206000	150120	48240	198360
Other pests	-2.5	1744000	8165590	9909590	523200	1633118	2156318
Total					2034480	4732718	6767198

difference between these dates. The same is true for erosion. The biggest loss of DM was due to planted forestry on former pasture.

Between 1990 and 2018 the three major livestock classes consumed an estimated 3.9M t of additional DM/yr. This is only 56% of the estimated net balance of extra DM produced due to the range of practices considered here, but importantly no consideration has been given to regional and seasonal needs, and feed wastage and loss. Even if it is assumed that utilisation of the extra DM produced was 65-80%, the estimates of additional DM production look initially to be somewhat optimistic. However, it can also be assumed that in a system's context, not all the practices are additive, with the most limiting factor likely to dominate.

When considering the extra DM produced, it is unclear if the range of options is mutually exclusive. For example, N and P are applied to irrigated grasslands which may lead to double accounting on the same area of land. Also, farmers may take action against pests and weeds hence limiting their pasture losses, or pests and weeds may impact together in the same area thus increasing the loss. Also, there may be other areas not covered in detail e.g., other nutrients such as potassium, sulphur, trace elements or pasture management or species impacts. It has not been possible to disaggregate or identify the extent of the interactions, and this is an area for future research. In terms of forage eaten, there are livestock types that have not been included such as deer, horses, goats and other small ruminants, including livestock on smallholdings, although their feed consumption is small compared with the main livestock species due to lower animal numbers. Uncertainty estimates have not been developed but we have attempted to estimate the extremes of responses, as identified in the literature.

The future needs of New Zealand grasslands to enhance resilience

Impacts of climate change in New Zealand on grasslands

It is accepted internationally that further climate impacts will result from increasing concentrations of GHGs in the atmosphere, including elevated temperatures, changed rainfall patterns and increased frequency of extreme events. These are additional to variations between years and between decades due to natural climate processes such as El Niño-Southern Oscillation. Some climate change effects over the next decades are predictable with some level of certainty and the impacts will vary spatially and temporally (Ministry for the Environment 2018).

Table 13 Estimated impacts of a range of management practices and environmental changes on national feed production and national dry matter (DM) production for 1990/91 and 2017/18.

Additions	Tonnes DM annually 1990/91	Tonnes DM annually 2017/18	Difference 1990 to 2018 t DM/yr	Comments
Supplements				
- Dairy	440000	4740000	4294000	PKE, maize silage and fodder beet
- Sheep and beef	2220000	1640000	- 580000	Winter brassicas
Nitrogen fertiliser	593000	4578000	3985000	Increased nitrogen fertiliser use
Irrigation	1463000	4108000	2645000	Mainly Canterbury
Phosphorus fertiliser	-	-	506000	Mean flat and hill country using two contrasting methods
Climate change	-	-	562000	CO_2 fertilisation
Pasture renewal	288000	406000	118000	Average per year over 10 years
Sub-total gains			**11530000**	
Losses				
Erosion pasture loss	-332000	-330000	0	Cannot estimate difference
Invertebrate pests	-6767000	-6767000	0	Cannot estimate difference Cost -$2.3B
Weeds	-5296000	-5296000	0	Cannot estimate difference Cost -$1.8B 77 percent of pests
Pasture to Forestry	-10542000	-14661000	-4119000	
Sub-total losses			**-4119000**	
Net Total			**7411000**	

New Zealand's temperate climate is important for grassland production and resilience. The most severe climate perturbation is usually drought, one measure of which is Potential Evaporation Deficit (PED). As such, the severity of estimated PED provides a robust measure of drought intensity and duration (National Institute of Water and Atmospheric Research 2020). From 1940 to 2017, PED has varied from 120 to 350 mm, a nearly 3-fold difference, with large national PED deficits in 1997, 2012, 2014, 2015 and 2019. The data suggest that the mean PED in the decade from 2010 has increased by 30% above the mean of previous decades back to 1940. This suggests a greater need to develop greater resilience to drought. Future opportunities to cope with drought are expected through more efficient irrigation, using water from water storage schemes. Management systems may need to shift to take advantage of higher temperatures giving more and earlier spring, winter and autumn pasture growth.

Possible implications for forages of future regulations and legislation to address environmental concerns

The Pastoral Industry Forage Discussion Document 2016-2036 (2017) provides a comprehensive assessment of the future needs for New Zealand grasslands. These are summarised here followed by a summary of the government policies (Additional online file: Table A1) on the horizon that may impact grasslands. Restrictions and prescriptive rules for farmers may become increasingly stringent in terms of where farming is allowed, and what farm practices and tools are permitted. This will require new farming and forage solutions and approaches. The following indicates some possible implications for forages.

Fresh Water

There are now greater restrictions on nutrient losses e.g., caps on permitted nitrate leaching rates and caps on N fertiliser applications. Pastoral farming could be limited on erosion-prone land susceptible to high P and sediment losses, particularly from steep slopes. There will be an imperative to optimise soil fertility, manage nutrients and improve nutrient utilisation. The economic imperative will be to develop and adopt forages that reduce nitrate losses, possibly through lower N content in herbage. There may be constraints to some stocking rates on extensively grazed pastures leading to de-intensification and reduced feed demand, and reduced pasture renewal rates.

One suggested solution is to develop pastures with high legume content in response to restrictions on N fertiliser use. Competitive interactions between legumes and grasses mediated by their differing requirements for nutrients such as P (commonly supplemented using fertilisers) and N (mainly supplied through N fixation by legumes in the absence of N fertilisers), and grazing management, present an ecological barrier to sustained legume dominance in such pastures. Moreover, if high legume pastures contribute the same N input as N fertiliser now, then the N leaching from urine patches will be the same. Legume-based pastures may be most appropriate for lower stocking rate systems that are associated with higher per head performance. This is possible but from a practical perspective, will be more difficult for farmers to manage using current practices.

Atmosphere

If the Emissions Trading Scheme (or a similar pricing scheme) fully applies to agriculture, the economic imperative will be to develop cost-effective mitigation approaches. Changing the attributes of existing forages or changed forage species provide a possible solution for methane emissions although current evidence suggests that forage characteristics such as digestibility, metabolisable energy, sugar and fibre content have only a minor impact (Hammond 2011). Sophisticated genomic techniques offer the potential to introduce or switch on particular attributes in forage plants, for example, lipid synthesis, but these approaches are only at the proof-of-concept stage and even if developed may not be able to be utilised in practice under current legislation. Developing forages that produce large amounts of DM at lowered N concentrations would be beneficial for reducing N and nitrous oxide losses from urine and dung patches.

Grazing practices and soil cultivation techniques are restricted

Already regulations are being brought to bear on deleterious impacts of intensive grazing of crops and pastures on soils, and off-site impacts of sediment, nutrients, GHG emissions and pathogens. This has significant implications for the sustainability of cattle wintering systems in particular. Cultivation of fragile soils may be restricted and pasture renewal on cultivatable land may be required to use compliant techniques that conserve soil. The timing of sowing of cover crops may need to be modified.

Weed and pest issues are compounded

Pasture renewal rates may be reduced in some areas, or new techniques suitable for fragile soils must be developed and adopted. Environmental protection (agrichemicals) commonly used may be more restricted or not permitted. Commonly used herbicides may be restricted or not permitted due to increasing social resistance. The economic imperative will be to register new chemistry and develop alternative methods of weed and pest control such as biological controls. A warming climate may also make more areas susceptible to an increasing range of weeds and pests and over a longer time period. For example, the southward spread of some sub-tropical species such as kikuyu.

The imperative will be to also develop alternative pasture renewal technologies that are effective without restricted herbicides. The forage sector must be proactive in developing new forages and tools to meet future requirements. The alternative is increasing constraints, less effective methods for pasture renewal, and a consequent weakening of the supporting structures, including commercial agribusinesses, which support and depend on farming.

How are sectors and government responding to environmental perturbations?

The dairy, and sheep and beef sectors will be subjected to a range of new environmental policies (Additional online file: Table A1) that will affect grassland agriculture in various ways. The full impacts of many of these policies and legislation are yet to be fully defined and understood. Farmers have been resilient in their responses to environmental and economic circumstances in the past, and we might expect the same in the future.

The future for grasslands in New Zealand

The dairy industry has increased efficiency to some extent by diluting maintenance requirements, i.e., consuming more feed per cow with an increasing proportion of this used for the production of milk. The increased consumption per cow has been made possible due to boosted pasture production, grazing animals off the milking platform and the use of supplements such as PKE. The sheep industry has shown increases in efficiency associated with higher lambing %, increased lamb carcass weights, genetic and managerial improvements and lower stocking rates. This has enabled the amount of lamb produced nationally to remain almost constant, even as the higher economic returns have seen large areas of land with sheep converted to intensive dairying and plantation forestry, and the national flock greatly reduced.

The next 30 years will see more pressure on the pastoral industry to reduce the use of external supplements because of environmental and market pressures. If this happens, the remaining routes to greater profitability include change of land use, increased efficiency of pasture production from the same nutrient input, increased ruminant performance from the same intake, and/or products of greater value from pastoral, arable, horticulture and forestry enterprises.

There have been reports outlining the potential for reduced GHG emissions and increased profitability if land use was changed from pasture to horticulture (e.g., Thomas et al. 2020). Thomas et al (2020) also identified areas where high value, low-GHG emitting crops can be grown now and in the future. Their analysis of export markets indicates that there are significant growth opportunities for horticultural and arable crops. The realistic area of land-use change to high-value crops and mānuka for honey is however estimated to be modest (200000 ha) and will not have a large impact on reducing methane or total national GHG emissions. This also applies to the continuing afforestation that would be required to make New Zealand's CO_2 emissions net-zero by 2050. The recent Climate Change Commission report (Climate Change Commission 2021) on future GHG budgets has highlighted the importance of the livestock sectors continuing to improve their productivity, as well as the importance of increased indigenous species in forestry.

Future New Zealand grasslands might be expected to evolve including:

- The continuing use of the farming systems identified here, but becoming more efficient and operating within environmental limits;
- Greater diversity within individual farm enterprises at the paddock and farm level e.g., farm tourism, integrated livestock and horticulture, energy farming;
- Greater matching of stock types and farm system to the environment and grassland productivity and suitability;
- More efficient/reliable supply and use of freshwater, which will become a scarcer resource promoting water storage to be implemented more widely;
- Greater vertical integration of farmers to processors to consumers at all levels, with clear price signals and provenance recognition;
- A greater requirement for custodianship of biodiversity, both indigenous and introduced species; and
- Farmers taking on a more proactive stewardship role for the land and in return having a clear 'licence to operate'.

Some grassland science areas to address include:

- Knowing what grassland species including weeds and invertebrate pests exist, their abundance, and how they have spread over the last 30 years and will spread in the next 30 years; it is 30 years since the last national forage species survey;
- Gaining a clearer understanding of the levels of pasture utilisation by livestock types and the key factors affecting this;
- Understanding the full impacts of climate change and how farmers might adapt their grasslands, limiting the negative effects of weeds, pests, drought and erosion under changing temperature and rainfall patterns;
- Understanding the limits to ruminant production

efficiency gains under grassland pastoral systems, without importing more animal feeds into New Zealand;
- Distinguishing more clearly, the genetic and environmental impacts on forage productivity change due to the changing CO_2 concentration in the atmosphere; and
- Understanding how much more animal productivity efficiency gains can be made through animal genetic gains and the impact on consumption of forage.

What further responses are needed?

The world is demanding safer and more food. The Minister of Agriculture has recently released the 'Fit for a Better World' strategy for the primary sector in a Covid-19 environment to accelerate the economic potential of the primary sector. It covers productivity, sustainability and inclusiveness. For grasslands, there also needs to be a reinvigoration and refresh of the Forage Strategy of 2017. There also needs to be greater and more rapid technological innovation for grasslands using the most appropriate technologies to address pests, be more nutrient efficient, lower GHG emitting, reduced N and P inputs, and have more productive, higher quality and resilient grasslands. To do this, our science, industry-good and private sector bodies need to work together more closely and extend knowledge more rapidly than is currently achieved.

Conclusions

This paper describes the estimated impacts of a range of perturbations on national grassland production systems and their use to provide resilience for New Zealand livestock systems. The impacts of N fertiliser application, supplement feed use for the dairy industry, irrigation, sheep and beef supplements, P application, climate change CO_2 fertilisation and pasture renewal are partially offset by the effects on DM production of soil erosion, weeds and invertebrate pests. Not all perturbations have been addressed e.g., animal disease impacts, farm management consequences, other major and minor fertiliser elements, and other climate factors, due to the paucity of data.

Future changes in environmental policies, market prices, and consumer demands and their drivers, will require a host of changes and new ways of thinking in our grassland sector. To continue to use and expand the farming systems identified here, they will need to become more efficient and be used within environmental limits. This assessment is preliminary. It has been hampered by a lack of reliable time-series information on our agricultural production base. Primary production underpins New Zealand's economic performance. As the need to manage land-based activities responsibly and profitably continues to intensify, so does the requirement to understand the resource base and the activities thereon. Increased effort should be directed to gathering such information at a scale that allows well-informed national and farm-based management policies and farm plans, based on reliable data, to be formulated.

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SUPPLEMENTARY MATERIAL

Additional Online File 1: Table A1-Policies and legislation that may affect New Zealand grasslands. https://www.nzgajournal.org.nz/index.php/rps/article/view/3461

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