Research article

Long-term measurement and modelling of net herbage accumulation in grazed pastures do not align with predictions under climate change

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Abstract

A long-term phosphorus (P) fertiliser and sheep grazing experiment at the AgResearch Research Station at Ballantrae (1975-2022) provides a unique resource to examine long-term changes in net herbage accumulation (NHA) and animal production under conditions where soil P fertility have been non-limiting for more than 35 years. This paper examined historical NHA, soil phosphorus (P) and nitrogen (N) fertility from the high fertiliser (HF) farmlet, and pasture growth trends using the climate driven pasture growth module AgPasture within the Agricultural Production Systems Simulator (APSIM). On the medium slope of the HF farmlet, NHA in 2020-21 was only 87% of that measured on the same farmlet between 1982-88, even though P was non-limiting. The measured decline in NHA aligned with a reduction of on-site nominal sheep stocking rates since the late 1990's. Prior to this paper, climate driven modelling has often predicted a likely positive outcome in NHA for this environment into the future. Understanding the apparent discrepancy between predictions into the future with what is happening on the ground today is discussed in the paper.

Keywords: Long-term, phosphorus, fertility, nitrogen, sheep grazing

Introduction

Scientific publications and reports have indicated that predicted future climatic changes and elevated CO_2 in New Zealand, using climate driven modelling, will likely show generally positive or neutral outcomes for herbage accumulation in wetter and cooler environments and a neutral to small negative outcome in summer dry environments, (Lieffering et al*.,* 2016; Ausseil et al*.,* 2019, Keller et al*.,* 2021, Newton et al*.,* 2022). In three locations (Hawke's Bay, Waikato, and Southland), Lieffering et al. (2016) found that future predicted pasture yields in response to warming, would be greater than present yields, with the predicted increases greatest and least variable in Southland, and the lowest and more variable in Hawke's Bay. They also predicted likely changes in the seasonality of pasture yields, notably earlier spring growth.

Exploring the performance of a model farm under ambient and a future atmospheric CO_2 concentration of 600 ppm, which would be achieved in 2060 at the current rate of CO_2 emissions, Newton et al. (2022) reported increased herbage accumulation in the elevated CO_2 sward due to greater photosynthesis, based on the findings from the Free Air Carbon Dioxide Enrichment experiment. Future simulations need to consider the influence of elevated CO_2, temperature, rainfall, along with changes in the frequency of extreme events together, on the performance of the system (Newton et al., 2022).

Evidence, based on the analysis of pasture and animal production data from both dairy and sheep and beef systems collected over the last 20-40 years, suggested that herbage accumulation is static (Glassey et al*.,* 2021, Mills and Neal 2021) or declining (Gobilik et al*.,* 2021). Over the last 30 years, Gobilik et al*.,* (2021) estimated that herbage accumulation and the amount harvested declined by 11% and 14% in southern North Island 'hill country' sheep and beef cattle systems. This finding was further supported by some pasture growth modelling that Gobilik et al. (2021) conducted using NIWA climate data for that period. A comparison of historic long-term modelling and measurement of forage production in Waikato dairy systems pointed to a divergence between a modelled reduction in climate-driven pasture production and relatively stable actual measured herbage accumulation (Glassey et al., 2021).

The long-term phosphorus (P) fertiliser and sheep grazing experiment at the AgResearch Ballantrae Research Station (1975-2022) provided a unique resource to examine the long-term changes in herbage accumulation and animal production (*i.e*., sheep liveweight gain to attain similar post-grazing herbage mass across farmlets) under conditions where soil P fertility has been non-limiting for more than 35 years. This paper examined historical net herbage accumulation (NHA) trends and linked this to changes in the on-site nominal sheep stocking rate along with changes in soil P and N fertility over the same period and pasture growth trends using the climate driven pasture growth module AgPasture, within APSIM NextGen.

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Materials and Methods

Study site

The study, conducted at Ballantrae in Southern Hawke's Bay New Zealand (408180S 1758500E), is typical of much of the North Island's hill country which covers 3.0 million ha (28% of the total farmland in New Zealand). It is located 125 m to 350 m above sea level with an average air temperature of 12.8°C and an annual rainfall of 1270 mm evenly distributed throughout the year. The soils include brown soils (43% of NZ soils) and some pallic soils (13% of NZ soils), formed under forest which was cleared and sown to grassland about 100 years ago. The characteristics of the self-contained experimental farmlets, that formed part of the long-term P fertiliser and sheep grazing experiment established in 1975, are described in detail in Mackay et al. (2021). Since 1980, the HF farmlet has received 375 kg SSP/ha/year. Breeding ewes have been grazing the HF farmlet in a rotational fashion since 1975. These are reported in Mackay et al. (2021).

Pasture and soil sampling

Herbage accumulation was measured using a pre-trim and exclusion cage method (Lambert et al*.,* 1983). Cages were placed on the six (three aspects [east (E; 35 - 155°), southwest (SW; 155 - 275°), and northwest (NW; 275 - 35°)] x two replicates) permanent sites (established in 1975) located on medium slopes (13-25°) of the HF farmlet, from May 2020 through to June 2021. Herbage accumulation was measured previously on the same sites in 2015-16 (Mackay et al*.,* 2016) and from 1975-1988 (Lambert et al*.,* 1983; Lambert et al*.,* 1990). Soil samples for monitoring soil fertility (0-75 mm), soil bulk density, organic carbon and nitrogen (0-75, 75-150 and 150-300 mm) were collected from the same frame sites. The soil sampling protocol and sample preparation, and subsequent analysis, are described in Mackay et al*.,* (2021).

Modelling pasture growth (1972-2020)

The AgPasture module (Li et al*.,* 2011) of the Agricultural Production Systems Simulator (APSIM; Holzworth et al*.,* 2018) Next Generation version, released in 2020, was used to explore the influence of climate over the last 50 years on pasture growth. AgPasture is a process-based multi-species pasture growth model that can explore the influence of climate, soil properties and some management practices on a range of soil-plant system attributes, including pasture growth and biological N_2 fixation.

For the modelling, daily weather files for the period 1972-2021 were obtained from the National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station network node (Tait et al*.,* 2006) within 5 km of the AgResearch Ballantrae Research Station. Virtual Climate Station node = Latitude -40.3, Longitude 175.8, mean annual temperature = 12.1°C, mean annual precipitation = 1220mm. Soil profile physical and chemical characteristics to parameterise the model were obtained in the National Soils Database (NSD) and Gradwell (1976). In brief, the soil bulk density was <1 Mg/m^3, field capacity 45%, and permanent wilting point 21.7% in the topsoil. Total soil depth was 750 mm on medium slopes and water holding capacity 100 mm to 760 mm.

Model simulations of a perennial ryegrass/white clover pasture on a 15° east aspect were run from 1972-2021, using a 'simple grazing' model with a 21 d rotation interval harvest to a residual of 1600 kg DM/ha, with excreta return (80% of N intake) by considering nutrient transfer effects. With the soil P fertility (Olsen P values) of the HF farmlet at or above optimum (Olsen P >25 µg/ml) required for maximum growth since the mid 1980's (Mackay et al*.,* 2021), P availability was not a factor in the modelling. There is a nominally five- to ten-year spin-up period for the soil parameters in the model to come to equilibrium (*e.g*., soil carbon), so the first 10 years of the model outputs should be treated with some caution.

Statistical analysis

Net herbage accumulation data for each of the seven measures between May 2020 and June 2021 and total soil organic N data for 2003 and 2020 from each of the three slope classes were presented as box plots (includes means, upper and lower quartiles, and outliers). For model simulations a four-year running average was calculated from the annual NHA data.

Results

Pasture growth 2020-21

Seasonal NHA were averaged for the three aspects (two exclusion cages on each of the E, NW, and SW aspects) on the medium slope for 2020-21 and are presented in Figure 1. Mean NHA values were 13 and 60 kg DM/ha/day for winter and early summer, respectively. Annual NHA was 11,563 kg DM/ha for the 2020-21 year.

Olsen P and total soil organic nitrogen

The mean Olsen P value was 38 µgP/ml for the medium slope on the HF farmlet in 2020.

Total soil organic N stocks in the 0-75 mm soil depth decreased with slope from 3.15 Mg N/ ha (1 Mg = 1*t*) on the low slope to 2.42 Mg N/ha on the high slope in 2020 (Figure 2). Averaged across the three slope and aspect classes, total soil organic N stocks were 2.74 Mg N/ha in 2020, a small decrease of 120 kg N/ha (or 7 kg N/ha/y) compared with 2003. On the medium slope class the total soil organic N in 2020 was 389 kg N/ha (or 22.9 kg N/ha/y) less than that measured in 2003.

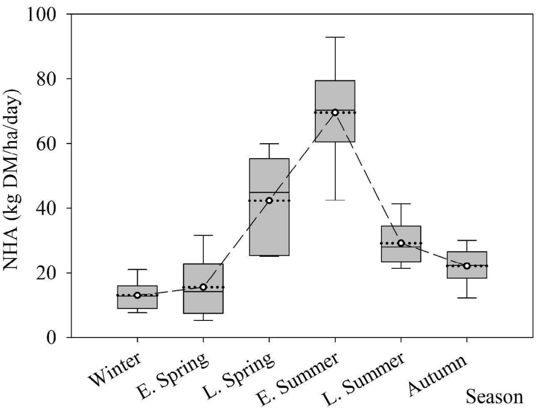

Figure 1 Net herbage accumulation (NHA) in winter (30/07/20), early spring (22/09/20), late Spring (11/11/2020), early Summer (12/01/20), late Summer (01/03/2021) and autumn (25/05/21) from the medium slope for the HF for 2020-21. The dotted line is the mean of the six cages. Box plots show 10th, 25th, 50th, 75th and 90th percentiles. The solid line is the median, the dotted line is the mean.

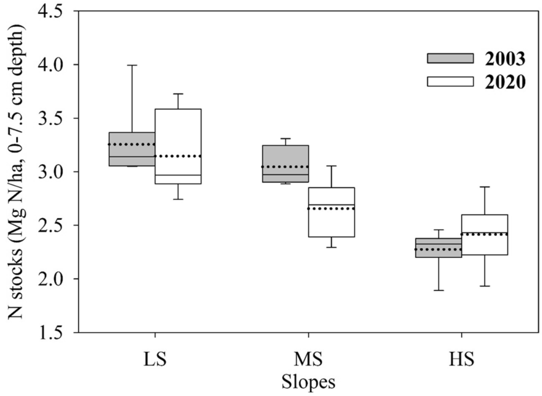

Figure 2 Total soil organic nitrogen stocks (Mg N/ha) in the 0-75 mm soil depth from three slope classes (low slope (LS), medium slope (MS) and high slope (HS) averaged across the three aspects (E, NW, SW) for the HF farmlet in 2003 and 2020. The dotted line is the mean of the six soil sampling sites.

Modelling of net herbage accumulation

A summary of the monthly and total rainfall and mean daily maximum temperature for 1982-1988 (July/June) and differences for 2015-16 and 2020-21, which were periods where NHA rates were measured from the medium slope class on the HF farmlet, and listed in Table 1. While there is no clear trend in annual rainfall since 1982-88, mean daily maximum temperatures are 1.4°C and 1.5°C warmer in 2015-16 and 2020-21, respectively. The January to June period in both 2015-16 and 2020-21 were 1.9°C warmer compared to the same months in 1982-88.

Annual net herbage accumulation (kg DM/ha) from 1972-2020 simulated with the AgPasture module of APSIM, using the daily weather files for the period 1972-2021 (Figure 3) offers a way of exploring the interactions between rainfall, temperature and solar radiation on herbage accumulation and legume growth. Aligning the modelled estimates of annual NHA with the periods when pasture growth has been previously measured indicated that the mean NHA for the period 1982-1988 was 9520 kg DM/ha/y, 8370 kg DM/ha/y for 2015-16 (88%) and 5610 kg DM/ha/y for 2020-21 (60%). Annual biological N fixation simulations indicated no clear trend in activity over the whole simulation period (Figure 3).

Discussion

Net herbage accumulation rates averaged 35.7 kg DM/ha/day from 1982-88 on the medium slopes of the HF farmlet, which translates into an annual NHA of 13,250 kg DM/ha (Lambert et al., 1983; 1990). In 2020-21, the annual NHA on the HF farmlet was 11,563 kg DM/ha, which is very similar (11,289 kg DM/ha) to the NHA in 2015-16 year reported by Mackay et al. (2016). These were equivalent to 87% and 86% of the NHA from the same sites from 1982-88.

Table 1 Monthly and total rainfall and mean daily maximum temperature for 1982-1988 (July/June) and differences from these means in 2015-16 (July-June) and 2020-21 (July-June). Data taken from the NIWA Virtual Climate Station network node close to the AgResearch Ballantrae Research Station.

Period	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	**Year**
1982-88 rain	100	70	103	103	89	119	73	94	81	85	96	107	1119
2015-16 diff	-26	39	6	14	-10	-56	13	-57	29	-47	170	0	75
2020-21 diff	-39	-14	47	-41	46	-51	-14	-72	-9	-49	-38	-9	-242
1982-88 tmax	10.8	12	13.6	15.3	17.7	19.5	21.3	21.2	19.4	16.8	13.8	12.3	16.1
2015-16 diff	0.3	0.4	-0.4	0.7	-0.2	0.1	1.7	4.3	2.6	2.3	2.9	1.8	1.4
2020-21 diff	1.4	1.7	0.5	2.2	1	0.5	1.1	2.8	1.9	1.7	1.9	1.9	1.5

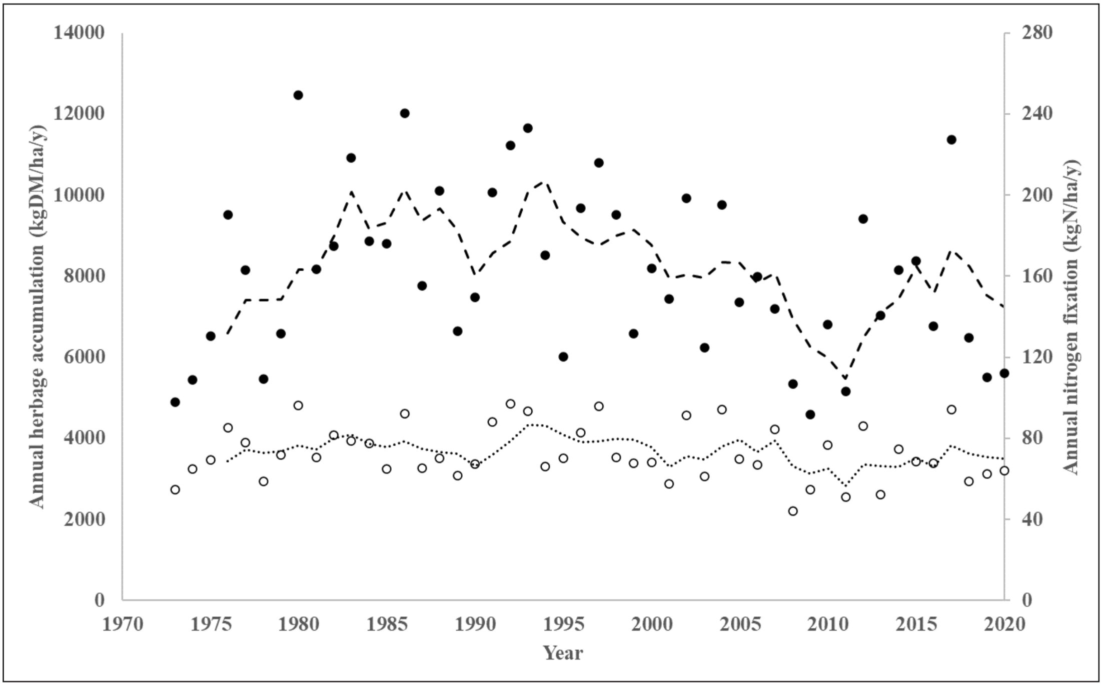

Figure 3 Simulated annual herbage accumulation (kg DM/ha/y) and nitrogen fixation (kg N/ha/y) from 1972-2020 for a perennial ryegrass/white clover pasture on a medium slope at Ballantrae, using the AgPasture module of APSIM. Daily weather files were obtained from the NIWA virtual Climate Station Network for the grid point closest to the AgResearch Station, and the hydraulic soil parameters were obtained from measured characteristics. Dotted lines represent 4-year running averages from the annual data.

With individual year measurements there is potentially a risk of selecting non-representative years (*i.e*., climatically favourable or unfavourable). Relative to the two decades post-2000, the modelling suggested that 2015-16 was a relatively favourable year (fifth highest annual HA) and 2020-21 was a relatively unfavourable year (fifth lowest annual HA, Figure 3). Overall, the ecosystem modelling based solely on the weather files from the site suggested that climatic conditions for pasture growth during the 2000-2020 period were less favourable than in the 1980 and 1990, with a resultant trend of declining annual NHA (Figure 3).

The apparent decline in NHA aligns with the fact that the on-site nominal sheep stocking rate for the HF farmlet has been gradually reduced since the early 2000's to sustain pasture covers and animal performance (Mackay et al*.,* 2021). Both the measured and modelled decline in NHA and animal production in this study fitted with the results published by Gobilik et al. (2021) who calculated a decline in herbage accumulation of 11% on southern North Island 'hill country' sheep and beef cattle systems over the period 1980-2011 using the change in the energy harvested by animals detected by metabolic energy budget over that period. That decline was reflected in some pasture growth modelling that Gobilik et al. (2021) conducted using actual NIWA climate data for that same period.

Climate-driven modelling using projected future climates suggested that, in this summer moist environment without including the fertilisation effect of enriched CO_2 in the atmosphere, HA should increase, rather than decline into the future (Lieffering et al*.,* 2016; Ausseil et al*.,* 2019, Keller et al 2021). Given that climate driven pasture growth models were able to capture the changes in pasture growth over the study period using actual climate data collected by NIWA suggested that a closer investigation of the climate models used to predict future weather patterns is required.

The average Olsen P value was 38 µgP/ml on the medium slope of the HF farmlet in 2020, which was well beyond the optimum range of 20-25 mg/kg for near maximum legume and pasture growth. Hence, it was surprising to find that the C:N ratio was still >12.5:1 in the topsoil of the HF farm (Mackay et al*.,* 2021). It appeared that, since 2003, there was a downward rather than upward trend in soil organic N, which was more pronounced on the medium slope (Figure 2). Lambert et al. (2000) reported an annual increase in total soil organic N of 18.7 kg N/ha/y in the HF farmlets from 1975 to 1987. This was associated with an increase in pasture production and animal performance. The increase in soil N content in the HF from 1975 to 1987 was presumably the result of greater symbiotic N_2 fixation (Lambert 1987) stimulated by the high level of fertiliser P and S inputs. Over that period, the soil C:N ratio declined from >13.5:1 to <12:1 with pasture improvement, which was in line with previous work (Walker et al*.,* 1959). Linking soil data back to 1987 should be treated with caution, as Lambert et al*.,* (2000) reported changes from five HF farmlets, whereas the findings in 2003 and 2020 in the present study were from the one HF farmlet retained as part of the long-term P fertiliser and sheep grazing experiment at Ballantrae. That said, the total organic N in soil in 2003 and 2020 appeared to be lower, rather than higher than reported in 1987 by Lambert et al*.,* (2020), when the expectation would have been for organic N to continue to accumulate. The lower values translated into a small decline of 12.5 and 16.7 kg N/ha/y from 1987 to 2003 and 2020, respectively. Over the same period, the C:N ratio progressively widened, and was recently >12:1 (Mackay et al*.,* 2021). The increased C:N ratio was not the result of a change in soil organic carbon (SOC) stocks, as these have shown little or no change with P fertiliser input or sheep stocking rate history (Mackay et al*.,* 2021).

The apparent decline in the N status of the soil, which could have explained, in part, the decline in pasture and livestock production, as a previous study has shown these systems are responsive to N throughout the year (Lambert et al*.*, 2003). The decline in N is either the result of a decline in legume growth and or biological N_2 fixation, or an increase in N losses from the systems, or a combination of the two. The modelling suggested that annual biological N fixation has not changed (Figure 3), which indicated higher N losses. Hotter days would increase the risk of ammonium emissions from urine patches in the days following grazing, as volatilization rates are closely linked to temperature. The warmer autumn and winter days (Table 1) and associated increased pasture growth and grazing days might have contributed to higher N leaching losses from urine patches. Further research is planned to (i) better understand what is happening to the N cycle and how that can potentially affect pasture growth and animal performance and (ii) extend the modelling to include the influence of changes in solar radiation, temperature and moisture on pasture growth with slope and aspect and how that in turn influences animal behaviour and the return of nutrients in dung and urine and pasture growth.

Conclusions and implications

Trends in NHA and nominal sheep stocking rates in the HF farmlet of the long-term P fertiliser and sheep grazing study suggested that less pasture is growing currently than in previous decades. The fact that the total soil organic N has remained unchanged or even showed a small reduction since 1987, despite the fact the C:N ratio was still greater than 12:1, might explain, in part, this decline. The measured and modelled decline in NHA reported in this paper appeared at odds with the literature reporting a generally positive outcome of climate change on pasture growth in summer moist environments. This long-term P fertiliser and sheep grazing experiment provided the ideal field laboratory alongside a modelling programme to better understand what is happening to New Zealand pastures under current conditions, and use such data to improve the ability and hence confidence to provide advise into the future.

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