Are observed rates of productivity compared to model predictions indicating negative climate impacts in perennial plants?

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Abstract

Understanding the apparent discrepancy between observed and predicted primary production is explored in this paper using long-term pasture and radiata pine (*Pinus radiata*) growth data sets and relevant biophysical models. To better understand the historical trends on primary production from pastoral agriculture and forestry, annual net herbage accumulation (NHA) and total volume yield was predicted (APSIM and PPM88) and compared with long-term pasture and forestry data sets from key regions in New Zealand. Ballantrae and Poukawa (Southern and Central Hawke's Bay) showed declining trends in NHA (observed and predicted), over the last 20 years. In contrast, Woodlands and Waikato have shown no changes or a slight increase in NHA despite large changes in management practices and nutrient inputs, particularly at the Waikato site. In Kaingaroa Forest in the central North Island empirical models have overestimated tree growth and volume production in recent years relative to observations. The minimal changes or decline in vegetation growth challenge the prevailing notion of expected increases in vegetation growth under future climate scenarios.

Keywords: Future climates, pasture growth, *Pinus radiata*, models.

Introduction

New Zealand is a primary industry-based economy, and trades on its combination of rich natural capital stocks and mild climate, with pastoral agriculture plus plantation forestry the largest land users (12 million ha) and contributors to the economy ($35-40B per annum export earnings over the past five years). Forage from pastures accounts for >90% and >70% of the sheep and beef, and dairy sector total feed intake, respectively (DairyNZ Economic Survey 2020-21, Beef + Lamb New Zealand 2022). A small shift in this feed base, as demonstrated in historic years of adverse climate (e.g., a reduction of $600M in GDP in 2019-20) impacts on economic, social, environmental, and cultural dimensions of sustainability, rural community resilience and feed security (Nixon et al. 2021).

Multiple modelling studies (Korte et al. 1990; Lieffering et al. 2016; Ausseil et al. 2019; Watt et al. 2019; Keller et al. 2014; Newton et al. 2022) have been conducted in New Zealand over the last 30+ years exploring the potential impacts of changes in climate on the future of primary production. These predicted effects are most likely attributable to warming and CO_2 enrichment of the atmosphere. The prevailing view, based on those modelling studies, across our two largest land-based industries is that future climates will likely have a neutral or positive impact on net herbage accumulation (NHA) in pastoral systems and stand growth rates in plantation forestry systems in wetter and cooler environments, and a neutral to slightly negative impact in summer dry environments.

An examination of pasture production data from both dairy and sheep/beef systems collected over the last 20-40 years, suggests that NHA has not increased, but has been either static (Smith 2012; Glassey et al. 2021) or in decline (Mills et al. 2021; Gobilik et al. 2021; Mackay et al. 2022). This has also been noted by leading farmers and consultancies domestically and in other parts of the world (Ortiz-Bobea et al. 2021). This apparent discrepancy has major cost and production implications for an industry largely based on homegrown feed. Furthermore, technological advances (genetics, management) and increased inputs (nitrogen, water) may be masking a more fundamental underlying decline in net primary production. A similar picture is emerging when looking at plantation forestry in NZ (Watt et al. 2019), with data in the last 3-5 years indicating that trees are growing at a slower rate (5-8% reduction) compared with model predictions (Timberlands Limited, unpublished data). Again, this is despite technological advances in genetics and management (Kimberley et al. 2015; Moore 2021). This has implications for not only yields, but also

carbon (C) sequestration rates, an important tool for offsetting greenhouse gas (GHG) emissions.

This study aimed to better understand the historical trends in primary production from pastoral agriculture and radiata pine forestry across multiple regions. Annual NHA was predicted using a climate-driven pasture growth module within a larger process-based model [AgPasture in Agricultural Production Systems Simulator (APSIM)] and compared with long-term pasture data sets from AgResearch Ballantrae (southern Hawke's Bay), AgResearch Woodlands (Southland), On-Farm Research Poukawa (central Hawke's Bay) and DairyNZ Scott Farm (Waikato). The previous similar analysis of long-term modelling and data at Ballantrae (Mackay et al. 2022) is extended here to include the important element of slope. The growth and yield in *Pinus radiata* plantations was predicted with an empirical model (PPM88) and compared with observations from permanent growth monitoring plots and actual harvest yields from Kaingaroa Forest located in the central North Island.

Materials and Methods
Sites
The southern Hawke's Bay pasture site (1975-2023) is located at the Ballantrae Hill Country Research Station (40°18′ S 175°50′ E) and has been described in detail by Mackay et al. (2022). The Southland pasture site (1978-2023) is located at the Woodlands Research Station 15 km east of Invercargill, Southland (46°22′ S, 168°35′ E) and is described in detail by Smith (2012). It includes pastures dating from pre 1970 (old) and pastures more recently sown in 1995 (new). The central Hawke's Bay pasture site (1999-2023) is located at the Poukawa Research Farm (39°45′ S, 176°44′ E) and has been described in detail by Mills et al. (2021). Ballantrae and Woodlands are grazed by sheep and Poukawa is grazed by sheep and cattle. At these three sites NHA was measured using exclusion cages. The Waikato pasture site (1975-2023) is grazed by dairy cows and was located initially at the Ruakura No.2 Dairy (37°47′ S, 175°19′ E from 1979-2004) and more recently at DairyNZ Scott farm (37°46′ S, 175°22′ E from 2004 -2020) and have been described in detail by Glassey et al. (2021) and Macdonald and Roche (2023). Monthly NHA data were derived from pasture cover assessments conducted weekly by visual assessment, calibrated with ground-level herbage cuts. The central North Island forestry site is the 200,000 ha Kaingaroa Timberlands estate which is comprised mostly of *P. radiata*. The estate is owned by the Kaingaroa Timberlands partnership, with most areas into at least their third rotation of trees. Growth and yield data have been collected in both permanent growth sample plots and temporary inventory plots for more than 70 years.

Modelling pasture and *P. radiata* growth
The AgPasture module (Li et al. 2011) of APSIM Next Gen (Holzworth et al. 2018) was used to explore the influence of climate on pasture growth at each of the four pasture sites. AgPasture is a process-based multi-species pasture growth model that can explore the influence of climate, topography, soil profile properties and some management practices on a range of soil-plant system attributes, including pasture growth and biological nitrogen (N_2) fixation. For the modelling, daily weather files for each site were obtained from the National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station network node (Tait et al. 2006). Soil profile, physical and chemical characteristics to parameterise the model were obtained from the National Soils Database (NSD). Pastures were comprised of perennial ryegrass and white clover at Woodlands and Ruakura/Scott Farm; with browntop included at Ballantrae and Poukawa. Simulations were run from 1972-2022 with trends reported from 1982 onwards. Grazing management at each site was simulated as a rotation based on target pre-graze covers of 2800 kg DM/ha and residual covers of 1500 kg DM/ha.

For the model simulations of the three slope classes at the Ballantrae site (5°, 15° and 25°) on an easterly aspect, the ability of the model to capture the influence of spatiotemporal climate variables on pasture growth was evaluated by comparing the model output for 1972-1981 with NHA measurements across the three slope classes for the same period (Lambert et al. 1983).

Pinus radiata growth rates in the latter stages of the rotation (i.e., from approximately age 22 years through to harvest at 25-28 years) were predicted using the PPM88 empirical model which was developed in the 1980s using data from stands that were planted in the 1960s and earlier (Garcia 1999). The model was initialised using a measurement made around age 22 years, either in a permanent growth sample plot or in a pre-harvest inventory. Predicted yields were compared with measurements made at later ages in permanent growth sample plots or with actual yields recovered from the forest. A dataset of 17 permanent growth sample plots was used for this comparison. These were chosen to be more representative of current stand and climatic conditions, i.e., they reached 22 years of age within the last ten years (after 2012).

Statistical analysis
For both observed and predicted data, annual NHA was taken to be the period July-June, with a three-year running average calculated from the annual NHA data to indicate medium-long term trends. Analysis of variance was used to examine the effect of slope and the two 10-year periods (1982-1991 and 2012-2021) on NHA at Ballantrae.
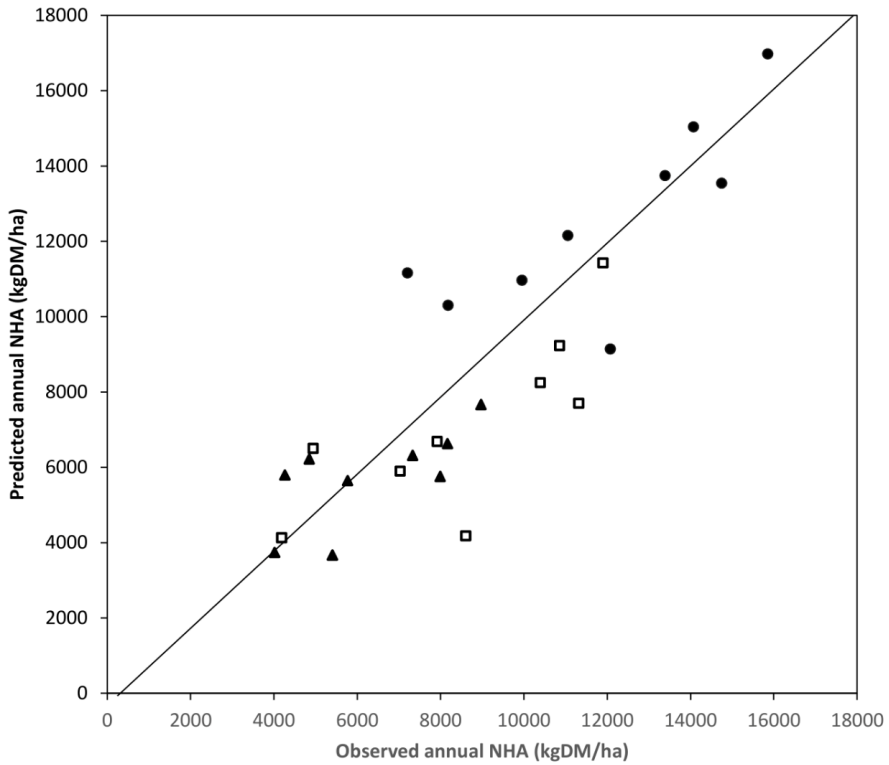
Figure 1 Relationship between observed and predicted net annual herbage accumulation (NHA; kg DM/ha) across three slope classes (▲= high slope, ☐=medium slope, and ●=low slope) from 1972-1981. Predicted NHA data were obtained using the AgPasture module of Agricultural Production Systems Simulator (APSIM), whereas observed NHA data were obtained using exclusion cages (Lambert et al. 1983).
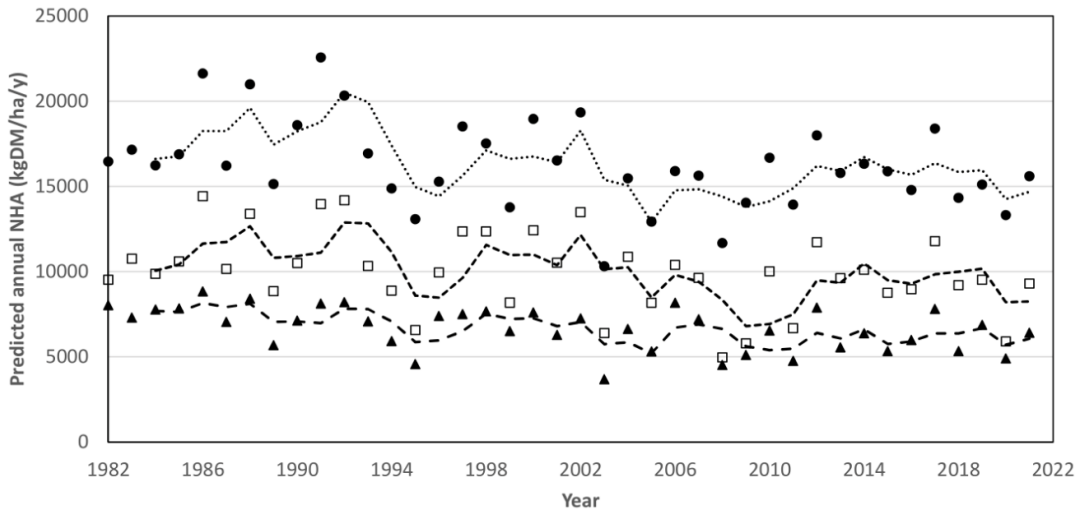

Figure 2 Predicted annual net herbage accumulation (NHA; kg DM/ha) from 1980-2021 of a perennial ryegrass/white clover pasture on low (●), medium (☐) and high (▲) slope classes at Ballantrae using the AgPasture module of Agricultural Production Systems Simulator (APSIM). Dotted lines represent three-year running averages from the annual data.

Results and Discussion
Pasture production

Annual NHA predicted with the AgPasture module of APSIM using historic daily weather files (1972-present) for each of the four pasture sites, offers a way of exploring the effect of long-term climate drivers captured in the model on NHA, legume growth and N_2 fixation, while maintaining consistent soil fertility, grazing management practices and fertiliser inputs. The impacts of biotic factors such as pest and diseases, are also assumed to be consistent. The underlying impact of climate, and reasons for any differences between trends in predicted and observed NHA attributable to non-climatic factors are discussed.

Southern Hawke's Bay (Ballantrae)

A good relationship was found between observed (Lambert et al. 1983) and predicted NHA across three slope classes; NHA varied from 4,000 kg DM/ha on the high slope class to >15,000 kg DM/ha on low slope class (Figure 1). Values were averaged across P fertiliser levels, sheep stocking rate and aspect locations. The relationship provides confidence in the model to capture the influence of spatiotemporal climate variables on pasture growth.

Predicted annual NHA on all three slope classes appears to show a declining trend since 2000 (Figure 2). Analysis of predicted annual NHA for the three slope classes during 1982-1988 compared with 2012-2018, indicates a significant (p<0.01) decline in NHA (Figure 2). Mean annual NHA in 1982-88 and in 2012-2018 were 12,340 kg DM/ha and 10,500 kg DM/ha, respectively; LSD = 890 kg DMha) in addition to the effect of slope (mean annual NHA on the low, medium, and high slope classes were 16,970,10,350 and 6,930 kg DM/ha, respectively, LSD = 1,090 kg DM/ha). While there was no interaction (p=0.6) between the two variables (time and slope), the decline in NHA tended to increase with increasing slope (88, 84 and 77% on the low, medium, and high slope, respectively, from 2012-2018 to 1982-1988). The decline in modelled NHA is consistent with the lower NHA observed in 2015-16 and again in 2020-21 compared with the 1980's (Mackay et al. 2022) and with the fact the nominal sheep stocking rate has declined at the site since 2000 (Mackay et al. 2021).

Predicted annual NHA of the clover component and biological N_2 fixation showed the same declining trends as total NHA (data not shown), but the percent decline in clover NHA from 1982-88 through to 2012-2018 was similar across all three slope classes. The predicted decline in clover growth and N_2 fixation aligns with the small, observed annual NHA decline in total soil N and increases of the soil C:N ratio in the high fertility (HF) farmlet in 2020 (Mackay et al. 2022) compared

with earlier reports (Lambert et al. 2000). While there has been no clear trend in annual rainfall since 1982, mean daily maximum temperatures have increased by 1.5°C (Mackay et al. 2022). The increase in mean daily temperature contributed to the increase (p<0.01) in the mean summer soil moisture deficit (January to March), which increased from 41 mm between 1982-88 to 55 mm between 2012-2018. Over the period of the study grazing management and fertiliser inputs have remained constant. The modelling suggests that the summer soil moisture deficit and temperature stress drivers of pasture growth are greater than the predicted benefits of higher CO_2 concentration and warmer winter-early spring temperatures, leading to long-term reductions in NHA, rather than an overall increase. We hypothesize that the direct impact of higher mean temperatures, including more hotter days, and changing precipitation patterns on our biological systems are already having a greater impact on growth rates and losses (e.g., ammonia volatilization) than warming and the predicted benefits of higher CO_2. This potentially significant cost to the industry and country currently goes unrecognised and is in addition to the growing costs associated with extreme weather events from climate change.

Central Hawke's Bay (Poukawa)

The quantitative alignment between observed and predicted annual NHA was poor over the first 10 years (Figure 3), possibly because the model was parametrized to represent a ryegrass-browntop-white clover sward, when the observed sward is a combination of perennial ryegrass (32±10%) and annual brome (36±6%), no white clover, but some subterranean clover (7%) (Mills et al. 2021). The modelling suggests there has been an overall decline in annual NHA since 1999, with quite an obvious cyclical pattern, while the observed NHA indicates a greater decline over the 20 years (Mills et al. 2021), despite good levels of fertility, with Olsen P between 20-43 µg/ml and pH >6.0. Using simple linear regression indicates a decline of 136 and 248 kg DM /ha/y in predicted and observed NHA, respectively, from 1999 through to 2020. While there has been little change in the maximum temperature (0.4 °C) over the last 40 years, there has been an increase (0.9 °C) in the minimum temperatures. There are no clear trends in rainfall over that period, with a long-term annual average of 750 mm. The observed and predicted decline in NHA agree with the predictions for the East Coast of the North Island under predicted future climates (Lieffering et al. 2016). Since monitoring was initiated in 1999, pastures have been routinely fertilised with 250 kg/ha/yr of superphosphate, but no pasture renovation or N fertiliser application has occurred (Mills et al. 2021), limiting the influence these two factors have
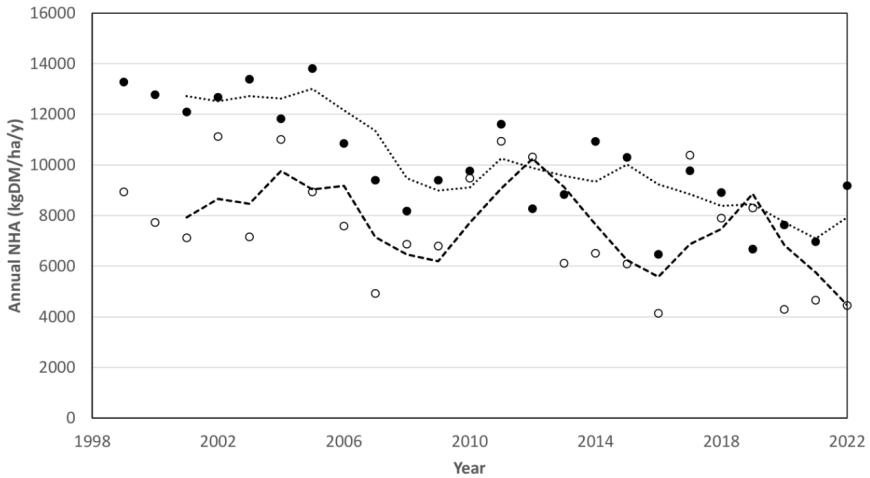
Figure 3   Observed (●) and predicted (○) annual net herbage accumulation (NHA; kg DM/ha) from 1998-2022 for the l egume-based pasture at Poukawa using the AgPasture module of Agricultural Production Systems Simulator (APSIM). Dotted lines represent three-year running averages from the annual data.
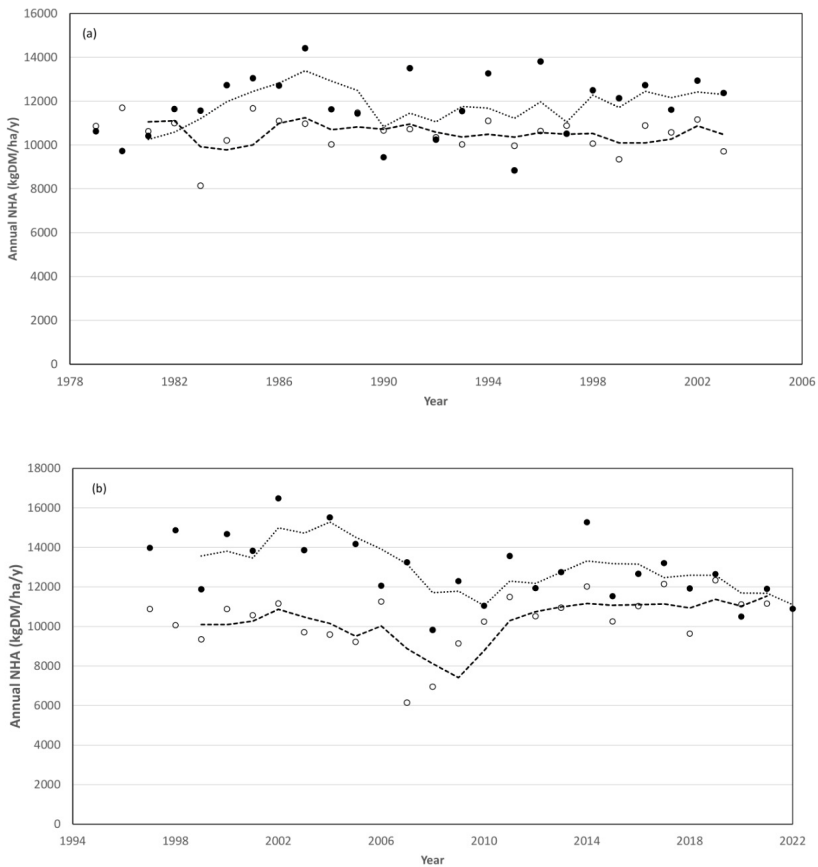

Figure 4   Observed (●) and predicted (○) annual net herbage accumulation (NHA, kg DM/ha) for the (a) old (1978-2003) and (b) new (2000-2020) pastures at Woodlands using the AgPasture module of Agricultural Production Systems Simulator (APSIM). Dotted lines represent three-year running averages from the annual data.

on herbage accumulation. The single biggest factor determining annual production continues to be the amount of summer rainfall and the timing of autumn rain. That has been reinforced by the annual NHA of 11,551 kg DM/ha in the 2022-23 season (July 2022 to June 2023), that was associated with one of the wettest years on record in the Hawke's Bay (https://niwa.co.nz/climate/summaries/seasonal/summer-2022-23).

Southland (Woodlands)
Using climate data sourced from the VMN node located close to Woodlands, the modelling results (Figure 4) suggest no real long-term trend for either the old pasture (1978-2003) or the new pasture (1996-2021). This is occurring in a climate that is slowly warming (close to 1.0°C and 0.5°C increase in annual mean maximum and minimum air temperature, respectively, over the same period (1978-2021), but with no clear trends in annual rainfall, which is 1,089 mm. The quantitative alignment between observed and predicted annual NHA with the new pasture was poor over the first 5-10 years (Figure 4) possibly due to the N return levels and harvest frequency used in the modelling.

Smith (2012) provides a detailed analysis of pasture growth rates and patterns of a well-managed old (1977-2000) and new pasture (2001-2012) at the Woodlands site. In agreement with the modelling results, the author reports no trends in annual NHA of the old pasture, and after an initial boost, a decline was shown in annual NHA of the new pasture from about 2008 (Smith 2012). Over the course of the study, nutrient inputs increased from annual applications of 27-30 kg P/ha as superphosphate with 2.5 t of lime/ha (up to 1991) to 32 kg P/ha as reactive phosphate rock (RPR) (1991-1995) to 45 kg P/ha as superphosphate and 0.5 t of lime/ha (1996 onwards). Consequently, mean soil Olsen P values have been increasing from about 12 **μg/ml** following several years of RPR application to 27 **μg/ml** over the period 1998 to 2011 through to 33 μg/ml in 2018. The prevailing view that future climate will have a positive impact on primary production, in the Southern parts of the South Island, in response to warming and CO_2 enrichment of the atmosphere (Lieffering et al. 2016) has yet to materialise.

DairyNZ Scott Farm
The modelling results of NHA, showed no clear long-term trend from 1980 to 2020, though some indication of a decline between 2004-2014 (Figure 5), somewhat consistent with the modelling reported by Glassey et al. (2021) and Babylon et al. (2022). The pasture data also showed little change over the entire period, with some indication of a downward trend from 2007-08, noting that 2004 was the change point from Ruakura No. 2 to Scott Farm. While annual rainfall has changed

little over the last 50 years (1,155 mm p.a.), Glassey et al. (2021) indicate there is a trend of declining rainfall in the summer-autumn months but this has yet to be reflected in NHA. Whilst maximum and minimum air temperatures have increased over the same period by 0.97**°C** and 0.75°C, respectively, the models NHA outputs have not changed.

Interestingly, over the period 1980-2020 milksolids [(MS); milk fat plus protein] production ha^{-1} has increased from about 925 kg MS/ha in 1980, to >1100 kg MS/ha in 2000, and up to 1750 kg MS/ha in more recent years as reported by Macdonald and Roche (2023).

This increase has been driven by changes in pasture management, plant and animal genetics, the introduction of off-farm grazing, an increase in P and potassium (K) based fertiliser inputs, introduction of N fertiliser inputs from 1990, with up to 200 kgN/ha/y and more recently, increased use of brought in supplements to the milking platform (Macdonald and Roche 2023). The annual addition of 200 kgN/ha/y would have the potential to lift annual NHA by up to 2.5 tonnes/ha/y. Nutrients in supplements, returned by the animal in dung and urine and in effluent represent another source of nutrients, especially N, for plant growth. The fact that NHA has remained unchanged despite changes in management practices and large increases in nutrient inputs over the last 40+ years suggest that pastoral systems are close to the theoretical Waikato Regional upper limit for ryegrass pastures calculated by Mitchell (1963) and/or the system is requiring more inputs to sustain current production due to a number of factors, including a changing climate.

Tree growth and volume
Comparison of predicted and realised (observed) yields in stands harvested since 2004 shows that there has been a consistent trend of overprediction of yields since 2010 (Figure 6). The gap between predicted and realised yields has increased over time to the point where the gap is now approximately 8%. This results in the scaling back of future projected stand growth rates, which flows through to C sequestration rates, wood flow projections and forest value. The reasons for this trend of reducing harvest yield could not readily be identified.

The shift to mechanisation of the harvesting process, was initially suspected as one of the reasons for the decline in yields, but this hypothesis was not supported by studies that showed that the "missing" volume was not found in the cutover (i.e., in woody debris left on the harvest site once the merchantable logs had been removed).

Over-stocking of trees resulting from an increase in rotation length and in final tree density over the last 30-
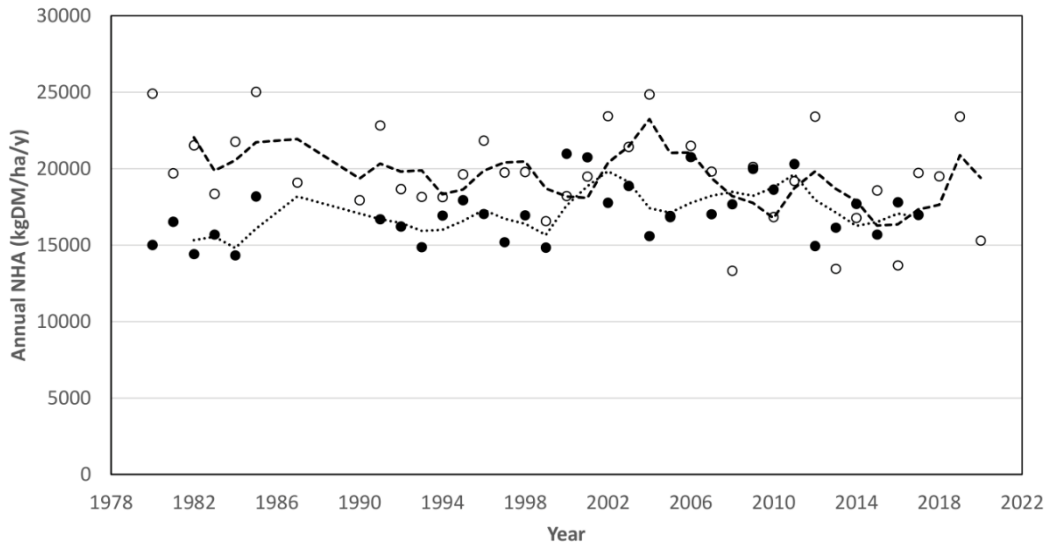
Figure 5 Observed (●) annual net herbage accumulation (NHA, kg DM/ha) from 1980-2020 for the legume-based pasture from Ruakura No. 2 Dairy (1980-2004) and DairyNZ Scott Farm (2004-2020) and predicted (□) NHA using the AgPasture module of Agricultural Production Systems Simulator (APSIM). Dotted lines represent three-year running averages from the annual data.
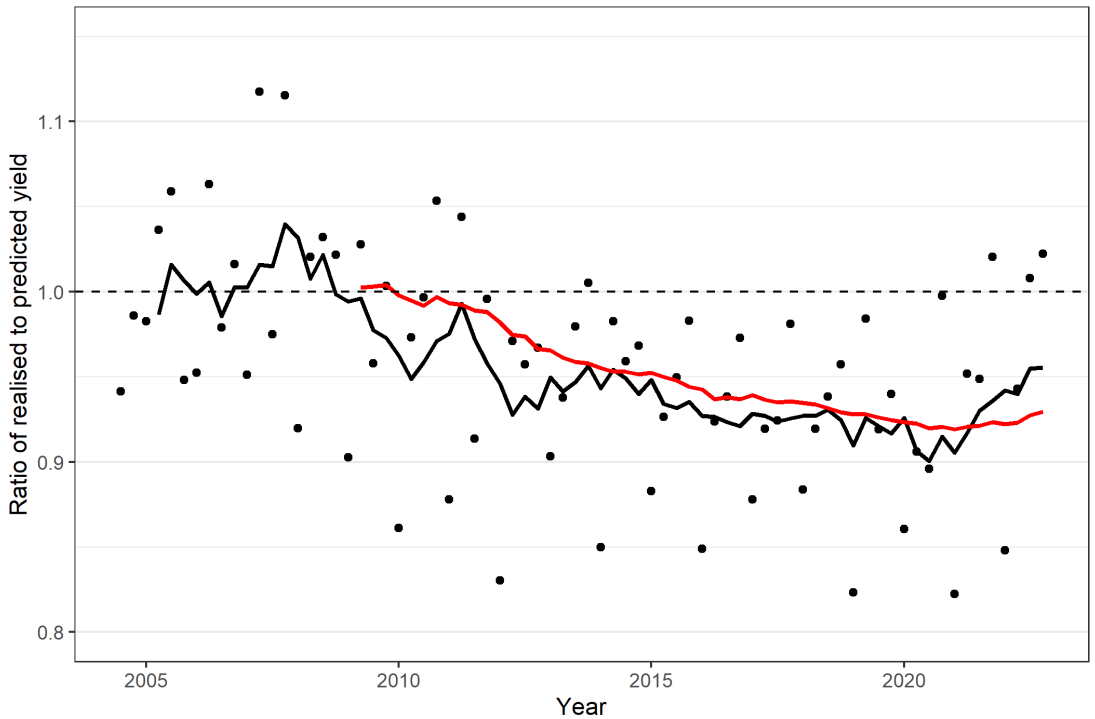

Figure 6 Change in the ratio of realised (observed) to predicted yield in radiata pine over time in the Kaingaroa Timberlands estate. The solid black line shows the 4-quarter rolling average, while the red line shows the 20-quarter rolling average. The dashed horizontal black line corresponds to a ratio of one.

40 years was also suggested as another possible reason for the decline in yields. Anecdotal evidence indicates that there appeared to be higher observed rates of tree mortality than predicted by the models. Ongoing testing and validation of growth models against observations has shown in the past that the PPM88 model has underpredicted mortality, but also underpredicts individual tree size. At the stand level, these two effects have negated each other, so that predictions of volume have been unbiased. However, the most recent comparisons using data from 17 permanent growth sample plots showed that the PPM88 empirical model was overpredicting growth in the final 4-6 years of the rotation by an average of 6.3%. In contrast to the previous model evaluations, these latest results show that tree diameter is correctly predicted but tree mortality is significantly underpredicted, resulting in the overprediction of stand volume.

Most recently, it has been hypothesised that variations in climate could be contributing to this yield gap. Historical climate data, sourced from the 166 virtual climate station network (VCSN) points across the Kaingaroa Timberlands estate, suggest that drought (as measured by standardised precipitation index) is becoming more frequent and more severe. A detailed analysis of rainfall patterns over the last 60 years, highlighted that rainfall has become more variable, and in the last 10 years has been below average. This led to a more comprehensive analysis that combined data on climate and tree growth over the past 60 years, which identified a weak but significant link between drought and reduced tree growth. A combination of reduced rainfall, increased stocking density of trees, and the limited water retention of the pumice soils found under the Kaingaroa forest, is now emerging as the most likely explanation for the gap between predicted and realised yields. Both the climate and the stand conditions that existed at the time when the empirical PPM88 model was developed may no longer be representative of those found today.

This situation is not unique to the Kaingaroa Timberlands estate, nor even forests in New Zealand. A recent global study (Cabon et al. 2022) suggests "we need to rethink the way we forecast forest growth in a changing climate, and that forests in the future may not be able to absorb as much C from the atmosphere as we thought". That has highlighted the need for growth models that can include the interactions between genotype, environment, climate variables, and silviculture as they influence growth and volume, along with the continued monitoring and collection of data from the field.

Summary and Conclusions
At the southern Hawke's Bay site, modelling showed

declining annual NHA over the last 20 years. This is consistent with the decline seen in observed NHA, but at odds with the expected impact of future climates on NHA in this summer moist environment. At the central Hawke's Bay site, the modelling appears to underestimate the decline in observed annual NHA, which aligns with the expected change under future climates for the East Coast. The absence of any change in old pastures at the Southland site, but a decline about 10 years after sowing of a new pasture and an increase in P fertiliser inputs, is puzzling given the climate in the southern South Island is also seen as more favourable for primary production under future climates. In the Waikato, modelling gave some indication of a short-term decline from 2004-2014 but little change over the whole period. This is supported by the fact there have been minimal changes in observed NHA, which is somewhat surprising given the changes in pasture management and increase in nutrient inputs over the last 20 years. The decline in tree growth rates relative to model predictions in the Kaingaroa Timberlands estate appears to be the result of a combination of factors, of which a changing climate is one.

Practical implications
Slower than predicted pasture and tree growth rates have implications for the attempts by both industry and government to enact climate change policy to balance economic, environmental, and social outcomes. If the effects seen represent a deceleration of the photosynthetic machinery, it will apply across all "crops": permanent pastures, annual crops, trees and native restoration, as it affects all primary plant production. This cost to the industry and country currently goes unrecognised and is in addition to the growing costs associated with extreme weather events associated with climate change.

The lack of a clear pasture productivity response to increasing nutrient inputs in the Waikato and Southland must be of serious concern. Once we have better evidence and understanding of mechanisms for the slower than expected growth rates, we need to engage with industry and policymakers to develop solutions and establishing field empirical studies to test these solutions, including a national monitoring network to enable future stakeholders to maintain awareness.

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