Detection of historical changes in pasture growth and attribution to climate change

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ABSTRACT: Few studies consider historical trends in biological systems in relation to changes in climate. These detection and attribution studies are particularly challenging in agricultural systems where other factors (such as management) are changing over time. Here we consider changes in pasture yield (net herbage accumulation [NHA]) over the period 1960–2004 in a dataset from a trial in New Zealand where management (grazing protocol and fertiliser application) was constant over time. We used 2 approaches: a statistical approach looking for trends in, and correlations between, NHA and climate variables and a process-based modelling approach where combinations of variables were held constant at their starting values or allowed to change with time enabling us to isolate the impact of individual factors. There was a significant positive trend for NHA in spring over the period and positive trends in rainfall and atmospheric CO_2 concentration; soil nitrogen (N) also increased over time. The statistical approach was useful for identifying trends but was unable to resolve the driving variables. Modelling identified CO_2, soil properties and their interaction as the most influential variables. The calculated impact of CO_2 was a 0.21 % increase in NHA ppm CO_2^{-1}; this compares to a value of 0.19 % from a FACE (free air carbon dioxide enrichment) experiment with a similar type of management and pattern of pasture production. The results instill confidence in experimental estimates of the CO_2 fertilisation effect, particularly at low levels of CO_2 enrichment, and provide evidence that climate change impacts are already in progress.

KEY WORDS: CO_2 fertilisation effect · ApSim · Grassland

1. INTRODUCTION

There are many studies that project the impacts of climate change, including changes in atmospheric carbon dioxide (CO_2), but far fewer that examine the impacts that climate change is already having on our biological systems (Gregory & Marshall 2012). These historical studies are valuable because they can provide locally relevant evidence of climate change, allow empirical estimates of the sensitivity of specific biological systems to change and, in some cases, allow us to assess how easily these changes can be managed by adaptation (Brander et al. 2011). Studies that attempt to link past changes in biological systems to climate change drivers come under the generic heading of detection and attribution studies (Hegerl et al. 2010, Rosenzweig & Neofotis 2013). Detection is required in respect of both the biological response and the climate driver, i.e. in both cases there needs to be evidence of a temporal change. Attribution requires that the climate driver can be shown to be responsible for the change in the biological variable. In practice, attribution can cover a range of certainty from a notional link based on correlation to a robust causal relationship based on a sound mechanistic understanding of the biological response and statistical tests that exclude other potential driving factors (Cole et al. 2010). Unfortunately such complete studies are rare because there are many confounding factors that can obscure relationships. This is particularly true of the agricultural sector where there are frequently confounding factors such as changes in management (e.g. choice of crop cultivar, fertiliser management) that may be

driven by non-climate factors, and adaption where autonomous or 'unthinking' adaptation to any change (such as change in the time of planting) can obscure the relationship between biological responses and climate drivers (Lobell et al. 2005, Magrin et al. 2005, Ludwig et al. 2009, Gregory & Marshall 2012). The most promising systems to explore detection and attribution have the following traits: (1) a well described mechanistic understanding of the relationship between the system responses and climate drivers, (2) a lack of other confounding factors such as changes in management, (3) a long, high-quality record of both biological and climate variables and (4) rapid (not lagged) responses between the climate signal and the biological response.

Most studies have focussed on crops, with little attention being paid to grassland, although this land use covers 37% of the global terrestrial area and makes a major contribution to food production, as well as acting as a potential sink for carbon (O'Mara 2012). In a study of the Tibetan Plateau, Du et al. (2004) found marked changes in temperature (about a 1°C increase over the 18 yr from 1978 to 1995), which correlated well with increased animal production. However, it was difficult to find a causal link between these two changes as the obvious link — increased grass production — would have had to have changed 1–3 times to produce the observed outcome in livestock production. Later research has shown that, while the temperature has increased on the Tibetan Plateau, the growing season has actually become shorter due to complex interactions between plant phenology and climate changes (Yu et al. 2012). Analysis of 22 yr of biomass data from an Inner-Mongolian grassland showed no effect of climate on annual production, but seasonal changes existed that could be related to increases in precipitation and temperature over the study period (Ma et al. 2010). In the 'Park Grass' experiment there is evidence for reduced stomatal conductance over the last century and a half (1857–2007), which is regarded as a response to increasing atmospheric CO_2 concentrations (Köhler et al. 2010); however, there was no change in yield, even though average temperatures and CO_2 have increased, which probably reflects the low nutrient (particularly nitrogen) status of the unfertilized, unlimed control plots used in the study (Köhler et al. 2010). We are not aware of any other detection and attribution studies for grasslands, although a CO_2 response has been inferred in a study of the greening and browning of grasslands on a global scale (Cook & Pau 2013).

In this study we explored potential changes in climate, including atmospheric CO_2 concentration, on the growth of pasture using a long-term dataset from New Zealand. This dataset provided us with a system that displays all of the desirable traits for a study of this kind. The records of pasture production and weather are high quality and extend over 44 yr, making it the longest running irrigated grazing trial in the world (McDowell & Condron 2012). The management of the systems has been constant over time, including low passive levels of N deposition; the effects of climate are therefore expected to occur rapidly in the pasture system.

Our analysis of these data made use of 2 methodologies. (1) A multivariate statistical approach where we looked for correlations between pasture growth and climate variables, and (2) a process-modelling approach where, after verifying that the ecosystem model was able to simulate the actual data, we excluded or included driving variables (e.g. CO_2 concentration) to estimate the amount of change in pasture growth that could be ascribed to each variable.

2. MATERIALS AND METHODS

2.1. General description

The data are from an experiment on the Winchmore Irrigation Research Station, Canterbury, New Zealand (171° 48′ E, 43° 47′ S). The soil is a Lismore stony silt loam soil (Pallic Orthic Brown soil; Hewitt 1998). Plant and soil data presented here were collected from an irrigation trial that ran in a number of configurations from 1948 to 2011 (Rickard & Moss 2012). Though the experiment consisted of 5 irrigation treatments, we focussed on the non-irrigated control treatment, as we anticipated this would show greater sensitivity to any climatic changes. The soil wilting point was 10% w/w, and field capacity was 30% w/w.

High-quality plant, soil and climate data available from 1960 to 2004 were used in this study. The average mean temperatures and total rainfall by season over this period were: autumn 11.4°C, 187 mm; winter 6.0°C, 184 mm; spring 10.8°C, 174 mm; and summer 15.7°C, 172 mm. In this cool-temperate zone, permanent pastures based on C3 grasses and legumes grow year-round, but show a pronounced late spring–early summer growth rate peak. Consistent site management was maintained over the duration of the experiment, in terms of: (1) livestock type

(hogget sheep from September to January, lambs in April), grazing method (rotational grazing, with all replicates within a treatment being grazed at the same time after the sheep were fasted for 30 h to prevent nutrient transfer from outside the treatment area), grazing intensity (80% utilization of the available herbage), stocking rate (approximately 7 sock units ha^{-1}) and fertiliser inputs (250 kg ha^{-1} single superphosphate per annum, applied in winter). Agricultural lime was applied in 1965 at a rate of 4100 kg ha^{-1} (McDowell & Rowley 2008). Nitrogen fertiliser was not applied, the only input of N coming from fixation by legumes.

Each plot was 0.9 ha, and there were 4 replicate plots of each treatment. The pastures were originally sown with 8 species of grass and clover, and were oversown with ryegrass (*Lolium perenne*) and white clover (*Trifolium repens*) in August 1976. The oversowing used direct drilling into the existing pasture, i.e. did not involve cultivation (R. Moss pers. comm.). Over time the dominant legume became the annual clover *Trifolium subterraneum*, with an increasing preponderance of temperate grasses other than ryegrass (Rickard & McBride 1986).

2.2. Measuring pasture production

Net herbage accumulation (NHA) (Hodgson 1979) was measured by the 'double-trim' cage technique (Rickard & Moss 2012). In each plot 2 sites of 2.75 × 0.6 m dimension were pre-trimmed to 25 mm (a residual of approximately 1000 kg dry matter ha^{-1}), with a mower and exclusion cages placed on them for 4−8 wk depending on pasture growth rates. At the end of the regrowth period, which was a standard grazing interval for that time of year, a 0.4 m wide strip was harvested to 25 mm height and the herbage was weighed wet and subsampled for dry matter content by oven-drying at 60°C for 48 h. Surplus mown herbage was returned to the site, and the location of the site was changed for each harvest. The individual harvest data were combined to give totals for each season, with winter being June−August, spring September−November, summer December−February and autumn March−May.

2.2.1. Measuring soil N

Soil samples were collected around the winter period in 26 of the 44 yr. Fifteen samples were taken per plot to a depth of 75 mm using a 25 mm

diameter soil corer. The samples were bulked for each plot, air-dried, sieved to pass 2 mm and archived at room temperature. Subsamples were retrieved from the archives in 2010 and analysed for total N (and carbon) using a LECO FP2000 analyser (TruSpec) and corrected for moisture content (Schipper et al. 2012).

2.2.2. Climate data

Archived daily rainfall, temperature (minimum and maximum) and radiation were obtained for the local meteorological station (Winchmore). Daily CO_2 concentrations for the dataset were estimated by determining the relationship between monthly averages at Baring Head, New Zealand (which only commenced recording in 1978) with those recorded at the South Pole (recording started in 1957), and extrapolating the Baring Head data back to 1960.

2.2.3. Statistical approach

The main aim of the statistical approach was to explore trends in annual and seasonal NHA together with trends in climate data which might have explanatory value. In addition we considered the influence of changes in total soil N.

Initially, we considered simple graphics with LOWESS (locally weighted scatterplot smoothing) smoothed curves utilizing locally weighted polynomial regression (Cleveland 1979) to examine annual and seasonal trends. We used two-thirds of the (nearest) data points in the plot to smooth at each value, noting that a larger number of nearest values adds to smoothness.

Further examination of trends in NHA was carried out using the Mann-Kendall test (Mann 1945). This is a non-parametric approach that utilizes rank correlations. Given the consecutive observations of a time series, say Y_t, $t = 1, …, n$, Mann (1945) suggested using the Kendall rank correlation of Y_t with t to test for monotonic trends. Here, the null hypothesis is that there is no trend and that the n observations were independently distributed. The NHA values were then related to the climate attributes via regression models. We employed a stepwise multiple linear regression modelling approach with AIC (Akaike's information criterion) to choose the best subset model. All analyses were carried out using the R software (R Core Writing Team 2013).

2.2.4. Ecosystem modelling

We used the pasture growth model *AgPasture* implemented in the APSIM (Agricultural Productivity System Simulator) (Keating et al. 2003). APSIM contains a number of modules that allow simulations of soil water and nutrient dynamics in response to management and climate. *AgPasture* provides a module that has been specifically designed to model temperate pastures with a mixture of plant species (Li et al. 2011); it is based on the plant physiological principles outlined by Thornley & Johnson (2000), and implemented in the Ecomod model by Johnson et al. (2003). The addition and validation of a CO_2 response function to *AgPasture* is described by Li et al. (2014). Parameter settings and a test of model predictions against the Winchmore irrigation trial data may be found in Li et al. (2011) for *AgPasture* and in White et al. (2008) for EcoMod (which is relevant, because it shares many of the same functions as *AgPasture*).

The rising atmospheric CO_2 concentration, changing climate, and changes in soil properties over time (particularly N) were identified as the possible drivers for the observed changes in NHA. To attribute the observed NHA change to these environmental changes, we ran a primary model simulation, with initial settings based on the measured soil characteristics, and used the actual pasture management (the model harvested the herbage at the dates when the pasture was actually harvested) and observed climate data and atmospheric CO_2 concentration. In the simulation, since the model was unable to satisfactorily reproduce the observed inter-annual variations in legume content, the observed legume content at each harvest was set according to the measured values. This primary simulation effectively reproduced observed changes in pasture production and soil properties, as was expected given previous work on parameter setting and validation at this site (White et al. 2008, Li et al. 2011).

To test the impact of the different driving variables we then compared a model where the main factors CO_2, climate and soil properties were held constant against runs of the model where individual factors or combinations of factors were allowed to change (Table 1).

This approach is similar to that used by Piao et al. (2006), with the addition of specific site soil properties as another potential driving variable together with CO_2 and climate. The constant situation (the 'no-change' model) was modelled as follows:

• CO_2 was held constant at the measured concentration at the start of the simulation — 318 ppm in 1960

• Climate was held constant by repeating the actual climate data for the 1961–1970 period. This approach was preferred to using an 'average' annual climate as the average resulted in simulations that tended to overpredict NHA compared to the observed data

• Soil properties were held constant by resetting the soil profile at the start of each simulation year. Organic N in each soil layer was returned to the values for 1960, while parameters with large fluctuation (e.g. mineral N content and fresh organic matter) were reset to the average value for July over the whole simulation. The C/N ratio was preserved in these simulations so that organic C was also set to each soil layer as for organic N.

3. RESULTS

3.1. Statistical approach

Annual NHA increased from about 6000 kg ha^{-1} yr^{-1} in 1960 to just under 8000 kg ha^{-1} yr^{-1} in 2004; this increasing trend with time in annual NHA was marginally significant (Mann-Kendall test p = 0.062) (Fig. 1). We then examined potential trends in seasonal NHA (Fig. 2) and identified a significant positive trend in spring (Mann-Kendall p = 0.007), but not

Table 1. Model formulations where variables (climate, CO_2, soil properties and climate [rain only] where rainfall was allowed to change but not temperature) were held constant (−) or allowed to change (+) over time in simulations of net herbage accumulation in spring. The trend is the difference between the 'no-change' model and model runs with the variables included (see Fig. 7). Significance of the trends was assessed using the Mann-Kendall test. Where the trend was significant (**bold**), we show the response per year (the slope value from a linear regression) and the response in parts per million of CO_2 which increased by 55 ppm over the duration of the data collection

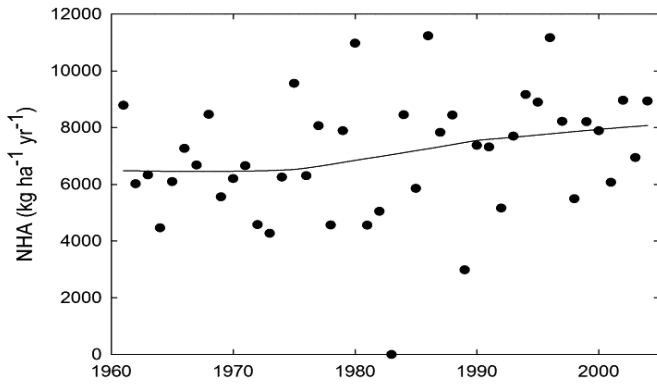| Model formulation	Interpretation	Trends		
		p	Change (yr^{-1}; %)	Change (ppm CO_2)$^{-1}$
−Climate +CO_2 −soil	CO_2 effect	**0.001**	0.26	0.21
+Climate −CO_2 −soil	Climate effect	0.706		
−Climate −CO_2 +soil	Soil properties effect	**0.001**	0.46	0.37
+Climate (rain only) −CO_2 −soil	Rainfall effect	0.799		
+Climate (rain only) +CO_2 −soil	CO_2 × rainfall	0.175		
−Climate +CO_2 +soil	CO_2 × soil properties	**0.001**	0.86	0.77

Fig. 1. Trend in annual net herbage accumulation (NHA). The data points are annual NHA, and the line is a LOWESS curve

in other seasons. Pasture production in spring was consistently greater than in other seasons and contributed on average 56% to total annual production.

The spring data showed a significant trend in atmospheric CO_2 concentration (Mann-Kendall p < 0.001), an apparent but non-significant increasing trend in rainfall (Mann-Kendall p = 0.154) and no trends in minimum temperature (p = 0.335), maximum temperature (p = 0.572), or radiation (p = 0.523) (Fig. 3). Consequently, it was not surprising that positive relationships between climatic variables and NHA were only evident for rainfall and CO_2 (Fig. 4, Table 2). The correlations between NHA and explanatory variables were relatively small, the largest being 0.43 between NHA and rainfall. Maximum

temperature was negatively correlated with spring NHA. There was a strong correlation (0.94) between total N and CO_2 (Table 2).

To further estimate the contribution of the 5 climatic variables to NHA, we fitted a stepwise regression model. Spring rainfall and CO_2 were the only variables to have a significant effect on spring NHA, with rainfall the most dominant effect (Table 3); in addition we tested for an interaction between rainfall and CO_2, but this was non-significant. The overall fit of the model was relatively poor, with an adjusted r^2 of about 22%, indicating that the unexplained variation in NHA could be due to some other factors. The addition of total N to the model was not helpful in explaining the variance due to the strong correlation between total N and the CO_2 concentration (Table 2).

3.2. Modelling approach

The overall positive trend in NHA during spring in the observed data was well captured by the model, but the model output showed smaller year-to-year variations than the actual data (Fig. 5). The increasing trends in soil total N were also well captured by the model (Fig. 6). Having demonstrated that the model was able to simulate the observed trends in NHA and soil N, we then ran the model holding the climate, soil properties (N and C) and CO_2 concentrations at their initial values (see 'Materials and methods') and then compared this output to where one of the variables was allowed to change with time (Fig. 7, Table 1). An analysis for trends using the Mann-Kendall test showed that there were significant trends for the CO_2 effect, soil properties and the combination of these 2, but not for climate (temperature + rainfall + radiation), rainfall on its own, or rainfall in combination with CO_2 (Table 1). Soil properties were a stronger influence on NHA (0.46% yr^{-1}) than CO_2 (0.26% yr^{-1}) (Table 1), but the effect of combining both CO_2 and soil properties was more than additive — that is, the sum of the main effects of CO_2 and soil properties, shown as the grey line in Fig. 7, had a lower slope than the interactive effects (dot-dashed line; the $CO_2 \times$ soil properties case).
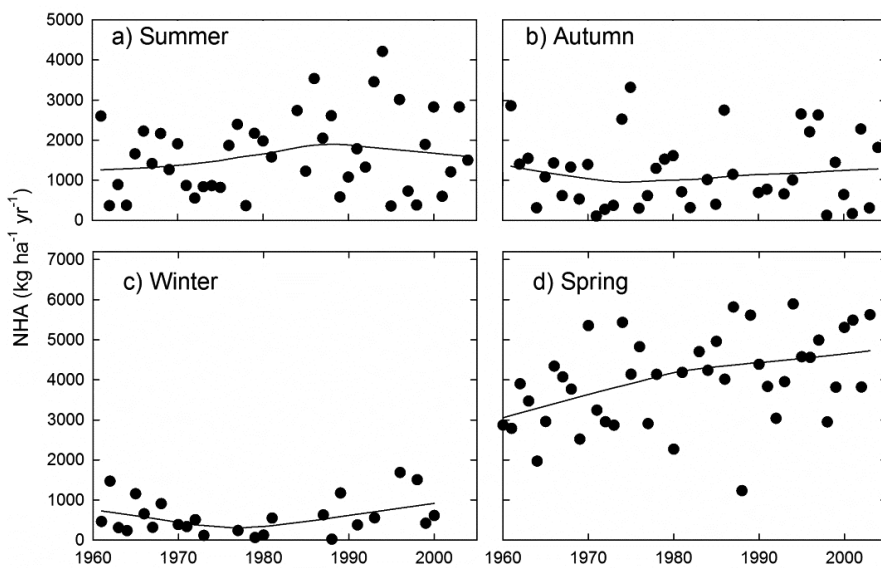

Fig. 2. Trends in seasonal net herbage accumulation (NHA) (a–d). Each data point is the NHA for that season, and the line is a LOWESS curve
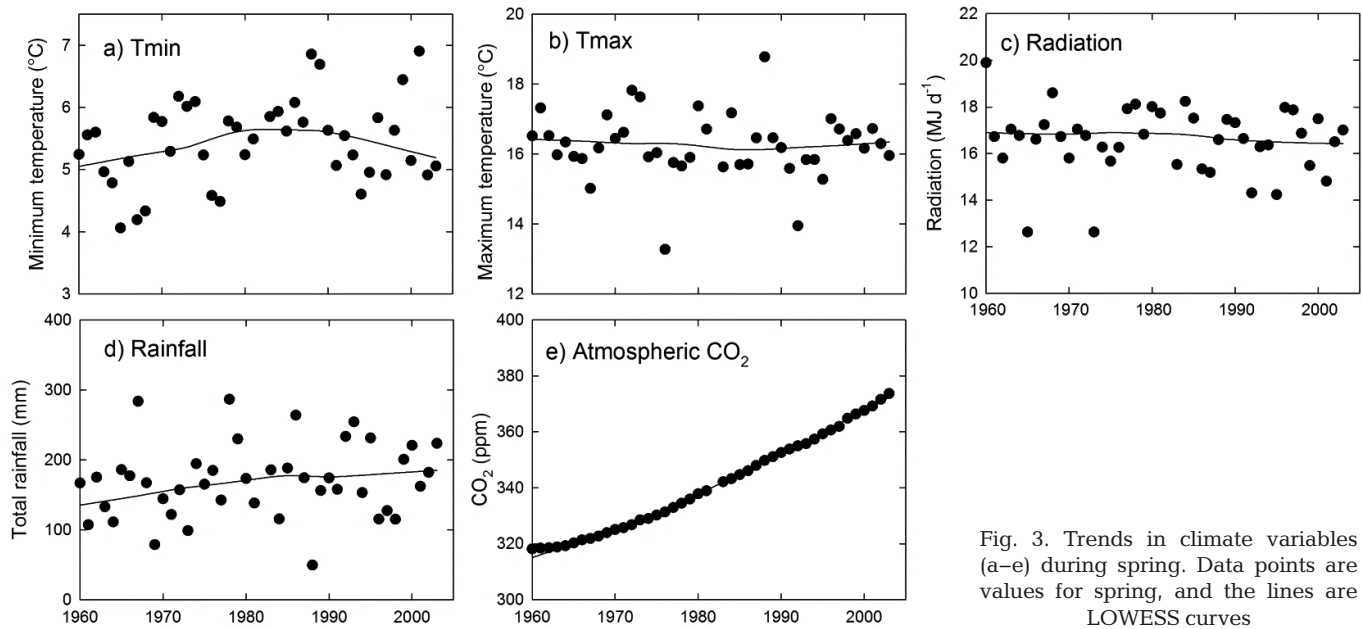
Fig. 3. Trends in climate variables (a–e) during spring. Data points are values for spring, and the lines are LOWESS curves
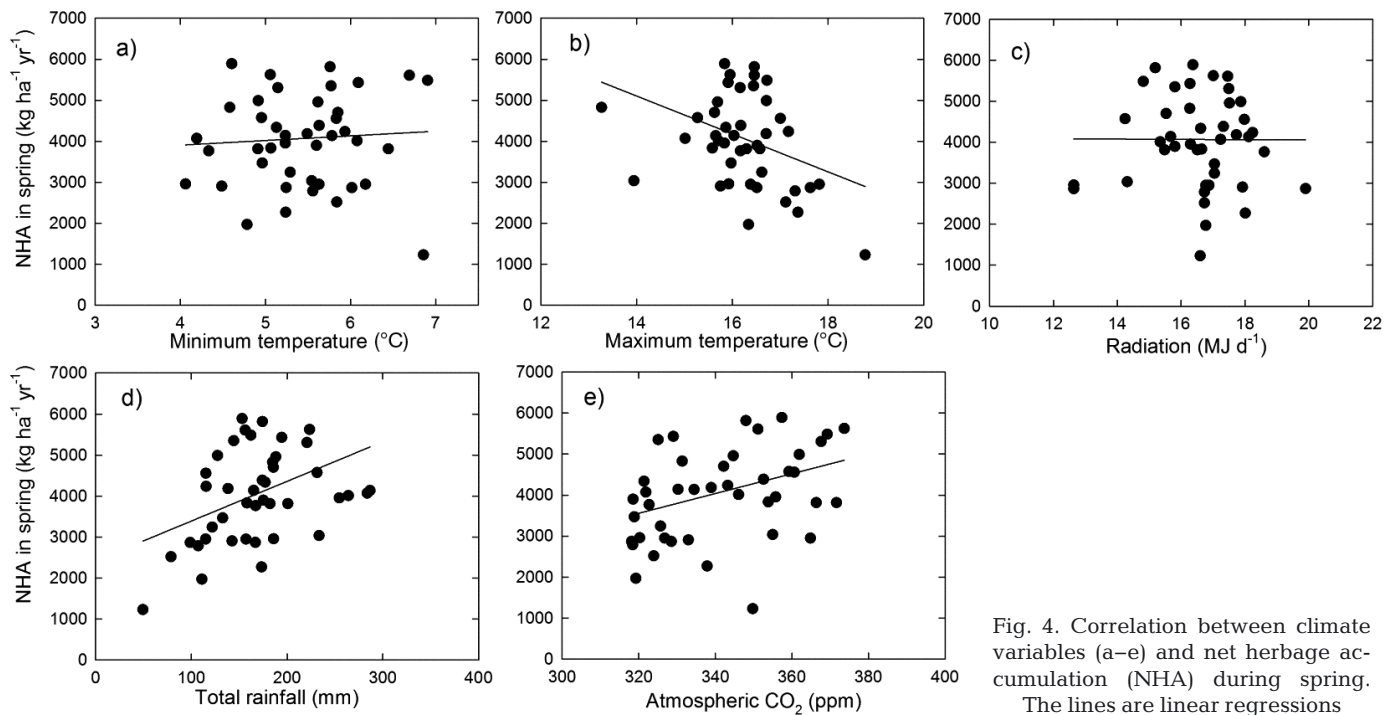

Fig. 4. Correlation between climate variables (a–e) and net herbage accumulation (NHA) during spring. The lines are linear regressions

4. DISCUSSION

Our analysis showed there was a non-significant trend (Mann-Kendall p = 0.062) for increasing annual NHA at the Winchmore site over the period 1960–2004. When we looked at NHA in each season, there was a highly significant (Mann-Kendall p = 0.007) trend of increasing NHA in spring. From the statisti-

cal approach we identified an increasing (though non-significant) trend in spring rainfall and an increasing concentration in atmospheric CO_2 as the most important factors explaining variance in the positive spring response of NHA. There was a negative correlation with maximum temperature; however, because there was no evident trend in maximum temperature over time, we concluded that

Table 2. Correlation matrix for net herbage accumulation (NHA), climate factors and soil total nitrogen during spring. Values for soil N were taken from the ecosystem model rather than the actual data in order to provide a continuous dataset

	NHA	T_{min}	T_{max}	Rainfall	Radiation	CO_2	Total N
NHA	1	0.06	−0.35	0.43	−0.01	0.35	0.35
T_{min}	0.06	1	0.49	−0.21	−0.10	0.24	0.27
T_{max}	−0.35	0.49	1	−0.64	0.14	−0.04	−0.06
Rainfall	0.43	−0.21	−0.64	1	−0.13	0.19	0.20
Radiation	−0.01	−0.10	0.14	−0.13	1	−0.06	−0.10
CO_2	0.35	0.24	−0.04	0.19	−0.06	1	0.94
Total N	0.35	0.27	−0.06	0.20	−0.10	0.94	1

Table 3. Results of a stepwise regression relating spring net herbage accumulation (NHA) to 5 climate variables. Only significant terms are shown (F statistic: 6.797 on 2 and 40 df, p-value: 0.003). The adjusted r^2 was 0.216

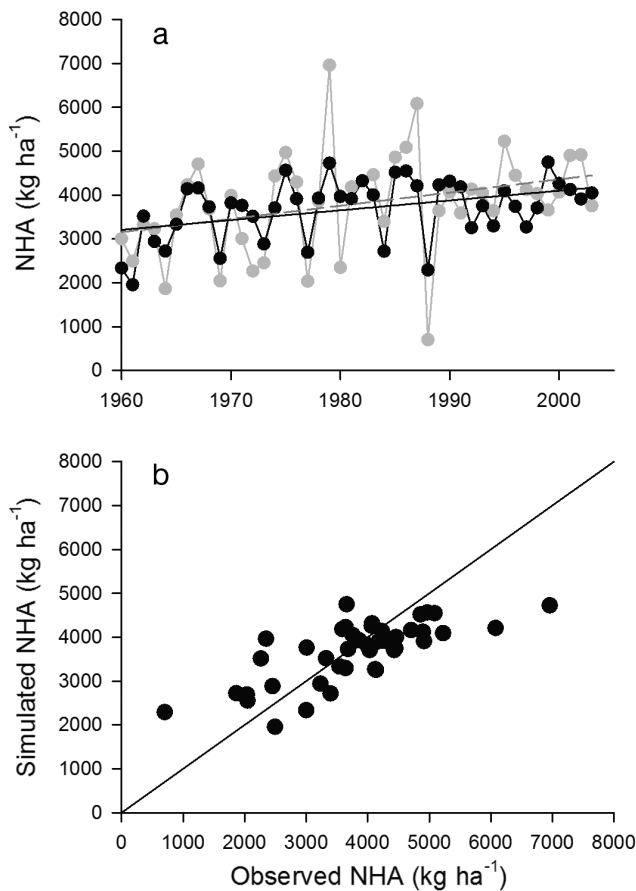|	Estimate	SE	t-value	p
Intercept	−4151	3247	−1.28	0.208
Rainfall	781	292	2.68	0.011
CO_2	20	10	2.05	0.046

Fig. 5. (a) Net herbage accumulation (NHA) during spring for observed (grey symbols) and modelled (black symbols) data. Straight lines: linear regressions for observed (dashed line) ($y = 30.0x − 55\,732$, $r^2 = 9.1$, p = 0.028) and modelled (solid line) ($y = 22.3x − 40\,153$, $r^2 = 15.2$, p = 0.005) data. (b) Observed and simulated NHA values. Solid line: 1:1 line

temperature here was having an effect on variation between years rather than as a consistent influence on NHA over time. It was evident that, although rainfall and CO_2 were identified as the most important positive influences on NHA changes, a substantial part of the NHA response was unexplained, as evidenced by the fact that correlations were <0.5. The opposing effects of rainfall and maximum temperature on NHA probably accounted for the lack of a climate response in the modelling analysis. In the modelling approach there was a strong impact of increasing CO_2 on the positive trend in spring NHA. Modelling highlighted changes in site soil properties over time as an important influence on NHA — a variable that was not included in the first statistical model. Adding total N to the statistical model did not explain more of the variance, however, because a strong correlation between total N and CO_2 existed. Thus, the statistical approach used here was effective at identifying trends, but unable to effectively discriminate between the effects of all the potential driving variables, particularly those that showed the same trends over time. However, discrimination was possible using the process model, and this combination of approaches seems a fruitful way of approaching detection and attribution studies (Ito 2012).

From the modelling analysis, we are able to calculate a spring-time CO_2 fertilisation effect (CFE). This effect is important, as the CO_2 response of agricultural systems frequently appears as the dominant term in impact studies. For example, the CFE determines whether models of future global crop production (Parry et al. 2004, Gornall et al. 2010) and agricultural production in the USA (Edmonds & Rosenberg 2005) and Europe (Ewert et al. 2005) lead to a positive or negative outcome. This makes the strength of the CFE the most 'critical factor' in impact projections (Gornall et al. 2010, Rosenzweig et al. 2014). As well as being important, the CFE is often the response with the greatest uncertainty (Howden et al. 2007, Lobell & Field 2008, McKeon et al. 2008,
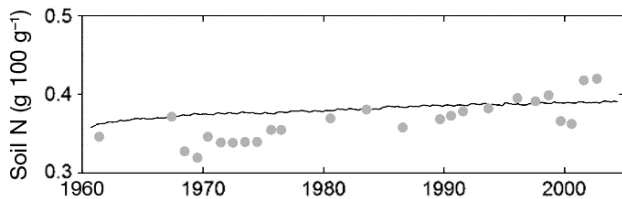
Fig. 6. Annual average total N content (g kg^{-1}) in the topsoil for observed (grey symbols) and modelled (black line) data. Note that the observed values are for the top 75 mm, while the modelled values are for the top 100 mm

Finger et al. 2010, Rosenzweig et al. 2014) because experimental data provide a wide range of values (Lobell & Field 2008) resulting from differences in experimental conditions, including potentially large differences between the results of experiments in controlled environments, such as growth chambers and glasshouses, and those of field experiments (Long et al. 2006). To compare such an estimate with experimental data, we used the results of a free air carbon dioxide enrichment experiment on grazed pasture of the North Island of New Zealand — the NZFACE experiment (Newton et al. 2006). Although separated geographically, the NZFACE and the

Winchmore sites have common management features — the addition of P but not N fertiliser and the inclusion of grazing by sheep — and have similar patterns of pasture production (Fig. 8). The CFE calculated from the modelling analysis of the Winchmore site was an 11.4 % increase in NHA over 1960–2004, or 0.21 % ppm CO_2^{-1}. The CFE for annual production from the NZFACE over 10 yr of enrichment was 0.14 ppm^{-1} (range −0.03 to 0.43), or 7.7 % calculated for the 55 ppm change between 1960 and 2004 to match the Winchmore timeframe; the CFE for spring production in the NZFACE was 0.19 ppm^{-1} (range −0.01 to 0.50), giving a value of 10.4 % for the same period covered by the Winchmore dataset. The similarity in these independent estimates gives us some confidence that a value for the CFE for grazed pasture of a 0.14–0.21 % increase in NHA ppm CO_2^{-1} is reasonably robust.

If we compare our CFE estimate with estimates from other long-running experiments on grassland we find our CFE is the largest (Fig. 9, Table 4), but note this was for the season with the strongest response to CO_2. Fig. 9 shows the CFE from this study (the diamond) compared to the CFEs from experiments, shown as circles, including the NZFACE identified as No. 5. The experimental results show a declining response in parts per million of CO_2 as the level of enrichment increases. This means that the CO_2 response curve is steeper at low levels of enrichment. This being the case, estimates from historical data are thus particularly useful as they are calculated over periods when CO_2 change is limited (a low enrichment level) and for CO_2 concentrations that are similar to current levels as compared to most experiments where the initial part of the CO_2 response curve relevant to the next few decades needs to be inferred from an enrichment level not likely to be achieved until after 2050. There are no other historical estimates of the CFE for pasture, but we have plotted some values for different crops on Fig. 9 (shown as squares). Interestingly, these historical estimates of the CFE fit on the curve of response by enrichment level rather well, suggesting that a strong response to CO_2 at low levels of enrichment may be a generalisation that has
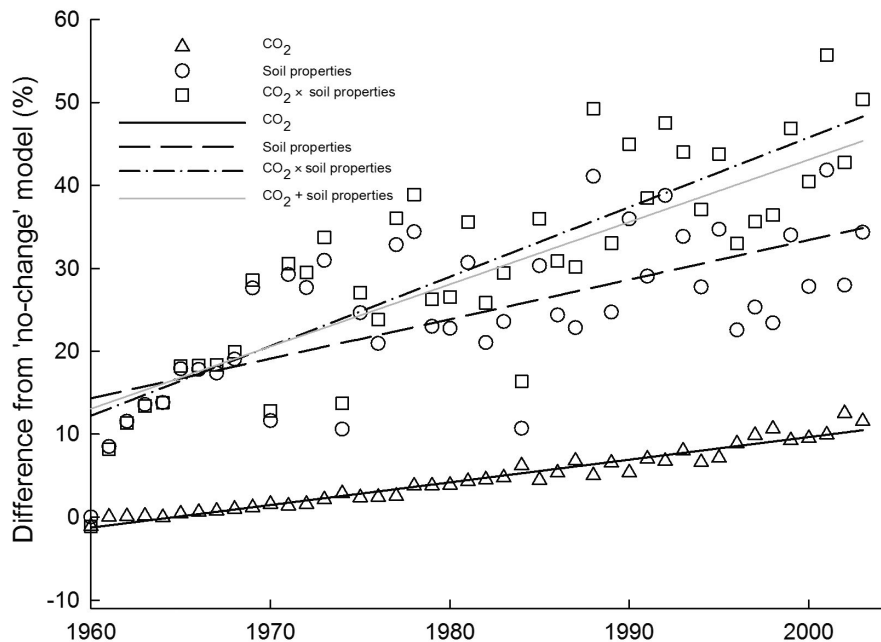

Fig. 7. Simulations of spring net herbage accumulation (NHA) using different model formulations (see Table 1). The values are comparisons between the 'no-change' model (where climate, soil properties and CO_2 were kept constant) and model runs where CO_2, soil properties, or both ($CO_2 \times$ soil properties) were allowed to change. The lines are linear regressions. The grey regression line is from the sum of the individual main effects of CO_2 and soil properties ($CO_2 +$ soil properties), i.e. the additive case
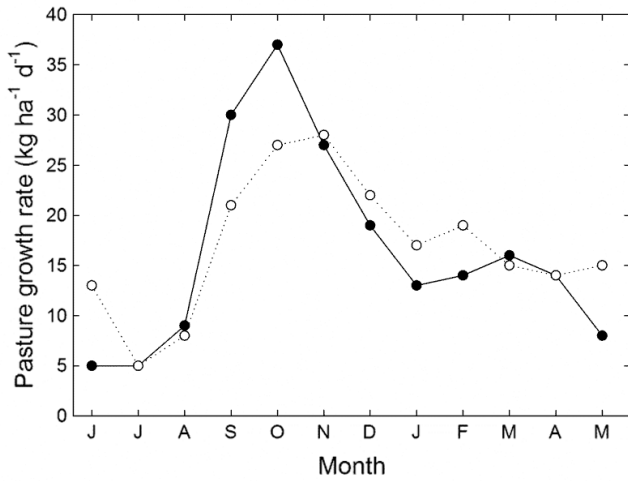
Fig. 8. Seasonal patterns of growth at Winchmore (study site; solid symbols) (Rickard & Radcliffe 1976) and Flock House (site of the New Zealand free air carbon dioxide enrichment experiment, open symbols) (Radcliffe 1976)
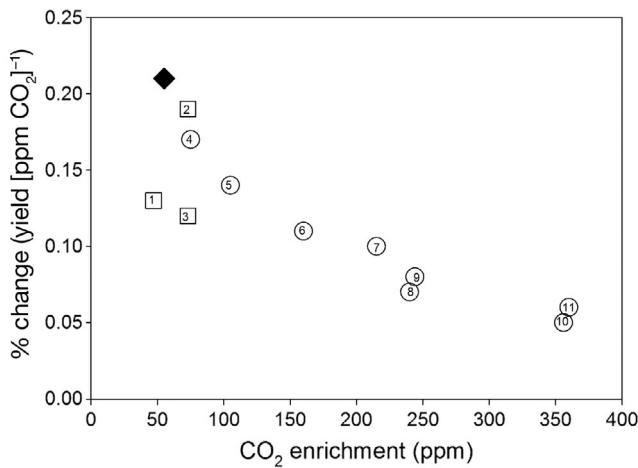

Fig. 9. Response to CO_2 from long-running grassland experiments and for some crops calculated from historical data. (◆) Present study; (□) other historical analyses for (1) wheat (Lobell & Field 2008), (2) soybean and (3) maize (McGrath & Lobell 2011); (O) experiments (details in Table 4). Note that the historical estimate from this paper refers to the CO_2 fertilisation effect in spring only, while the other estimates are for an annual response

some value. It is also worth noting that the historical estimates do not suffer from any 'step-change' effects (Klironomos et al. 2005) that might have an influence on experimental systems, i.e. an initial response to a sudden application of elevated CO_2 that does not represent the long-term effect. The similarity in the historical estimates and the result from the NZFACE is a valuable outcome as it means there can be some confidence that the NZFACE is providing a 'real' CO_2 response and therefore that detailed studies on

mechanisms in the experiment can be viewed as relevant to the future response of pasture ecosystems in New Zealand.

We observed changes in rainfall (marginally significant) and soil properties; as these drivers often interact with CO_2—see examples for rainfall in Morgan et al. (2004b) and soil fertility in Reich et al. (2006)—we anticipated that we might identify interactions that were important in explaining changes in NHA. There was no evidence from the regression approach or from the simulation modelling of any rainfall × CO_2 effect; this may reflect the fact that we were only considering the spring period when soil moisture deficits were infrequent, but further analysis would be necessary to confirm this. The regression analysis did not identify a CO_2 × soil total N interaction, because these both increased at similar rates and their effects could not be separated; however, the modelling showed a very strong soil effect (Table 1). Because the combined model (CO_2 × soil properties) had a greater effect than just adding the main effects of CO_2 and soil properties (Fig. 7), we can infer an interaction between CO_2 and soil properties—in this case a positive interaction that increased over time. As plant responses to CO_2 are sensitive to soil N supply (Reich et al. 2006), we assume the interaction is likely based on increasing N availability over time, as suggested by an increasing total soil N content (Fig. 6). The availability of N for plant growth at elevated CO_2 has been found to both increase (Dijkstra et al. 2008) and decrease (Schneider et al. 2004, Hovenden et al. 2008, Newton et al. 2010) in experiments. Decreases are less likely where N inputs are maintained either through fertiliser application or by biological nitrogen fixation (Hu et al. 2006), as was the case at the Winchmore site. We have previously shown that simulations of grassland responses to CO_2 are very sensitive to the legume content (Li et al. 2014), hence the decision to use the measured legume content in the modelling for this study. Further study of other sites varying in soil N availability would be necessary before any general conclusions can be drawn about historical CO_2 × soil interactions.

It would be ideal if we could repeat this study at other sites in New Zealand, both to confirm the results found here and to build up a picture of national historical changes in production. Unfortunately, although there are historical records of pasture production from other sites, none of these datasets runs for the extended period of the Winchmore trial. However, as we have some confidence that the model would be able to simulate NHA at other sites (Li et al. 2011) it should be possible to run the model at sites

Table 4. Details of experiments illustrated in Fig. 9. The numbers in column 1 correspond to those on the figure. FACE: free air carbon dioxide enrichment; SACC: screen-aided CO_2 control; OTC: open-top chamber

	Ecosystem	Duration (yr)	Enrichment system	CO_2 levels Ambient	CO_2 levels Elevated	Reference for site description	Reference for biomass response if different
4	Permanent pasture; 1.1 g N m^{-2}, legume <2% yield, *Arrhenatherum elatius*, *Holcus lanatus*; 600 g m^{-2} yr^{-1}; Germany	5	FACE	370 (1997)	+20% ambient	Kammann et al. (2005)	
5	Permanent pasture under grazing; maintenance applications P, K and S fertiliser; legume-based; C3 and C4 grasses and forb; 800 g m^{-2} yr^{-1}; New Zealand	11	FACE	370	475	Newton et al. (2006)	P. C. D. Newton & M. Lieffering unpubl. data
6	Native pasture; nutrient poor; C4 and C3 species very diverse; 560 g m^{-2} yr^{-1}; Australia	7	Mini-FACE	380	540	Hovenden et al. (2006)	M. J. Hovenden pers. comm.
7	Shortgrass steppe previously grazed; *Bouteloua gracilis* (C4), *Pascopyrum smithii*, *Stipa comata*; 100 g m^{-2} yr^{-1}; USA	4	Mini-FACE	385	600	Morgan et al. (2011)	J. Morgan pers. comm.
8	Newly sown; *Lolium perenne* monoculture; + 56 g N m^{-2}; 1200 g m^{-2} yr^{-1}; Switzerland	10	FACE	360	600	Schneider et al. (2004)	
9	Permanent pasture previously grazed; nutrient poor; *Bromus erectus*; 350 g m^{-2} yr^{-1}; Switzerland	6	SACC (a variation on OTC)	356	600	Niklaus & Körner (2004)	
10	Tallgrass prairie previously winter grazed; C4 and C3 species; 700 g m^{-2}yr^{-1}; USA	8	OTC	356 (1989)	712 (2 × amb)	Owensby et al. (1999)	
11	Shortgrass steppe previously grazed; *Bouteloua gracilis* (C4), *Pascopyrum smithii*, *Stipa comata*; 100 g m^{-2} yr^{-1}; USA	5	OTC	360	720	Morgan et al. (2004a)	

where long-term climate data are available, perhaps using the short run of pasture data at these sites as 'spot' checks on model performance.

There are aspects of the model performance that, while not affecting the current analysis, do bear further scrutiny. In particular, the inability of the model to capture the full range of interannual variability in NHA; while it does not concern us if we are simply looking at mean responses, this does become important if the object of the study is to examine changes in variability over time. Variability in NHA is a significant issue for farm management (Smit et al. 1996, White et al. 2010) and is expected to be a dominant influence under climate change (Li et al. 2014). The second issue is the difficulty the model shows in simulating actual changes in legume content. This is not surprising given the complex cycles that legumes exhibit in mixtures with grasses (Schwinning & Parsons 1996), but it does present a problem where the actual legume content is unknown. This is clearly an important issue for further study.

As a detection and attribution study the CO_2 effect, as shown by both the statistical and modelling ap-

proaches, appears to satisfy the criteria to add this study to the short list of detection and attribution studies in managed ecosystems. On the detection side the analysis identified a CO_2 response, and this is supported by our mechanistic understanding of the biological responses of the pasture and by independent experimental evidence from the NZFACE. On the attribution side, the atmospheric concentration of CO_2 is increasing as a result of human-produced emissions (Solomon et al. 2007), thus satisfying the requirement that the driver of change in the biological system should have an anthropogenic origin. As regards the effect of rainfall, while the statistical approach did identify a (weak) relationship between rainfall and NHA — a relationship that has sound biological support — and while there was an increasing trend in rainfall over time, it is not possible to make a full attribution, as the cause of the increasing rainfall pattern, though consistent with general trends for the west coast of New Zealand (Griffiths 2007), cannot be formally identified as a consequence of change in greenhouse gas concentrations and therefore of anthropogenic origin.

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