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OBSERVED AND MODELLED CARBON FLUXES AT A GRAZED SITE WITH CO_2 ENRICHMENT

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Introduction

Grazed grasslands are one of the most important providers of food and fibre (e.g., Asner et al., 2004), and their future productivity is closely aligned with the shifting environmental conditions under a changing climate. Of particular interest is their response to increasing atmospheric CO_2 concentration (Toreti et al., 2020; Walker et al., 2021). Experimental studies of the response to increasing CO_2 are mostly using Free-air CO_2 enrichment (FACE) approaches (e.g. Ainsworth and Long, 2005; Leakey et al., 2009). In FACE experiments, intact plant communities are exposed to elevated CO_2 concentrations.

In pastoral agriculture, the inclusion of animal grazing provides particularly important interactions through defoliation and the export or return of carbon and nutrients in faeces and urine that constitute major carbon and nutrient fluxes in the system with important consequences for productivity and soil organic carbon (SOC) stocks. Ultimately, SOC under pastoral production is both directly affected by a photosynthetic response to elevated atmospheric CO_2, but also indirectly by the partitioning of carbon between plants and the soil (e.g. Kirschbaum et al., 2017). The New Zealand FACE experiment, therefore, provides a unique opportunity to comprehensively study CO_2 responses in a grazed pastoral system (Newton et al., 2014). In this grazed-grassland system, plants have been exposed to elevated CO_2 for over two decades.

The objectives of the present study were: 1) compare observed response patterns to CO_2 enrichment on above-ground biomass and SOC with simulations by two ecosystem models: CenW and APSIM. We used two models to derive a more generic understanding of expected responses; and 2) compare the performance of the two ecosystem models that have previously been used to model various aspects of the performance of New Zealand's grazed pastures.

Materials & Methods

The New Zealand FACE site was established in 1990 near Bulls in the Manawatu region (Newton et al., 2014). The site was fertilised annually with P, K and S but not with N, thus relying entirely on N fixation by legumes. The site has 6 circular plots ("rings") with 12-m diameters. Around the CO_2 treated rings, 24 vertical pipes released carefully controlled amounts of CO_2 to maintain CO_2 concentrations at the centre of each ring to set target values. CO_2 enrichment commenced in June 1997 (Fig. 1). Initially, CO_2 concentrations were increased from the ambient concentration of about 360 ppm to 475 ppm in October 1997. As the ambient concentration kept increasing over the years, the target concentration was further increased to 500 ppm in December 2013 to maintain a similar difference between ambient and elevated CO_2 concentrations.

The pastures were rotationally grazed by "dry" (non-gravid, non-lactating) and mature (i.e. minimal weight gain, if any) sheep that were contained within each ring by an electric fence. Grazing was usually initiated when estimated herbage mass reached 1800-2000 kg dry matter (kgDM) ha^{-1}. Typically, 3 or 4 sheep grazed for about 3 days. Sheep were removed when pasture biomass had been grazed down to 800-1200 kgDM ha^{-1}. There were typically 7 - 12 grazing events per year. Further details have been given by Newton et al. (2014).

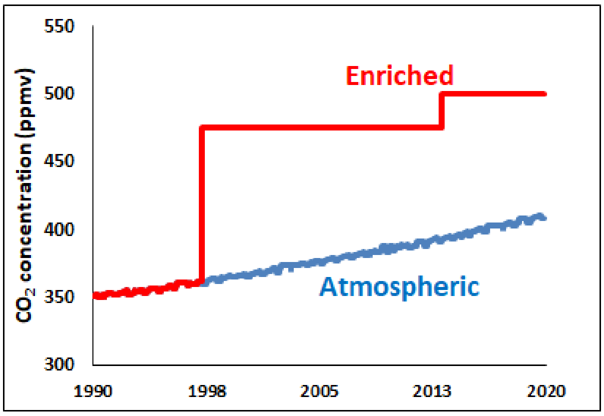

Figure 1*: Atmospheric CO_2 concentration (in blue) and set target CO_2 concentrations (in red) at the study site from 1990 to the end of the simulation period (31 Dec 2020).*

From October 1997 to July 2010, and from October 2015 to November 2021, retained biomass above 2 cm height was recorded before and after each grazing event. The amount of pasture consumed by grazing animals was then calculated as (pre-grazing mass) – (post-grazing mass).

Modelling Details

The simulations shown in the following are based on independent and parallel simulations with the simulation models CenW vers. 6.0 and APSIM 'Next Gen'.

CenW

CenW (carbon, energy, nutrients, water) version 6.0 models the system's major carbon, energy, nutrient and water fluxes (Kirschbaum, 1999; Kirschbaum et al., 2020). The SOC routines of the model are based on the CENTURY model (Parton et al., 1987) with the modifications described by Kirschbaum and Paul (2002). The model includes all major ecosystem processes: photosynthetic carbon gain by plants and losses through both autotrophic plant respiration and heterotrophic respiration by soil organisms and grazing animals. These fluxes are modified by temperature, nitrogen availability and water status. The model contains a fully integrated nitrogen cycle.

The model contains a fully coupled water cycle, with soil water availability being an important productivity constraint over the summer months. Total evapotranspiration is modelled by separately modelling canopy evaporation (after rain), soil evaporation and plant transpiration using the Penman–Monteith equation, with canopy resistance used in the calculation of transpiration rate explicitly linked to photosynthetic carbon gain. In past work, model simulations were compared against available observations, especially eddy-covariance measurements, at a range of sites, with generally very good agreement under a wide range of soil, climatic and management conditions (e.g. Kirschbaum et al., 2020).

APSIM

The second model was the APSIM 'Next Gen' (Agriculture Production System Simulator) model originally developed by Keating et al. (2003). In APSIM, a number of modules are linked to provide the required outputs. The relevant modules for this exercise are the climate and plant, soil water and nutrient dynamics and manipulation of grazing management. The main processes used to simulate pasture species growth in "AgPasture" are given by Li et al. (2011). "AgPasture" has been validated previously using data from the NZ-FACE experiment and was shown to adequately simulate both intra- and inter-annual variations in dry matter response to elevated CO_2 albeit with an overprediction of the CO_2 response (Li et al., 2014).

Here, we used the updated version of APSIM (APSIM Next Gen) rather than the APSIM 7.X version used by Li et al. (2011, 2014).

Modelling Protocols

Soils were parameterised based on the observations reported by Li et al. (2014). For the periods when grazing records were available, modelled biomass was reset to observed biomass after each grazing event. For the periods when no grazing records had been recorded, the model used an automatic grazing routine that initiated grazing when set biomass thresholds had been reached, and animals were then assumed to graze biomass down to set biomass residuals. These thresholds were set based on the observed average thresholds over the periods when grazing had been recorded, set to 1800 kgDM ha^{-1} for the commencement of grazing and a residual threshold of 800 kgDM ha^{-1} at the end of the grazing period. This automatic grazing routine was run for the ambient treatment, with set dates used for ambient and elevated plots.

The models were then parameterised through manual adjustment of specific parameters supplemented by automatic parameter optimisation routines that modified selected parameters to minimise the residual sums of squares of the difference between available observed and modelled data. Available observations consisted of soil data and estimated pasture biomass before and after grazing over the periods from October 1997 to July 2010, and from October 2015 to November 2020. Measurements consisted of biomass cuts above a height of 2 cm.

We used consistent sets of parameters throughout the simulation period from the commencement of the experimental period in 1990 through to the end of 2020 and for both ambient and elevated CO_2. Differences in modelled rates between sites thus resulted from differences in environmental conditions. Since both ambient and elevated-CO_2 sites were run with the same soil parameters, experienced identical weather conditions and were grazed on the same days, any modelled differences could be directly attributed to the system responses to the different CO_2 conditions. Agreement between observed and modelled data was assessed by regression analysis and calculated model efficiencies (Nash & Sutcliffe, 1970).

Results

Figure 2 shows the observed and modelled values of biomass growth rates and removal through grazing recorded from 1997 with the commencement of CO_2 enrichment up to 2009, followed by a five-year break, and then from 2015 to the end of the experiment in 2020.

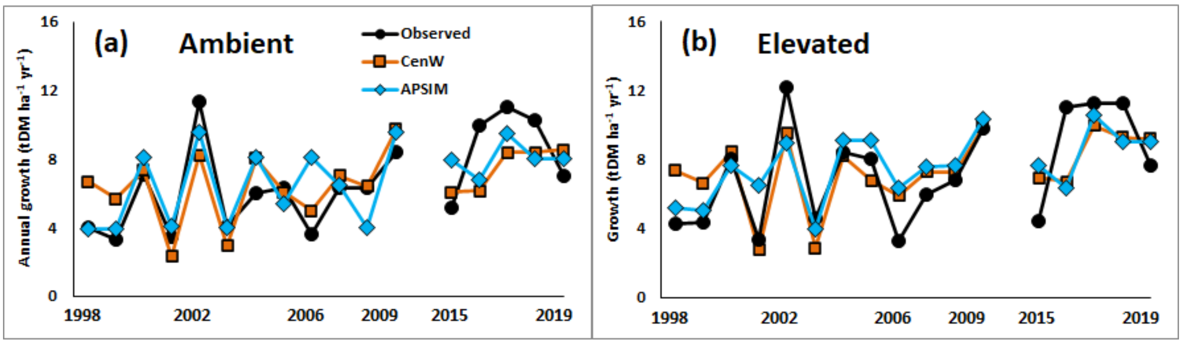

Figure 2: Observed and modelled annual above-ground biomass growth rates with time under ambient (a), and elevated CO_2 (b).

Observed annual above-ground growth rates under ambient CO_2 concentrations under ambient CO_2 fluctuated between less than 4 and up to about 12 tDM ha^{-1} yr^{-1} (Fig. 2), driven by year-to-year differences in weather conditions. The year 2002 had particularly good growth conditions, flanked by years with poor growth conditions. The observed rates under elevated

CO_2 (Fig. 2b) were slightly higher than rates under ambient CO_2 (Fig. 2a) but followed similar interannual patterns.

These rates and patterns were generally well modelled by both CenW (Figs. 2, 3a) and APSIM simulations (Figs. 2, 3b). The simulations broadly followed the same year-to-year variations as the observations, covering both good and bad production years (Fig. 2), leading to good agreement between modelled and observed values close to a 1:1 line. Model efficiencies were 0.51 for the CenW simulations (Fig. 3a) and 0.48 for the APSIM simulations (Fig. 3b).

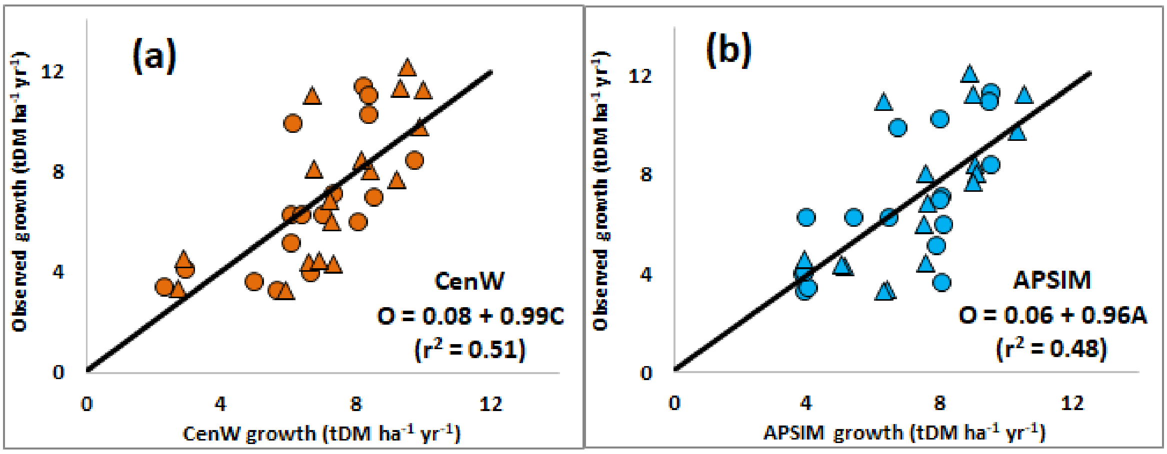

Figure 3: Observed vs modelled annual biomass growth rates modelled by CenW (a) and APSIM (b). Comparisons are shown for ambient (●) and elevated CO_2 (▲). Model efficiencies were 0.51 for CenW and 0.48 for APSIM.

The comparison between observed growth under ambient and elevated CO_2 makes it possible to calculate the growth enhancement by elevated CO_2 from either the observed or modelled data. The average response of CenW-modelled and observed data was nearly identical (dashed and solid lines in Fig. 4), but there was little correspondence in the individual annual enhancements in different years. In particular, there was no consistent seasonal pattern observed in CenW-modelled growth enhancements by elevated CO_2 (Fig. 4b). APSIM simulated CO_2 growth enhancement by about 18% (available only for annual values; Fig. 4a) which was thus slightly higher than the observed enhancements or those modelled by CenW.

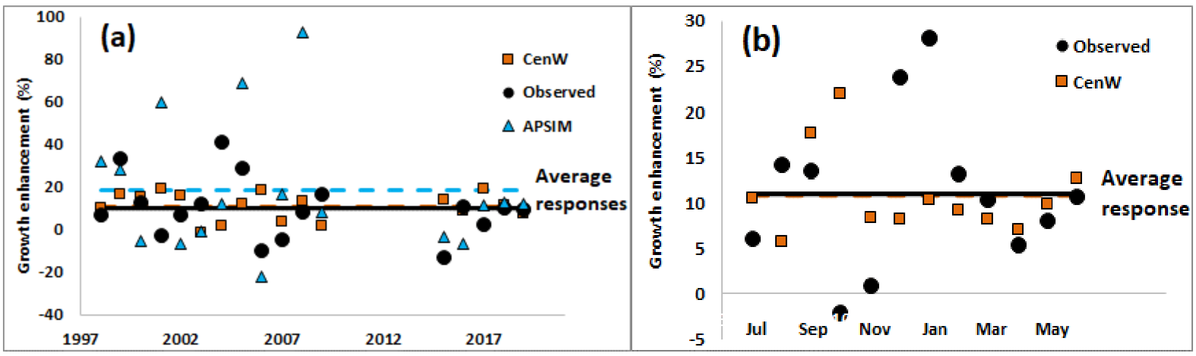

***Figure 4**: Observed and modelled annual (a) and seasonal (CenW only) (b) growth enhancement by elevated CO_2. The horizontal lines show the average enhancements in the observed (solid lines) and modelled data (dashed lines; orange: CenW; blue: APSIM).*

On the whole, there was good correspondence between observed and modelled data, including their absolute magnitude and inter-annual growth patterns (Fig. 2) and the average response to

CO_2 enrichment (Fig. 4). It is not clear to what extent any discrepancies corresponded to model deficiencies or were due to the limitations of the available observations.

Soil organic carbon changes

Having confirmed that the simulations for pasture growth largely matched the observed response to climatic factors and CO_2 enrichment, it became possible to look at some patterns of particular interest that could not be assessed, or only incompletely, through experimental observations, especially trends in SOC.

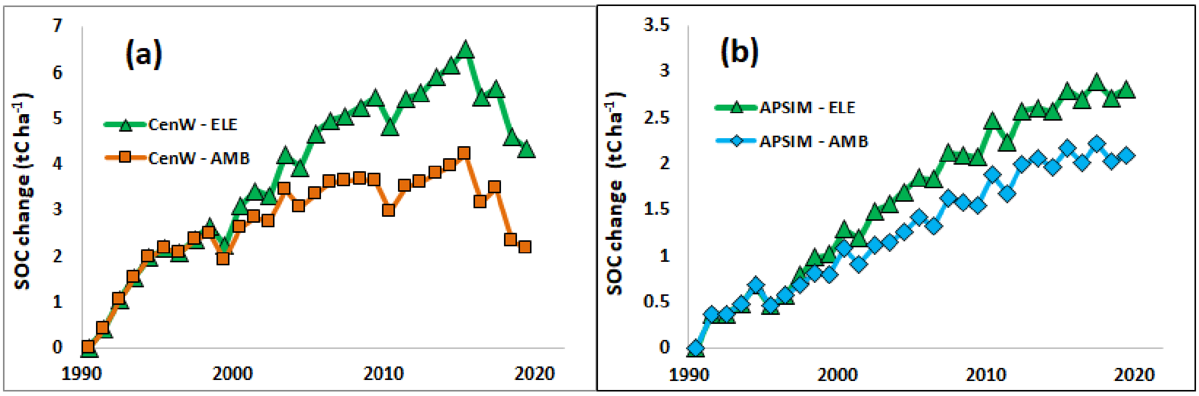

***Figure 5**: Changes in SOC under ambient and elevated CO_2 modelled by CenW (a) and APSIM (b). CO_2 enrichment commenced in 1997, hence modelled SOC under the different treatments were identical before 1997.*

The simulations by both models suggested that SOC increased slightly over the 30-year experimental period under the influence of increasing ambient CO_2 concentration, and further in response to elevated CO_2 (Fig. 5). Both models showed increases under ambient CO_2 by about 2 tC ha^{-1} and further increased under elevated CO_2 by about 2 tC ha^{-1} by CenW (Fig. 5a) and less than 1 tC ha^{-1} by APSIM (Fig. 5b).

Measurements of SOC taken in 2020 showed no significant differences between ambient and elevated CO_2 treatments, but considerable within-treatment variability could have hidden any treatment differences if there were any. The modelling suggested only slight enhancements of SOC stocks that would be very difficult to experimentally confirm due to the typical high variability in observed SOC.

The data also show the importance of considering the fate of any grazed biomass. Measurement had been collected either from sites with normal patterns of treading and excretal returns after grazing or from sites without treading and excretal returns. In measurements with residues retained on-site, SOC values were about 10 tC ha^{-1} higher than under treatments without treading and excretal returns (Fig. 6).

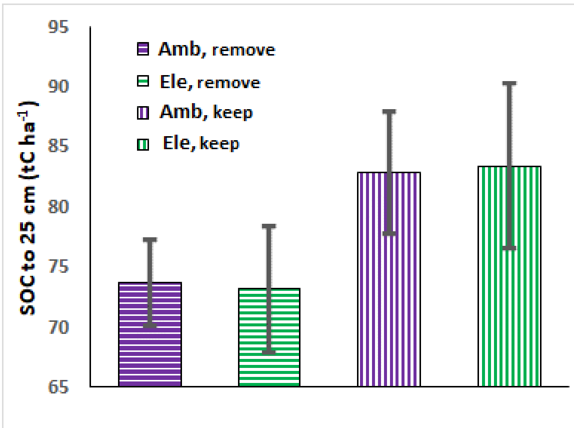

Figure 6: Observed SOC under ambient and elevated CO_2 and with treading by animals and excreta either removed or retained on site. Measurements taken in 2020. Data show means and 95% confidence intervals.

Discussion

The NZ FACE site was established to study the response of ecosystems to elevated CO_2. Over the 23 years of CO_2 enrichment, photosynthetic carbon gain was modelled to have increased by about 10% (data not shown). That was based on the basic photosynthetic response to elevated CO_2 that were further modified through interactions with temperature, soil-water and nitrogen availability. This extra carbon gain increased harvested biomass by about 10% (Fig. 4). The simulations also suggested slight SOC increases by an average of 50-100 kgC ha^{-1} yr^{-1} (1-2 tC ha^{-1}) over the 23 years of CO_2 enrichment. Such changes are below the detection limit given the typically large intra-site SOC variability (Fig. 6). Observations gave a divergent picture of trends at the site. While no significant SOC changes were observed in recent sampling (Fig. 6), Ross *et al*. (2013) had previously reported increasing SOC contents in the top 5 cm over the first ten years under the elevated CO_2 treatment at the site.

Overall, the modelled outputs of both models of above-ground dry matter production broadly matched the observed data (Fig. 3). The APSIM simulations showed slightly stronger CO_2 stimulation than was apparent in the observations (Fig. 4a). The CO_2 stimulation modelled by CenW more closely corresponded to the observed stimulation. This may be related to CenW simulating larger SOC increases than APSIM, with APSIM simulations channelling a larger proportion of extra photosynthetic carbon gain to biomass production than CenW, leading to APSIM modelling a larger biomass response but reduced SOC response than the CenW simulations. However, the extent of year-to-year variability in both modelled and observed rates make it difficult to draw firm conclusions about the extent of productivity enhancements.

Our comparisons indicated that the models captured and reproduced the key processes controlling pasture production at the NZ-FACE site and their responses to elevated CO_2. The work presented here, thus, shows an overall consistent picture. Biomass production was enhanced by elevated CO_2 to the extent expected based on theoretical expectations as shown through good correlations between experimental observations and simulations by two independent ecosystem models. The good correlation included matching the overall average production rates, response to interannual variations in production rates in response to varying weather conditions. The extent of productivity enhancements under elevated CO_2 were also closely matched for CenW simulations while APSIM predicted enhancements slightly greater than the observed enhancement.

Various subtler effects could have also played a role. Animals grazing plots under elevated CO_2 left larger biomass residuals uneaten, estimated as 900 kgDM ha^{-1} under elevated CO_2 instead of 800 kgDM ha^{-1} under ambient CO_2 (data not shown). Allard *et al*. (2005, 2006) found higher rhizodeposition and root turn-over under elevated CO_2, and Yeates *et al*. (2003) reported increased damage from root-feeding nematodes under elevated CO_2 with consequences for root growth and functioning. Terrer *et al*. (2021) also showed the importance of carbon-allocation effects in a literature review of CO_2 enrichment studies. They found a negative correlation between CO_2 effects on plant production and SOC changes. When CO_2 enrichment led to increased allocation to plant biomass, biomass-growth responses were magnified with lesser responses in SOC and vice versa. To understand any likely response of plant productivity and SOC in any specific system therefore requires an understanding not only of CO_2 responses on plant productivity but also on any possible shifts in the proportion of biomass that can be harvested and removed from paddocks.

In conclusion, soil carbon stocks were observed and modelled to be increased only marginally, or not at all. The simulations suggested slight soil carbon increases by 50-100 kgC ha^{-1} yr^{-1}, which was within the uncertainty range of the empirical measurements. This work suggests that enhanced photosynthetic carbon gain is likely to be primarily evident in greater agricultural productivity with only minor short-term effects on soil carbon.

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