CHANGES IN SOIL CARBON STOCKS OF A NEW ZEALAND GRAZED PASTURE IN RESPONSE TO VARIATIONS IN MANAGEMENT AND ENVIRONMENTAL FACTORS

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Abstract.

Dairy farming is New Zealand's pre-eminent primary industry. It achieves large export earnings but is also responsible for a large proportion of the country's greenhouse gas emissions. One of those greenhouse gases is CO_2, and in order to lower New Zealand's net greenhouse gas emissions, it is important to identify any management options that can lead to carbon sequestration in pasture soils and thereby minimise net CO_2 emissions to the atmosphere. It is equally important to understand what factors could lead to losses of soil carbon from pasture soils and thereby add further to New Zealand's CO_2 emissions.

We addressed these questions by using two years of observations from an eddy-covariance system on a dairy farm in the Waikato that provided estimates of the exchanges of water and CO_2 with the atmosphere. We used CenW 4.1, a process-based ecosystem model, to describe these observations in terms of their biophysical drivers and the interactions between them. Agreement between the model and observations was excellent, especially for evapotranspiration and net photosynthesis, for which 91% and 79% of observed daily variations could be explained.

The validated model was then used to run different scenarios to assess the effects on soil organic carbon of changes in the application of fertiliser and irrigation water, grazing scheduling, differences in plant-internal resource allocation, and changes in temperature and CO_2 concentration. We found that it was important to consider the combined effect of changes in net primary production, the amount of carbon taken off-site through grazing, the proportion of carbon allocated to pools, especially pools in the soil, that facilitates the stabilisation of carbon in organic matter, and any changes in the rate of organic matter decomposition.

Soil organic carbon stocks were positively correlated with rates of fertiliser application and with the rate of water application (rain or irrigation) up to some moderate water application rates. For other changes in key properties, changes in soil organic carbon were often negatively correlated with changes in milk production. That was clearly evident for changes in the grazing regime and in plant root:shoot ratios. Anticipated environmental changes, such as increases in temperature and CO_2 concentration, and both increases and decreases in precipitation from moderate values had either neutral or detrimental effects on soil organic carbon stocks. Milk production was generally more positively affected under most environmental changes.

Key words: CenW, CO_2 concentration, fertiliser, grazing, irrigation, model, temperature

Introduction

Dairy farming is New Zealand's largest export-earning primary-industry sector. The profitability of dairying compared to sheep farming or commercial forestry, in particular, has increased over recent decades, and it has become the dominant primary industry sector (DairyNZ, 2012).

However, dairy farming is also the biggest contributor to New Zealand's net greenhouse gas emissions, with emissions primarily due to nitrous oxide and methane (Kirschbaum et al., 2012; MfE, 2014). Concern also relates to potential losses of soil organic carbon, and Schipper et al. (2007) analysed archived soil samples and reported significant soil carbon losses of 21 ± 18 (95% confidence intervals) tC ha^{-1} from flat dairy pastures in New Zealand. At the same time, grazed pastures in hill country appear to have gained similar amounts of carbon as those lost on flat dairy land (Schipper et al., 2010). In further more refined analyses, Schipper et al. (2014) found that significant losses on flat land were confined to gley and allophanic soils, with no significant differences between dairy and drystock. To date, no readily apparent, and well-substantiated, reasons for either of those patterns have been identified, but they clearly show that soil carbon stocks are not inherently constant, but can be changed through pasture management or environmental changes.

The management of farms has been changing over the last few decades, with much greater use of fertilisers (Parfitt et al., 2012), leading to higher pasture productivity and, together with inclusion of increasing amounts of supplemental feed, have allowed higher stocking rates (MacLeod and Moller, 2006; DairyNZ, 2012). Increasing areas of pasture are also being irrigated. Environment conditions are also changing, with gradually rising temperatures and slow, but persistent, increases in CO_2 concentration (Hartmann et al., 2013). There is interest in understanding how any of these external factors may have changed soil carbon stocks, or whether management can be purposefully modified to increase soil carbon stocks and thereby assist in the task of reducing net carbon emissions to the atmosphere and mitigate climate change.

The challenge lies in understanding the complex array of interacting factors (Fig. 1) that together determine the trajectory of future soil C. Individual external factors may change any or all of the following:

1) the rate of carbon gain of the system, principally through net primary production, but it can also be supplemented through imported feed. A higher rate of carbon gain will make more carbon available for organic matter formation;

2) the proportion of biomass that is harvested and taken off site, thereby making it unavailable for organic matter formation, versus the fraction retained on site and remaining available for organic matter formation. This also affects nitrogen stocks and may thereby have an indirect effect on subsequent productivity;

Figure 1: Conceptual interaction between the different steps and components that together determine soil C stocks.

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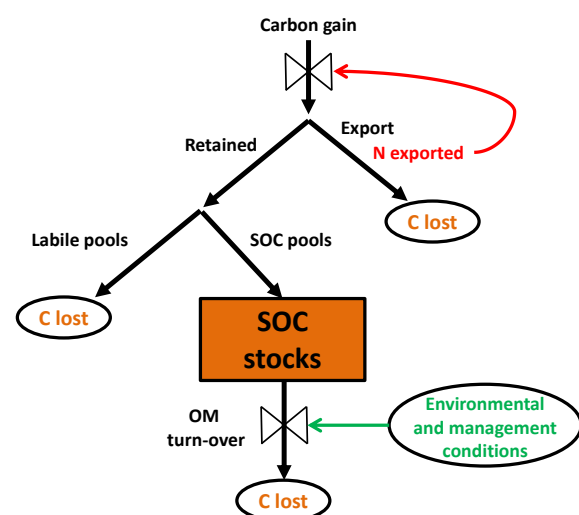
3) the proportion of carbon allocated to labile or more resistant pools. Surface deposition of carbon, for example, can be relatively easily respired without organic matter formation. Soil deposited carbon can more easily be incorporated into organic matter;

4) the specific rate of organic matter decomposition that can changes the rate at which organic matter is lost from the soil.

The challenge lies in describing and quantifying each of these factors and weighing up their combined net effect on soil carbon stocks. In the present work, we have used the ecosystem model CenW vers. 4.1 to explore the carbon storage consequences of different feasible management options. CenW is a detailed ecosystem model that includes all the essential controlling factors of the gas exchange of any kind of vegetated surface and the interactions between these factors (Kirschbaum, 1999). That includes detailed modelling of the soil, plant canopy and animal grazing and follows the interacting cycles of carbon, water and nutrients (Fig. 2).

We tested the model for an intensively studied dairy farm located near Hamilton in New Zealand's Waikato region. (Kirschbaum et al., 2015). We then used the model to study changes in soil carbon stocks in response to any changes in key input variables.

Figure 2: Overview of CenW, showing the major pools and fluxes in the system (modified from Kirschbaum, 1999).

It is important to keep in mind what a model can and cannot do. Any model is essentially just a sophisticated form of combining assumptions and interpretations of the observed reality. We can test it against observations under experimental conditions, and that can build confidence that the actual model implementation provides a set of assumptions and interpretations that are consistent with observations. However, other assumptions could be equally valid in explaining the set of available observations.

This presents a challenge when the model is used to extrapolate to conditions outside the range of observation, which is being done in any kind of scenario analysis. The strength of the model is its grounding in a set of fundamental relationships, such as conservation of mass - that should hold under any circumstances - but other factors are less well constrained, such as assumptions about plant-internal connections between different physiological variables, such as resource allocation to different plant organs. It is necessary to include such inter-connections, because realistic simulations about a wide range of external conditions must include any relevant feedback processes, but it is often difficult to test the veracity of these system-internal interactions that may not be directly observable, especially when the range of observations covers only a narrow range of conditions.

The present simulations use the currently considered best set of assumptions about the functioning of the system, but our scenario analysis would have led to different outcomes if different assumptions about the system had been made that might have been equally adequate in explaining the set of available present-day observations. Modelling is always a work in progress. Models are continuously refined through testing against newer sets of observations. That may force changes in the underlying assumptions, with possible implications for scenario runs. The results shown here are the outcomes obtained using our best current understanding, but that may have to be modified under emerging new knowledge.
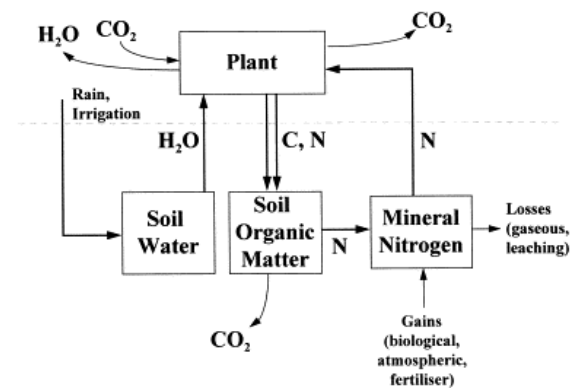
Materials and Methods

Modelling Details

CenW (Carbon, Energy, Nutrients, Water) is a process based model, combining the major carbon, energy, nutrient and water fluxes in an ecosystem as shown in Figure 2 (Kirschbaum, 1999; Kirschbaum et al., 2015). The model's soil organic matter component is based on the CENTURY model (Parton et al., 1987) which was originally developed for pasture systems. The model combines these fluxes to simulate the carbon balance of a system over time. For the present work, we used CenW version 4.1, which is available, together with its source code and a list of relevant equations, from http://www.kirschbaum.id.au/Welcome_Page.htm.

The model runs on a daily time step. Major processes are carbon gain by plants through photosynthesis and losses through autotrophic plant respiration, heterotrophic respiration by soil organisms and respiration by grazing animals. These fluxes are modified through nutrient and water balances. The model contains a fully integrated nitrogen cycle which allowed the testing of the interaction between nutrient gains through fertiliser additions and biological nitrogen fixation and nutrient losses from produce removal, leaching and gaseous losses.

Biological nitrogen fixation was assumed to be inversely proportional to the extent of nitrogen limitation on plant productivity. When nitrogen was completely non-limiting, as it might be with heavy fertiliser additions, biological nitrogen fixation reduces to zero. With lower fertiliser additions, pastures become progressively more nitrogen limited, with biological fixation rates commensurately increasing.

Soil water balances are also modelled in detail and can constitute an important constraint on productivity. Water balances are affected by soil depth and water-holding capacity. Water is gained by rainfall or irrigation and lost through evaporation from the soil surface or wet foliage after rainfall, or through plant transpiration. If soil water exceeds the soil's water-holding capacity, the excess is lost by deep drainage beyond the root zone.

To model grazed pastures, it was essential to appropriately deal with grazing events. At each grazing event, it was assumed that animals consumed 55% of foliage (Pal et al., 2012), of which 50% was assumed to be lost by respiration, 5% as methane (Kelliher and Clark, 2010) and 18% removed in milksolids (Crush et al., 1992; Soussana et al., 2010; Zeeman et al., 2010), with the conversion between carbon and milksolids based on Wells (2001). The remaining 27% was assumed to be returned to the paddock in dung and urine. This separation of fluxes was important for modelling carbon-stock changes as any removed carbon is not available for soil carbon formation.

CenW was used and tested using detailed measurements from an experimental grazed dairy farm in the Waikato region (Scott Farm 37.46°S 175.22°E). The experiment was conducted over 2 years (2008-2009) with continuous measurements of carbon and water fluxes with an eddy covariance tower. The paddocks were predominantly covered with perennial ryegrass (*Lolium perene*) and white clover (*Trifolium repens*), the species that dominate New Zealand's typical pastoral systems. Full details are provided by Mudge et al. (2011) and Kirschbaum et al. (2015).

Statistics

The overall goodness of fit was described by giving model efficiency (*EF*), which was determined as (Nash and Sutcliffe, 1970):

$$EF = 1 - \frac{\sum (y_o - y_m)^2}{\sum (y_o - \bar{y})^2}$$

where y_o are the individual observations, y_m the corresponding modelled values and $\bar{y}$ the mean of all observations.

This statistical measure quantifies both tightness of the relationship between measured and modelled data and assesses whether there is any consistent bias in the model. High model efficiency can only be achieved when there is a tight relationship with little unexplained random variation and little systematic bias.

Scenarios Used

The simulations shown here are all based on the soil and environmental conditions observed at our experimental site in the Waikato. We used an 8-year weather sequence that was used repeatedly for longer runs. That approach ensured representation of inter-annual variability while avoiding any confounding effects by any climate-change signal that might have been present in a longer weather sequence.

Base plant and management conditions were as specified in Table 1, including key environmental variables (CO_2 concentrations

Table 1: Base conditions for the simulations shown here.

Variable	Value
CO_2 concentration	400 µmol mol^{-1}
Annual precipitation	1214 mm yr^{-1}
Fertiliser addition	200 kgN ha^{-1} yr^{-1}
Grazing threshold	2 tDM ha^{-1}
Target root:shoot (high N)	0.96
Target root:shoot (low N)	1.86

and annual precipitation), management choices (fertiliser addition and grazing thresholds) and empirically fitted target root:shoot ratios under nutrient-unstressed and stressed conditions as obtained by Kirschbaum et al. (2015).

The model was run for 50 years under those base conditions which allowed all system properties to come to some pseudo equilibrium state. Conditions were then changed according to specified scenarios as detailed below, and the system was run for a further 50 years under the new conditions. Reported responses for properties other than soil carbon stocks are the average over the final 8 years of those simulations. Reported changes in soil organic carbon are the average rates of change over the full 50-year simulation period under the new conditions.

Fertiliser Addition

The base condition used an annual fertiliser application rate of 200 kgN ha^{-1} yr^{-1}, and we here explored the effect of varying that application rate between 0 and 300 kgN ha^{-1} yr^{-1}. Fertiliser was applied in three annual applications in late summer, early spring and early summer. It was assumed that 25% of applied fertiliser would be lost by volatilisation as ammonia.

Grazing Threshold

To deal with the variable availability of animal feed, we used a flexible grazing routine that assumed that grazing would commence when a certain threshold amount of feed was available and that cows would graze 55% (Pal et al., 2012) of that available feed. The base condition assumed that the feeding threshold was 2 tDM ha^{-1}. We explored the effect of varying that threshold between 500 kgDM ha^{-1} to 3 tDM ha^{-1}, with the consistent assumption that cattle would remove 55% of available feed before being moved off the grazed paddock.

Target Root:Shoot Ratio

Plant biomass allocation was calculated based on the assumption that carbon allocation would be varied by plants towards achieving certain target root:leaf ratios. Those target ratios themselves are assumed to be variable, with more root growth under nutrient-limited conditions, while allocation shifts towards more leaf growth when nutrition is adequate.

Without grazing, plants can generally maintain root:leaf ratios close to any set target values. However, grazing removes foliage while leaving root biomass largely undisturbed. Grazing thus alters root:leaf ratios to greatly exceed their target values. Following grazing, new growth is then preferentially allocated to leaf growth until target root:leaf ratios are met again. Details of this routine are described in Kirschbaum et al. (2015).

Under base conditions, root:leaf ratios were set to 0.96 for nutrient-sufficient conditions and 1.86 for notionally extremely nutrient-limited plants (Table 1) based on the parameter fitting for our experimental site (Kirschbaum et al., 2015). We then explored the effect of changing the non-stressed target ratios over the range from 0.5 to 2, while keeping the ratio of the stressed and unstressed target ratios to that obtained in our parameter fitting (1.94 = 1.86 / 0.96).

These changes essentially correspond to changes in species composition towards species that may naturally grow more or less roots, or changes within the dominant species through plant breeding. This scenario thus does not describe a readily-implementable management change, but explores the potential consequences of a more fundamental change in a system property.

Temperature Change

Temperature affects the rate of soil organic matter decomposition, plant processes through direct physiological effects and indirectly through the rate of water loss in evapotranspiration (e.g. Kirschbaum, 2000). We used the weather conditions observed at our experimental site near Hamilton as the base condition and explored the effect of changes in temperature from a cooling by 1°C to warming by 5°C.

To the extent that warming has indirect effects through changed water relations, it is critically important to consider any changes in the absolute atmospheric humidity. If absolute humidity remains constant while temperature is increasing, it would greatly increase the rate of water loss and dry the soil, with possible effects on plant productivity and organic matter decomposition rates. However, it is likely that atmospheric water vapour will increase with any general increase in temperature so as to maintain a fairly constant relative humidity with warming (Trenberth et al., 2007). This corresponds to maintaining a constant temperature difference between daytime and overnight minimum temperatures.

In practice, this was done by taking absolute vapour pressures from the observed weather record and calculating the dewpoint temperatures corresponding to those observed vapour pressures. Dewpoint temperatures were then changed in line with any given temperature-change scenario, and new absolute vapour pressures were calculated from the adjusted dewpoint temperatures (Kirschbaum, 2000).

Atmospheric CO_2 Concentration

The CO_2 concentration has reached nearly 400 µmol mol^{-1} by 2014 and is increasing further by about 2 µmol mol^{-1} yr^{-1} (Hartmann et al., 2013). We used 400 µmol mol^{-1} as the base condition and explored the effect of varying CO_2 concentration from 300 to 800 µmol mol^{-1}. This covers the approximate range of CO_2 concentrations from pre-industrial values to those that might be experienced by the end of the 21st century.

Rainfall Plus Irrigation

The average annual rainfall at our standard site was 1214 mm yr^{-1} (Table 1), and we explored the effects of the site receiving between half and twice as much as the actually observed annual rainfall. To simulate rainfall less than the standard amount, observed daily rainfall was simply reduced by an appropriate fraction to achieve respective target values.

To simulate rainfall in excess of the standard amount, additional irrigation water was added at weekly intervals to achieve to respective annual target amounts. This approach ensured that rainfall in excess of the standard amount also progressively eliminated any periods of drought. If rainfall had simply been increased by a fractional amount, if would not have prevented droughts from occurring. There are obvious problems in constructing scenarios of water supply since the distribution of any rainfall + irrigation can have a strong bearing on the effectiveness with which any amount of supplied water can be utilised. The specific scenario given here therefore gives only one possible scenario under a given total amount of annual water supply.

Results and Discussion

Model validation

The model was tested against 2 years of daily aggregated eddy covariance data and one year of foliar biomass measurements (Fig. 3). Details of the experiment, the parameter fitting and the challenges of appropriately capturing all carbon losses during grazing events have been described by Kirschbaum et al. (2015). Evapotranspiration was modelled extremely well (Fig. 3a), with a model efficiency of 0.91 for daily comparisons and 0.96 for weekly averaged data in a validation data set. The model was thus able to simulate the interaction between seasonal and plant factors as well as short-term phenomena, such as responses to day-to-day changes in the weather.

Photosynthetic carbon gain was also very well modelled, with model efficiencies of 0.79 and 0.84 for daily and weekly comparisons (Fig. 3b). This covered a wide range of values ranging from near zero during a severe drought period in the first summer of the experiment, low values of about 25 kgC ha^{-1} d^{-1} in the middle of winter and peaks of up to 125 kgC ha^{-1} d^{-1} during summer periods without water shortages Kirschbaum et al., 2015).

Getting agreement between modelled and observed respiratory carbon losses was more problematic. Much of that related to the capture of grazing events that were highly episodic and could release carbon at rates that were an order of magnitude greater than combined plant and soil respiration rates. The challenges inher   ent in the correct capture of these events was described and illustrated in detail by Kirschbaum et al. (2015). Weekly-averaged respiration rates could still be reasonably well described, with a model efficiency of 0.84, while daily respiration rates could be described with a model efficiency of only 0.63, probably owing to the challenge of full capture of all grazing events (Kirschbaum et al., 2015).

As a consequence, the simulation of combined carbon fluxes was not as good as the simulation of carbon gain alone with model efficiencies of 0.54 and 0.56 for weekly and daily values, respectively (Fig. 3c). The adequate modelling of carbon gain and loss with their seasonal dynamics and response to important aspects of pasture management then allowed an adequate description (EF=0.58) of the dynamics of foliar biomass (Fig. 3d). Overall, the comparisons confirmed that CenW is an appropriate tool for describing the key dynamics of grazed pastures and allowed its application for scenario analyses.

Figure 3: Observed versus modelled rates of evapotranspiration (a), gross primary production (b), net ecosystem production (c) and foliar biomass (d). Small symbols in (a) to (c) show daily observations and larger symbols show weekly averaged data. Data in (a), (c) and (d) are shown for a calibration data set with up-arrows and a validation data set with down-arrows. Gross primary production was not explicitly included for model optimisation so that a distinction between calibration and validation data sets would not be relevant. Net ecosystem production is the net CO_2 exchange of the pasture as a whole, with positive values indicated net uptake. The figure has been drawn based on the data of Kirschbaum et al. (2015). "EF" refers to model efficiency, and the subscripts 'd' and 'w' refer to daily and weekly data.
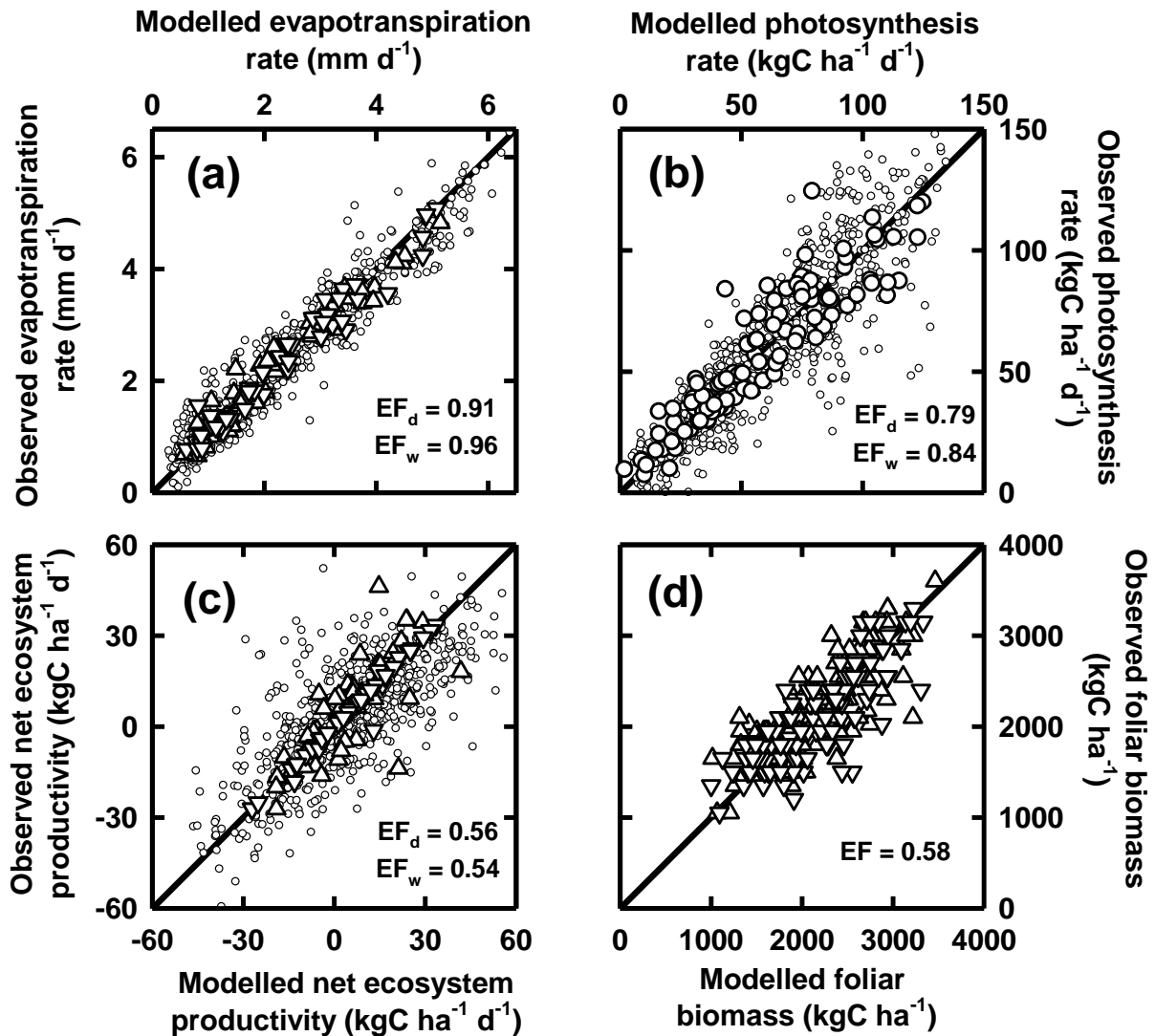
Changed Driving Variables

Having parameterised the model for our experimental site, it became possible to explore the effect of some changes in key driving variables. These are presented and discussed in the following.

Fertiliser Addition

Different fertiliser application rates were consistently correlated with milk production (Fig. 4b) and soil carbon stocks (Fig. 4c) across a wide range of fertiliser addition rates. Milk production constitutes a substantial and ongoing drain of nitrogen from the site. Over time, this lowers available nitrogen resources, and drives the system to a state of lower productivity. This affects not only milk production (Fig. 4b) but also soil organic carbon stocks, estimated here as a difference of about 200 kgC ha^{-1} yr^{-1} between the highest and lowest fertiliser addition rates (Fig. 4c).

The magnitude of the fertiliser effect is controlled through the interplay between rates of nitrogen loss through export in produce, leaching and gaseous losses, and nitrogen gains, principally biological nitrogen fixation. Biological nitrogen fixation is highest in nitrogen impoverished systems (e.g. Ledgard et al., 2009), which can partly, but not fully, compensate for differences in fertiliser application rates. Animal grazing also leads to nitrogen losses both in animal produce and through substantial leaching from urine spots (Haynes and Williams, 1993). Increased feed off-take thereby reduces the site's nitrogen balance that must be replenished through additional fertiliser application.
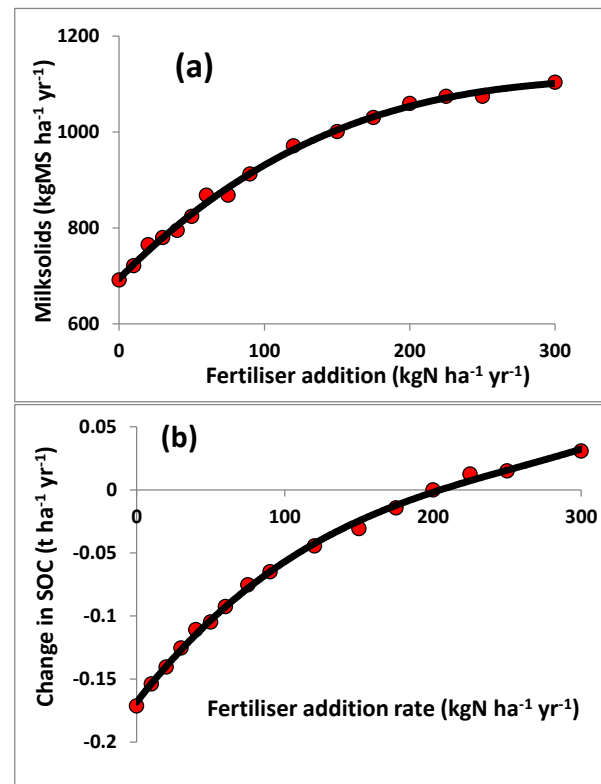
Figure 4: Modelled milksolid production (a) and changes in soil organic matter (b) with different fertiliser addition rate. Milksolid production is shown as the average over the last eight years of a 50-year run, and changes in soil organic matter are shown as the average change over the 50-year simulation period. Lines in the figure are simple polynomials for the visualisation of trends.

Grazing Threshold

Here, we explore the consequence of varying the threshold for the commencement of grazing while retaining the assumption of 55% feed removal for all grazing thresholds (Fig. 5)

The simulations showed a strong effect of the grazing threshold on net primary production from the lowest to intermediate grazing thresholds, with slightly decreasing net primary production at even higher thresholds (Fig. 5a). Foliage is required to fix carbon through photosynthesis, and low grazing thresholds lowered average standing biomass which reduced available photosynthetic surface area and consequently carbon gain. Photosynthetic carbon gain was thus reduced over the whole range of grazing thresholds investigated here (data not shown), but for the higher thresholds, the benefit of gaining more carbon in photosynthesis were outweighed by the dis-benefit of higher carbon losses through autotrophic respiration.

Milk production peaked at a fairly low grazing threshold (Fig. 5b). This was partly driven by changes in net primary production but is further accentuated by the grazing threshold itself, with lower thresholds allowing the capture of a larger proportion of net primary production. When the grazing threshold was high, a large average amount of standing biomass remained in the paddock, leading to carbon losses in respiration and through foliage senescence. The capture of available biomass for animal consumption was thus maximised with a lower

grazing threshold. Large reductions in milk production were then seen both for the lowest and highest grazing thresholds (Fig. 5b).

In contrast, soil carbon stocks increased monotonically across the range of investigated thresholds (Fig. 5c). Since a lower grazing threshold allowed a greater capture of biomass for animal feed, it thereby reduced the amount available for organic matter formation. Grazing not only removed carbon off-site in produce (18% of ingested feed), but it also enhanced carbon losses in animal respiration (50% of ingested feed; Soussana et al., 2010; Zeeman et al., 2010) and methane emissions (5% of ingested feed; Kelliher and Clark, 2010). Overall, trends in milk production and soil organic carbon stocks went largely in opposite directions other than for very low grazing thresholds.
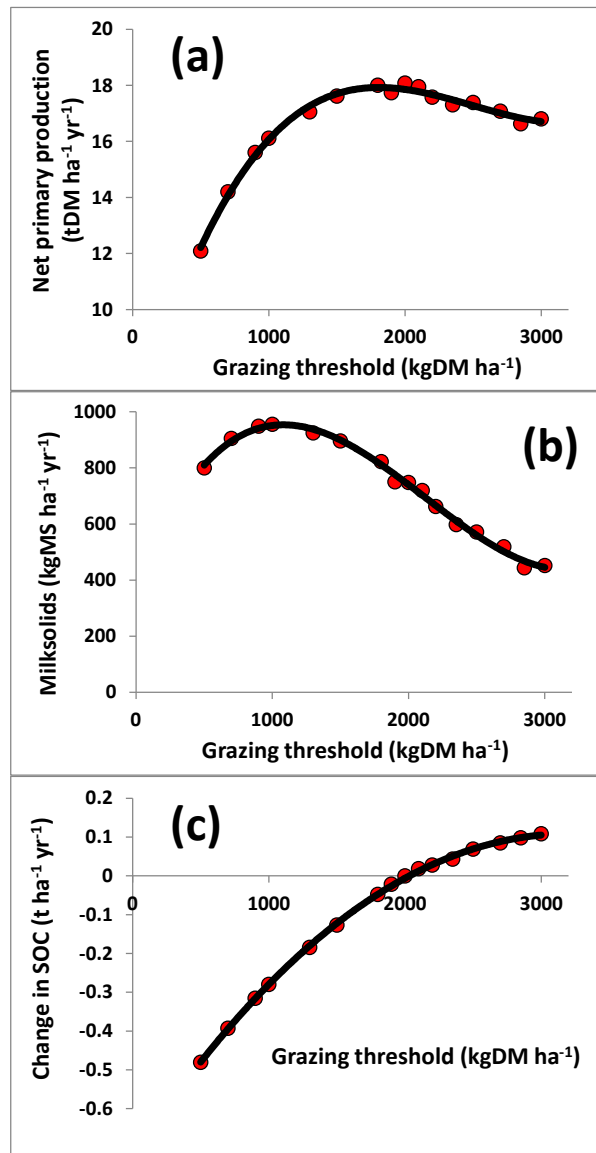
Target Root:Shoot Ratio

The simulations suggested that milk production could be strongly affected by changes in the root:shoot allocation ratio (Fig. 6b), which is largely driven by a strong effect of the root:shoot ratio on total net primary production (Fig. 6a). In addition, the changing ratio of biomass allocation itself even further extends the effect on milk production. Pastures with a high root:shoot ratio not only fix less carbon than pastures with lower ratios, but proportionately less of that smaller amount of carbon is allocated to foliage that can be grazed.

At the same time, the changes in soil organic carbon are remarkably small, with changes of less than 0.1 tC ha^{-1} yr^{-1} at all but the most extreme ratios. Soil carbon is at a maximum at an intermediate target root:shoot ratio because at low root:shoot ratios, too little

Figure 5: Modelled net primary production (a), milksolid production (b), and changes in soil organic matter (c) for different grazing thresholds. Other details as described in the Legend of Fig. 4.

carbon is allocated below ground with most carbon grazed and removed off-site. With higher root:shoot ratios, the reduced productivity reduces the amount of carbon that is available for organic matter formation. Soil carbon changes are so small because of the compensating changes in net primary production (Fig. 6a) that decrease with increasing ratio and the increasing below-ground allocation that obviously increases with the target ratio. With the two key processes changing in opposite directions, there is relatively little overall change.

Plants need roots to obtain water and nutrients from the soil, and leaves to fix carbon, but from a fodder production point of view, it could be beneficial if plants could allocate less of their resources to roots and more to leaves that can be grazed and turned into economic
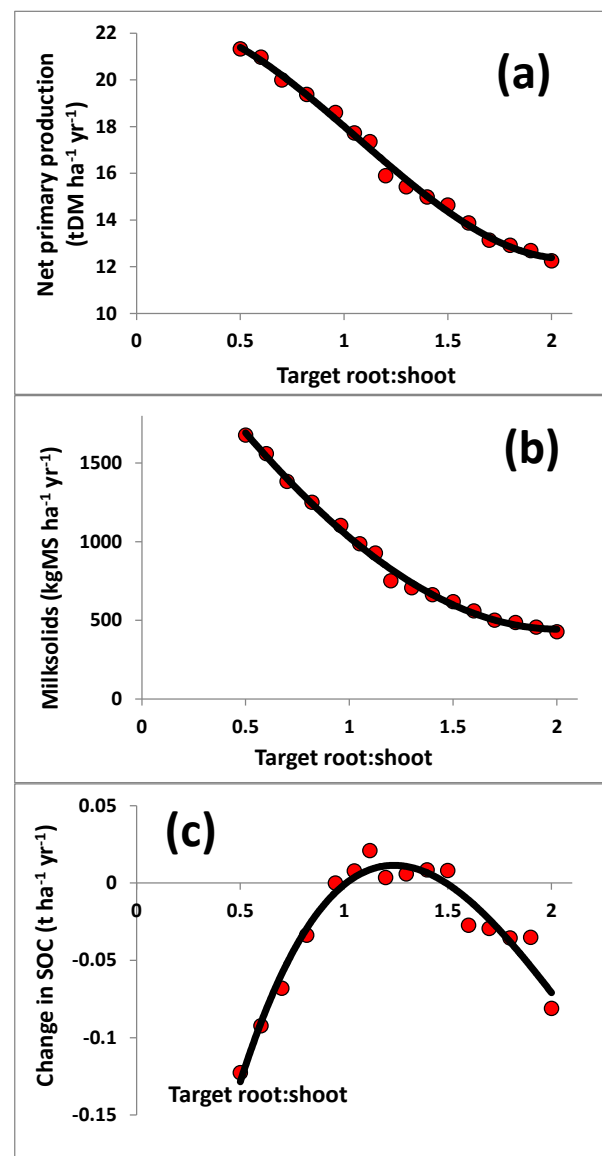
produce provided that there are enough roots for effective water and nutrient uptake. The simulations here are based on systems limited by water or nitrogen limitations. Both of these are very mobile in the soil (e.g. Wilkinson and Lowrey, 1973) so that sufficient water and nutrient uptake could be achieved with a much smaller root system. It means that whole-sward productivity could be maximised with less investment in root growth. However, systems limited by phosphorus, which is much less mobile in the soil (e.g. Wilkinson and Lowrey, 1973), may require greater root mass in the soil to adequately access available resources for optimum sward growth.

Increased sward productivity with less root allocation may thus not eventuate in phosphorus-limited systems. However, the modelled effects are likely to be only realistic under conditions where the primary non-photosynthetic limitations of net primary production are through water and nitrogen availability. Greater proliferation of roots is of little use for overall pasture production because both water and nitrogen (in NO_3^- form) are very mobile in the soil and their availability and uptake would not be increased by greater proliferation of roots. Increased rooting depth might well be beneficial but greater abundance of roots in the primary upper soil-layer root zone would not be. This situation would change somewhat if the primary limitation were phosphorus or other less-mobile elements in the soil, but the simulations shown here are based on limitation by nitrogen as the primary mineral limitation.

And one may further ask why pasture plants have such extensive root systems if it is of little benefit for overall production. That is where optimality between individual-plant and total swards needs to be considered (see King, 1993). While total swards would not obtain increasing amounts of nitrogen or water through greater root proliferation, any individual plants with more roots will nonetheless obtain a greater share of the available resources, thus forcing individual plants into a growth strategy that would be less than optimal for stands as a whole (King, 1993).

Figure 6: Modelled net primary production (a), milksolid production (b), and changes in soil organic matter (c) for different root:shoot allocation ratios.

The simulations here also retain a constant relative depth distribution with changing overall root allocation. There may, however, be benefits for plants to access deeper water in the soil during drought periods, but that is related to the vertical distribution of roots in the soil rather than the proportional allocation of plant resources to roots versus shoots. These simulations

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thus provide no information, and do not discount the possibility, of any possible positive effects if roots could grow to greater depths than their typical more shallow growth habit.

Temperature Change

Peak production was modelled for a warming by about 1 °C, but for moderate temperature changes between -1 to +3 °C, changes in net primary production were only slight (Fig. 7a). Productivity decreased more strongly for even larger temperature increases (> 3°C) due to a combination of direct physiological temperature effects and indirect effects through increased rates of water use that could eventually lead to increased water stress.

Milk production showed a trend similar to that for net primary production (Fig. 7b), but it was even slightly more strongly affected by warming because of seasonal shifts in productivity. With warming, productivity was reduced in summer and autumn, mainly due to increasing water stress, while production was increased in winter and spring (data not shown). Overall, these shifts caused a slight reduction in the efficiency with which fixed carbon could be utilised in grazing and milk production. Any possible direct effects of heat stress on cow metabolism were not included in these simulations.

At the same time, while the total amount of carbon gained did not change much with temperature (Fig. 7a), soil organic carbon stocks nonetheless decreased monotonically with increasing temperature. This was principally related to the stimulation of organic matter decomposition rates with increasing temperature, which led to an increasing rate of carbon loss from the system (Fig. 7c). That rate of loss was even further steepened at the highest temperatures when lowered productivity further added to the adverse effects on soil carbon dynamics.

Figure 7: Modelled net primary production (a), milksolid production (b), and changes in soil organic matter (c) in response to changing temperature. Simulation runs as described in the text and the Legend of Fig. 4.
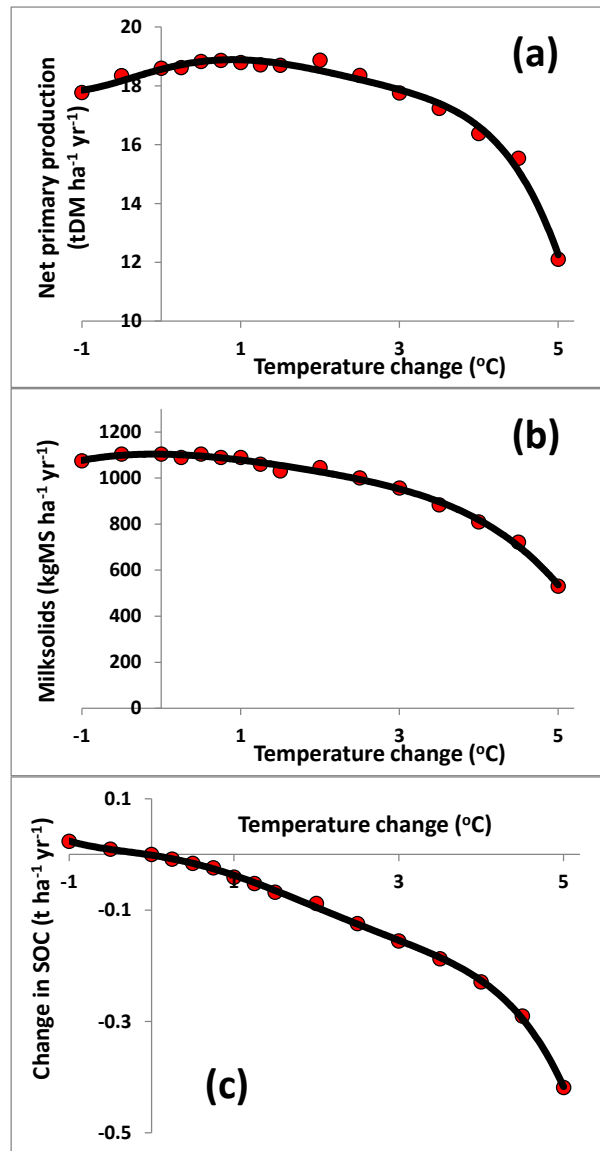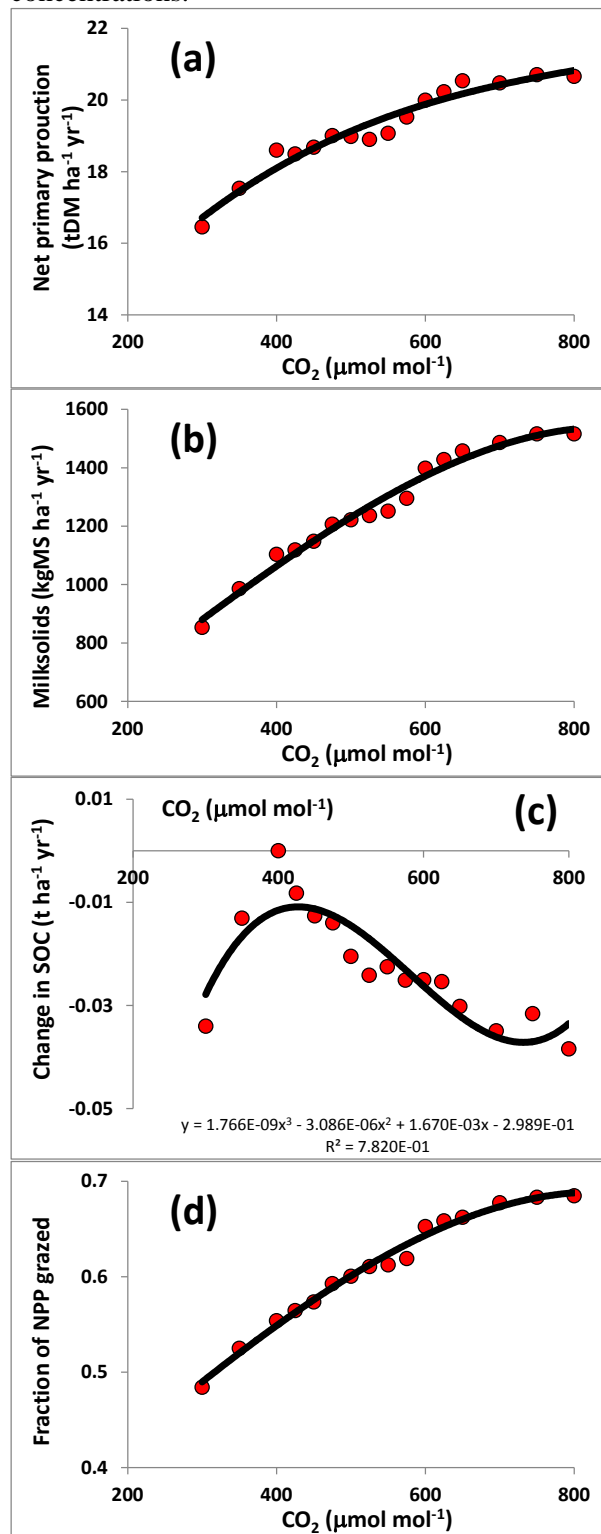
Atmospheric CO₂ Concentration

In these simulations, we assessed the response to changes in atmospheric CO_2 concentration from a pre-industrial 300 to a likely late-21st century concentration of 800 $\mu mol\ mol^{-1}$, which is twice the current concentration. These changes in the atmospheric CO_2 concentration had a moderate effect on net primary production with a change by about 20% across this wide range of CO_2 concentrations (Fig. 8a), while milk production changed almost two-fold (Fig. 8b). The strong stimulation of milk production was related to a changing proportion of fixed carbon that could be captured in grazing (Fig. 8d). At the lowest CO_2 concentration, only about 50% of net primary production was grazed and used for milk production, but that proportion could be increased to almost 70% at the highest CO_2 concentration.

There was a synergistic effect with greater net primary productivity also enhancing the ease with which that carbon could be captured in grazing. Under the defined grazing regime, total biomass remained similar irrespective of changes in productivity – the key difference was the number of times that it was grazed. With low productivity, standing biomass remained on site for an extended period while continuing to lose carbon through respiration and (mainly root-) senescence. That loss adversely affected the ratio of removed to total produced biomass. Increasing productivity shortened the interval between grazing events thus reducing those unproductive losses. Hence, the proportion of biomass grazed increased with increasing productivity, leading to a double benefit of increased CO_2 concentration on milk production.

It was even further enhanced through some changes in the seasonality of production, with elevated CO_2 shifting productivity from winter and spring towards increased productivity in summer and autumn by preventing water stress and thereby allowing greater productivity in the seasons that are currently partly limited by water availability.

Figure 8: Modelled net primary production (c), milksolid production (b), changes in soil organic matter (c), and the fraction of NPP that is grazed (d) under different atmospheric CO_2 concentrations.

$$y = 1.766E\text{-}09x^3 - 3.086E\text{-}06x^2 + 1.670E\text{-}03x - 2.989E\text{-}01$$
$$R^2 = 7.820E\text{-}01$$

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At the same time, increasing CO_2 concentration had almost no effect on soil carbon stocks (Fig. 8c). While more carbon came into the system under elevated CO_2 (Fig. 8a), a greater proportion was also being removed (Fig. 8b) for only a trivial remaining effect on soil carbon.
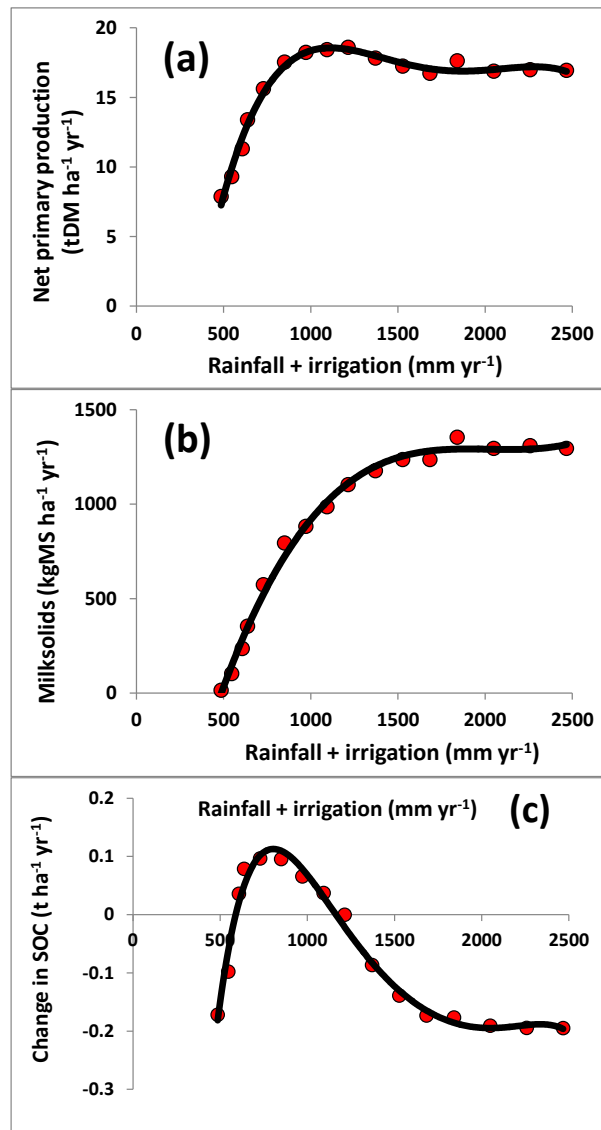
Rainfall Plus Irrigation

With rainfall+irrigation of less than 500 mm yr^{-1}, the model predicts no milk production at all (Fig. 9b). Productivity was reduced to such an extent that foliar biomass could not reach the grazing threshold at all. Milk production then increased sharply with increasing rainfall+irrigation to reach maximal values with about 1000-1500 mm yr^{-1} and plateaued with further increases in rainfall+irrigation.

Net primary production followed a similar pattern (Fig. 9a), but was reduced to a lesser extent at the lowest amounts of rainfall+irrigation, with nearly half maximal productivity still possible with 500 mm yr^{-1}, and with rainfall+irrigation above 1000 mm yr^{-1}, net primary production actually decreased marginally with further increases in rainfall due to increased nitrate leaching and some decrease in productivity caused by water-logging.

Soil organic carbon stocks also increased with rainfall+irrigation for low annual totals, but showed a peak at rainfall+irrigation of about 750 mm yr^{-1} before falling quite sharply with further increases in rainfall+irrigation (Fig. 9c). This was due to the combination of effects on net primary production and a direct stimulation of organic matter decomposition by preventing moisture limitations of decomposition, especially over the summer months.

With increasing rainfall+irrigation from 500 to 700 mm yr^{-1}, the positive effect of increasing carbon input dominated the

Figure 9: Modelled net primary production (c), milksolid production (b), and changes in soil organic matter (b) with different amounts of rainfall + irrigation. Simulation runs as described in the text and the Legend of Fig. 4.

response and led to increasing soil organic carbon. However, for increases in rainfall+irrigation beyond 700 mm yr^{-1}, effects on net primary production became minor, yet the soil remained moist for more of the year and conducive for organic matter decomposition, which led to a loss of soil organic carbon. Consequently, for soil organic carbon stocks, the most favourable combination of carbon input and decomposition rate was found at an intermediate level of rainfall+irrigation (Fig. 9c).

General Discussion

It was generally possible to obtain good agreement between model and measurements, including evapotranspiration rates, photosynthetic carbon gain, net ecosystem carbon exchange and resultant foliar biomass (Fig. 3). The model structure includes relevant within-system feedbacks and interactions between key processes and system component (Fig. 2). In particular, it explicitly models the key processes where changes in external conditions or internal aspects of the system could affect soil organic carbon storage. This model structure, together with the good agreement with observations, gives us the necessary confidence to model the response of the system to changes in various key drivers.

In principle, soil carbon stocks can be changed as a result of changes in the total amount of carbon fixed by plants, through the proportion of carbon retained on the site vs the amount exported and removed from the site in animal produce, through a change in the allocation of carbon to resistant or more labile carbon pools, or through the rate at which organic matter can decompose and be lost from the soil (Fig. 1). All of these can be important and may play a greater or lesser role in controlling overall system carbon balances in response to specific changes, and the ultimate effect on carbon storage is determined by the interplay between all of them.

One of the simplest and most direct consequences of management decisions on soil carbon stocks is related to fertiliser application rates as fertility affects soil-carbon stocks primarily through changing the rate of net primary production. The export of milksolids removes not only carbon but also nitrogen which, together with gaseous and leaching losses of nitrogen, can impoverish the system over time as biological nitrogen fixation is not generally sufficient to match the heavy rate of nutrient removal in a highly productive system. To prevent such impoverishment requires consistent and large fertiliser inputs. With large fertiliser inputs, the system can maintain high productivity (Fig. 4a, b) associated with high soil carbon stocks (Fig. 4c). With lower fertiliser inputs, the system degrades and reaches a new steady state with lower productivity and lower carbon stocks.

The situation is more complex if one considers the effect of the grazing threshold (Fig. 5) on soil-carbon stocks. For very low grazing thresholds, productivity is reduced because pastures are kept so short that they only inefficiently absorb available radiation (Fig. 5a), but that effect saturates at reasonably low grazing thresholds, and there is little effect on productivity for further changes in the threshold. Milk production, however, decrease with further increasing thresholds (Fig. 5b) because larger standing biomass lead to the loss of carbon in unproductive respiration and senescence as well as encouraging greater root growth. Reduced milk production, however, benefits the carbon stocks on the site through increased on-site carbon retention (Fig. 5c).

Increases in root:shoot ratios reduced total net primary production (Fig. 6a) because low allocation to foliage kept the swards with insufficient leaf area for maximum photosynthetic carbon gain while maintaining a large root system constituted and on-going respiratory carbon loss that further reduced the net primary production of the sward. Greater root allocation further reduced the amount foliage available for animal feed, thus further reducing milk production (Fig. 6b).

Soil organic carbon stocks increased with increasing root:shoot ratios from the lowest ratios up to a ratio of about 1 because the effect of gaining a greater share of fixed carbon (through roots senescence and exudation) outweighed the disadvantage of reduced total net primary production. At higher ratios, the negative effect of reduced overall net primary production dominated, for highest soil organic carbon stocks at intermediate root:shoot ratios of about 1 to1.5.

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In terms of the effects of changes in environmental factors, there was only a minor change in net primary or milk production for moderate temperature changes by up to 3 °C, but productivity was more sharply affected by temperature increases of 4° or more (Fig. 7a, b). Despite there being only relatively minor temperature effects on carbon gain and a reduced export of carbon in milk production, soil organic carbon stocks decreased monotonically for any increases in temperature, in this case driven by the direct effect of temperature in stimulating organic matter decomposition rates (Kirschbaum, 2000).

Under varying CO_2 concentrations, modelled net primary production increase by about 20% (Fig. 8a) over the wide range of CO_2 concentrations from a pre-industrial 300 to a likely late-21st century concentration of 800 µmol mol^{-1}, but, together with a substantial increase in the proportion of carbon captured in grazing (Fig. 8d), this led to a very large increase in milk production (Fig. 8b) with only trivial changes in soil organic carbon stocks. Soil carbon stocks changed little because the effect of increased carbon gain at elevated CO_2 (Fig. 8a) was almost completely negated by the increased capture in grazing (Fig. 8d) and thus reduced retention of carbon on-site.

It is thus quite remarkable that while the primary effect of elevated CO_2 was to increase carbon gain, both directly through increasing photosynthesis and indirectly by increasing water use efficiency, yet the ultimate effects were dominated by the secondary effects related to changed productivity, especially the substantial shift in the proportion of fixed carbon captured in grazing, thus making it unavailable for on-site storage. Increased carbon gain thus did not increase soil-carbon stocks at all. It highlights most starkly how the net effect of the response to any change in the system can be anticipated only through consideration of the comined effect of all direct and indirect effects and their interactions.

The response to precipitation was also quite complex. Starting from very low and very limiting rainfall+irrigation of 500 mm yr^{-1}, net primary production, milk production and soil organic carbon stocks all increased (Fig. 9). Further increases beyond about 1000 mm yr^{-1} had only minor further effects on net primary production and milk production, but soil organic carbon stocks decreased (Fig. 9a). This must have been primarily due to stimulation of organic matter decomposition with increasing wetness of the soil, especially over the summer months, that allowed ongoing decomposer activity throughout the year.

Overall, the simulations presented a very diverse picture, with overall responses that could be dominated by direct effects on primary production, such as in the case of fertiliser additions (Fig. 4), through changes in the proportion of carbon retained on-site, which was most strongly expressed in response to changing CO_2 concentration (Fig. 8), through the effect on within site allocation patterns, such as in the response to varying root:shoot ratios (Fig. 6), or through a stimulation of organic matter decomposition rates, which was most clearly seen in the response to changing temperature (Fig. 7) or precipitation (Fig. 9). All of these are important mechanisms, and the overall responses to any changes in any external or system property can only be understood if all direct and indirect effects are simultaneously considered in a combined assessment.

This work pointed to few management or environmental changes that might change to lead to useful increases in soil organic carbon. Soil carbon was predicted to increase with increasing fertiliser application rates (Fig. 4), but fertiliser application rates in New Zealand are already high (Parfitt et al., 2012) so that there is little scope for further increases to increase either productivity or carbon stocks, and even current application rates already lead to a raft of environmental problems.

The simulations did suggest that soil carbon could be increased through increasing the grazing threshold (Fig. 5), but only at the expense of significant reductions in milk production. Similarly, modifications to target root:shoot ratios (Fig. 6) hold some promise in terms of increasing milk production, but organic carbon stocks are likely to decrease for either increases or decreases in root:shoot ratios (Fig. 6c) either because of adverse effects on the total amount of carbon fixed in net primary production or on the proportion of carbon retained on-site.

Changes in rainfall+irrigation provide some scope for increasing soil carbon stocks (Fig. 9), at least up to some intermediate level of water application. Irrigation is typically applied only on sites that naturally receive very limiting amounts of rain. Under those conditions, added water can substantially increase net primary production (Fig. 9a), milk production (Fig. 9b) and soil organic carbon stocks (Fig. 9c).

The other environmental changes tested here showed little promise for increasing soil carbon in future. In response to warming, there is the expected loss of soil carbon due to increasing stimulation of organic matter decomposition by increasing temperature (Fig. 7). Increasing CO_2, however, is normally expected to lead to increasing carbon storage, but even with an increase in net primary production (Fig. 8c), effects on soil carbon storage failed to materialise (Fig. 8c) as the benefit of extra carbon gain was negated by a reduced proportion of carbon retained within the site. With respect to rainfall changes, staring from moderate amounts of natural rainfall, as is currently observed in Hamilton, both increases and decreases in rainfall could lead to losses in soil organic carbon (Fig. 9).

Model testing, refinement and application to scenario testing is ongoing and continuing work. That will use new data sets to test the currently used assumptions about system performance and feedbacks, and explore addition scenarios for their potential to enhance site carbon storage. Mitigation of greenhouse gas emissions continues to be an important task, and our work continues to search for ways to harness the potential of the biosphere to assist in that mission.

Conclusions

The work here showed that CenW simulations can provide modelling results that are consistent with available observations, especially for water fluxes and photosynthetic carbon gain. An important challenge in capturing all carbon fluxes in grazed systems are the episodic large carbon emissions related to the respiration by grazing animals. Agreement between modelled and observed data was therefore poorer for measures that include a large respiratory component.

In assessing changes in soil organic carbon, we found that it was important to consider the combined effect of changes in net primary production, the amount of carbon taken off-site through grazing, the proportion of carbon allocated to pools, especially pools in the soil, that facilitates the stabilisation of carbon in organic matter, and any changes in the rate of organic matter decomposition. The modelling tool employed separately quantified the effect of any perturbation on all of these aspects of the system's carbon balance.

We found that soil organic carbon stocks were positively correlated with rates of fertiliser application and with the rate of water application (rain or irrigation) across a range of low water application rates. For other changes in key system properties, changes in soil organic carbon were often negatively correlated with changes in milk production. That was clearly evident for changes in the grazing regime and for changes in plant root:shoot ratios that might be achieved through plant breeding or changes in species mixtures.

Anticipated environmental changes, such as increases in temperature and CO_2 concentration, and both increases and decreases in precipitation, had either neutral or detrimental effects on soil organic carbon stocks. Effects were more positive for milk production, with mostly positive effects under most environmental changes.

References

Crush JR, Waghorn GC, Rolston MP (1992). Greenhouse gas emissions from pasture and arable crops grown on a Kairanga soil in the Manawatu, North Island, New Zealand. *New Zealand Journal of Agricultural Research* **35**: 253–257.

DairyNZ (2012). New Zealand dairy statistics 2011–12. http://www.lic.co.nz/lic/user/File/DAIRY-STATISTICS-2011-12.pdf {Last accessed 1 December 2014}

Hartmann DL, Klein Tank AMG, Rusticucci M, Alexander LV, Brönnimann S, Charabi Y, Dentener FJ, Dlugokencky EJ, Easterling DR, Kaplan A, Soden BJ, Thorne PW, Wild M, Zhai PM (2013): Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 159–254.

Haynes RJ, Williams PH (1993) Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* **49**: 119–199.

Kelliher FM, Clark H (2012). Ruminants. In Methane and climate change, Reay D, Smith P, van Amstel A, editors. Earthscan, London, UK, pp. 136–150.

King DA (1993). A model analysis of the influence of root and foliage allocation on forest production and competition between trees. *Tree Physiology* **12**: 119–135.

Kirschbaum MUF (1999). CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. *Ecological Modelling* **118**: 17–59.

Kirschbaum MUF (2000). Forest growth and species distributions in a changing climate. *Tree Physiology* **20**: 309–322.

Kirschbaum MUF, Saggar S, Tate KR, Giltrap DL, Ausseil A–GE, Greenhalgh S, Whitehead D (2012). Comprehensive evaluation of the climate–change implications of shifting land use between forest and grassland: New Zealand as a case study. *Agriculture, Ecosystems and Environment* **150**: 123–138.

Kirschbaum MUF, Rutledge S, Kuijper IA, Mudge PL, Puche N, Wall AM, Roach CG, Schipper LA, Campbell DI (2015). Modelling carbon and water exchange of a grazed pasture in New Zealand constrained by eddy covariance measurements. *Science of the Total Environment* **512–513**: 273–286.

Ledgard S, Schils R, Eriksen J, Luo J (2009). Environmental impacts of grazed clover/grass pastures. *Irish Journal of Agricultural Food Research* **48**: 209–226.

MacLeod, CJ, Moller, H (2006). Intensification and diversification of New Zealand agriculture since 1960: An evaluation of current indicators of land use change. *Agriculture Ecosystems & Environment* **115**: 201–218.

MfE (2014). New Zealand's Greenhouse Gas Inventory 1990–2012. Ministry for the Environment, Wellington, New Zealand, 2014; also available online: http://www.mfe.govt.nz/sites/default/files/media/Climate Change/ghg-inventory-1990-2012.pdf [Verified 21 January 2015].

Mudge PL, Wallace DF, Rutledge S, Campbell DI, Schipper LA, Hosking CL (2011). Carbon balance of an intensively grazed temperate pasture in two climatically contrasting years. *Agriculture, Ecosystems and Environment* **144**: 271–280.

Nash JE, Sutcliffe JV (1970). River flow forecasting through conceptual models part 1. A discussion of principles. *Journal of Hydrology* **10**: 282–290.

Pal P, Clough TJ, Kelliher FM, van Koten C, Sherlock RR (2012). Intensive cattle grazing affects pasture litter-fall: an unrecognized nitrous oxide source. *Journal of Environmental Quality* **41**: 444–448.

Parfitt RL, Schipper LA, Baisden WT, Elliott AH (2012). Nitrogen inputs and outputs for New Zealand from 1990 to 2010 at national and regional scales. *New Zealand Journal of Agricultural Research* **55**: 241–262.

Parton WJ, Schimel DS, Cole CV, Ojima DS (1987). Analysis of factors controlling soil organic-matter levels in Great-Plains grasslands. *Soil Science Society of America Journal* **51**:1173-1179.

Schipper LA, Baisden WT, Parfitt RL, Ross C, Claydon JJ, Arnold G (2007). Large losses of soil C and N from soil profiles under pasture in New Zealand during the past 20 years. *Global Change Biology* **13**: 1138–1144.

Schipper LA, Parfitt RL, Ross C, Baisden WT, Claydon JJ, Fraser S (2010). Gains and losses in C and N stocks of New Zealand pasture soils depend on land use. *Agriculture, Ecosystem and Environment* **139**: 611–617.

Schipper LA, Parfitt RL, Fraser S, Littler RA, Baisden WT, Ross C (2014). Soil order and grazing management effects on changes in soil C and N in New Zealand pastures. *Agriculture Ecosystems and Environment* **184**: 67–75.

Soussana JF, Tallec T, Blanfort V (2010). Mitigating the greenhouse gas balance of ruminant production systems through carbon sequestration in grasslands. *Animal* **4**: 334–350.

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007). Observations: Surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L (eds). Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 235–336.

Wells C, 2001. Total energy indicators of agricultural sustainability: farming case study. MAF Technical Paper 2001/3. Ministry of Agriculture and Fisheries, Wellington, New Zealand.

Wilkinson SR, Lowrey RW (1973). Cycling of mineral nutrients in pasture ecosystems. In: Butler BW, Bailey RW (Editors), Chemistry and biochemistry of herbage, Volume 2, Academic Press, London, pp. 247–315.

Zeeman MJ, Hiller R, Gilgen AK, Michna P, Pluss P, Buchmann N, Eugster W (2010). Management and climate impacts on net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland. *Agricultural and Forest Meteorology* **150**: 519–530.