Ministry for Primary Industries
Manatū Ahu Matua

Modelling pastoral soil carbon

MPI Technical Paper No: 2012/49

Prepared for the Ministry for Primary Industries
by AgResearch (C10X0828)
December 2009

ISBN No: 978-0-478-40471-5 (online)
ISSN No: 2253-3923 (online)

November 2012

New Zealand Government

Growing and Protecting New Zealand

Disclaimer

The information in this publication is for consultation only: it is not government policy. While every effort has been made to ensure the information in this publication is accurate, the Ministry for Primary Industries does not accept any responsibility or liability for error of fact, omission, interpretation or opinion that may be present, nor for the consequences of any decisions based on this information. Any view or opinion expressed does not necessarily represent the view of the Ministry for Primary Industries.

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries website at http://www.mpi.govt.nz/news-resources/publications.aspx

© Crown Copyright - Ministry for Primary Industries

agresearch Farming, Food and Health. First

Te Ahuwhenua, Te Kai me te Whai Ora. Tuatahi

Modelling pastoral soil carbon

SLMACC Project C10X0828

December 2009

2020 SCIENCE

New Zealand's science. New Zealand's future.

Modelling pastoral soil carbon

Contract Report to MAF/FRST

December 2009

Mike Dodd and Paul Newton

DISCLAIMER: While all reasonable endeavour has been made to ensure the accuracy of the investigations and the information contained in this report, AgResearch expressly disclaims any and all liabilities contingent or otherwise that may arise from the use of the information.

COPYRIGHT: All rights are reserved worldwide. No part of this publication may be copied, photocopied, reproduced, translated, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of AgResearch Ltd.

Table of Contents

1. Executive Summary

Two ecosystem simulation models (DayCent and EcoMod) were applied to the simulation of long-term primary production and soil organic matter dynamics in two hill country sheep-grazed pasture sites in the North Island of New Zealand. The model output was compared with empirical data on net herbage accumulation (NHA), soil carbon (C) and nitrogen (N) from long-term fertiliser rate trials at the Ballantrae and Whatawhata research stations.

With appropriate parameterisation based on site characteristics and using actual daily weather data, both models were able to simulate levels of annual pasture production and soil organic C within the ranges indicated by the available data. However both models overestimated levels of soil N, which required adjustment to soil C:N parameters in the input files. The models were also unable to simulate the medium-term dynamics of soil C and N seen in the data, i.e. both increases and decreases of 1-2% over decadal scales. This is an important limitation for their use in predicting soil C dynamics at the scale most relevant for "C farming".

At this point it seems inadvisable to use these models for predicting the medium-term soil C and N dynamics at particular sites, in the context of either establishing baseline trends for net-net soil C accounting or predicting the impact of management on soil C sequestration into the future. Further refinement of EcoMod presents good potential for overcoming the issues identified, given its design appropriate to relevant management scenarios and relatively greater responsiveness to management and climate, compared with DayCent.

2. Introduction

An important means of mitigating greenhouse gas (GHG) emissions is the sequestration of carbon (C) in soils (Hutchinson et al., 2007). For pastoral agriculture in New Zealand, it may well prove to be one of the few options available to land managers, at least in the near-term. While soil C sequestration represents a finite and short-term solution (Lal, 2003; Six et al., 2002), small proportional gains in soil C can represent substantial total offsets and have additional benefits for soil quality (Sparling et al., 2003). However, for this potential to be realised in the context of New Zealand soils (11 million ha of which are under pastoral agriculture), it will be necessary to establish where gains can be made, in terms of the interaction between soil type, management regime and medium-term climate patterns.

There is a reasonably good understanding of the general effects of individual management regimes on soil C dynamics (Metherell, 2003), as well as a few time series data sets now available to document trends under certain conditions (A. Ghani, *unpubl. report.*). However, the ability to understand and predict the net effect of key interacting factors (management regimes, climate and soil type) will necessarily remain in the domain of modelling studies. Existing field data are not extensive enough, and new field experiments incorporating multiple factors would be prohibitively expensive and take a long time to yield useful data. However, the crucial element in taking a modelling approach is to develop confidence that the models being used are able to reflect complex ecosystem dynamics at the relevant temporal scale.

There is currently vigorous debate over medium-term trends in soil C stocks under pastoral systems. The conventional view is that pasture development and improvement leads to increases in soil C (Haynes et al., 1993; Stewart and Metherell, 1999), and that most NZ pastoral systems are at some sort of soil organic matter steady state after a century of pastoralism out of forest (Stewart and Metherell, 1999; Tate et al., 1997). This has been challenged by recent studies demonstrating wide variation in soil C and N changes (mainly losses) at decadal time scales (Bellamy et al., 2005; Lambert et al., 2000; Schipper et al., 2009; Schipper et al., 2007) and see also (Bellamy et al., 2005). The drivers of these changes are not clear, but the possibility that pastoral systems on certain soil types or under certain management regimes may be losing soil C (Parfitt et al., 2007) should be of concern in the context of attempts to mitigate GHG emissions by developing soil-based C sinks. Understanding the factors that may be contributing to soil C loss is currently the subject of research in the SLURI and Soil Services research programmes (FRST contracts C02X0405 & C09X0304), and this project will therefore align well with the ongoing experimentation and field data collection in those initiatives.

3. Objectives

The objective of this project was to evaluate the capability of currently available pastoral system research models for predicting medium-term (20-30 years) changes in soil C in response to management regimes, climate and soil type, for selected New Zealand pastoral systems where field data at the appropriate time scale is available to inform the evaluation. Well-recognised models such as CENTURY (Parton et al., 1988) and Roth-C (Coleman and Jenkinson, 1995) have been shown to perform adequately at time scales of 50-100 years (Smith et al., 1997), but we need to establish their value in the medium-term, since this is the time frame relevant to post 2012 Kyoto commitments and associated policy development.

4. Methods

The study compared the output of two simulation models with empirical data from two field sites, in terms of annual pasture (primary) production and topsoil content of organic carbon and nitrogen.

4.1 Data

Two soil C and N datasets were used in the comparison with model output. They were the data on soil organic C and N from the two long-term fertiliser trials at the Whatawhata Research Centre (Schipper et al., 2009) and the Ballantrae Hill Country Research Station (Lambert et al., 2000), the latter being supplemented with more recent data (R.L. Parfitt, unpublished data). Pasture net herbage accumulation (NHA) data were collected at both sites in the course of the fertiliser trials using cage cutting techniques to estimate pasture production (Gillingham et al., 1990); (Lambert et al., 1990) and these data were collated with similar measurements in subsequent years (M.G. Lambert, unpublished data, W. Carlson, unpublished data). The pasture data were all from easy slopes (<20º) and were used in this study for establishing the validity of the model simulations in terms of primary productivity prior to examining soil results.

4.1.1 Ballantrae

The Ballantrae Hill Country Research Station (2750375E, 6095850N) is 20 km east of Palmerston North undulating to very steep low-altitude hill country. The climate at the Research Station is mild sub-humid, with a mean annual rainfall of approximately 1270 mm. A phosphate fertilizer trial was established at the site in 1975 on 10 farmlets of 7-14 ha each. The site had been converted to pasture from indigenous scrub and forest in the early 20th century. The soil types include Pallic Soils of the Wainui series and Brown Soils of the Ngamoka series (Cowie, 1983); (Lambert et al., 2000).

No fertiliser was applied to the site until 1973, when 250 kg ha^{-1} of single superphosphate was applied for 2 years prior to the start of the trial. From 1975, two main fertiliser application rates were applied to 3 farmets each. The low fertility treatment (LF) had 11 kgP ha^{-1} y^{-1} applied from 1975-2006 and the high fertility treatment (HF) had an average of 57 kgP ha^{-1} y^{-1} applied from 1975-1979 and 34 kgP ha^{-1} y^{-1} applied from 1980-2006. All P fertiliser was applied in spring. Nitrogen fertilizer (<50 kgN ha^{-1} y^{-1}) was used intermittently in autumn from 1982-87.

Paddocks were set stocked with breeding ewes and steers from 1975-1977 and thereafter only with breeding ewes. Stocking rates were adjusted to maintain similar grazing pressure across the treatments at between 12-16 SU ha^{-1}.

Soil samples were collected in the late winter in 1972, annually from 1975-1987, and from 2004-2006. The earlier samples were collected from 18 fixed sites within each farmet, including three slope classes (easy, 1-12º; medium, 12-25º; and steep, >25º) and three aspects (E, SW, NW). At each site six 25 mm dia., 75 mm depth cores were collected (Lambert et al., 2000). The data used here were from the easy slopes only. The later samples (2004-2006) were collected from 15 fixed sites on easy slopes (1-8 º), comprising sixteen 25 mm dia., 100 mm depth cores (Parfitt et al. submitted). Soils were air dried, sieved and analysed for total C and N.

4.1.2 Whatawhata

The Whatawhata Research Centre (2693705E, 6375215N), is 22 km west of Hamilton on undulating to very steep low-altitude hill country. The climate at the Research Centre is mild to warm and humid, with a mean annual rainfall of approximately 1630 mm. A phosphate fertilizer trial was established at the site in 1980 on a 14.2 ha area subdivided into 20 paddocks of 0.25–1.22 ha in size, with easy (10-20°) to steep (30-40°) slopes and a north-westerly aspect. The site had been converted to pasture from indigenous scrub and forest in the 1920s. The soil types include Allophanic Soils of the Dunmore and Naike series on the easy slopes, and Brown Soils of the Kaawa series on the steeper slopes (Bruce, 1976; Hewitt, 1998).

The pasture was fertilized with single superphosphate (NPKS=0-9-0-11) at an average rate of 36 kg P ha^{-1} y^{-1} for at least 12 years before the start of the trial. The fertiliser trial started in 1980 when five single superphosphate application rates were established: 10, 20, 30, 50 and 100 kg P ha^{-1} y^{-1} on four replicate paddocks. Fertiliser was applied in late summer/early autumn. After 1989, single superphosphate was replaced with triple superphosphate (NPKS=0-21-0-1). From 1985 to 2006, the P rate treatments continued on only two of the replicate paddocks and fertiliser application ceased on the other two replicate paddocks. The (Schipper et al., 2009) study included the paddocks where the 5 rates were maintained and two 10 kg P ha^{-1} y^{-1} paddocks where application ceased in 1985 as nominal unfertilised controls (0 kg P ha^{-1} y^{-1}).

Paddocks were rotationally grazed by Romney-cross wethers or ewes from December to lambing (August) and set stocked through lambing to weaning (November). Stocking rates were adjusted to maintain pasture utilization across the P loading rates, from ~12 SU ha^{-1} on the unfertilized paddocks up to ~18 SU ha^{-1} on the highest fertilizer rate paddocks.

Throughout the trial, soil samples were collected from all paddocks in February or March of each year on both easy (10-20°) and steep (30-40°) slope classes. Sample depth was 0-70 mm with 15-20 replicate cores per paddock and slope class. All soils were air-dried, passed through a 2-mm sieve, stored in plastic containers and archived. In the (Schipper et al., 2009) study the archived samples were analysed for total C and N using a LECO furnace (TruSpec, St Joseph, Mississippi).

4.2 Models

The criteria for selecting models for this study were that they should a) incorporate the necessary structure for examining soil type/management/climate interactions on soil C in grazed pasture systems; b) have a sufficient history of validation studies in grazed pastures to engender confidence in their use; and c) be readily accessible in terms of software installation and developer support. The models thus selected were DayCent, the daily time-step version of the CENTURY model (Parton et al., 1998; Parton et al., 1988) and EcoMod (Johnson et al., 2008).

4.2.1 DayCent

DayCent simulations were conducted with v4.5 and included a 2500-year simulation of native forest prior to the pasture simulation, for the purpose of stabilising the phosphorus pools (W. Parton, pers. comm.). The forest simulation was broadly validated against available data for net primary production, aboveground biomass, soil organic carbon and soil P prior to the pasture simulation being extended from the forest simulation output file. Both the Ballantrae and Whatawhata forest simulations used the same option for native forest created within the TREE.100 input files. Key parameters adjusted from the default settings are outlined in Appendix 10.2. Some additional adjustments to the default C:N ratios of soil organic matter pools were also made (R. Parfitt, pers. comm.), noted in Appendix 10.3. Soil bulk density and texture data for the two sites were obtained from various sources (see Table 2 and footnotes). The schedule files at both sites included forest removal by burning in 1920.

Because the simulation of grassland production in DayCent does not explicitly model the grass and legume components and consequent interactions and effects on N fixation, we chose to use two crop type options for pasture – a low productivity (low-legume content) pasture representing that typical of undeveloped hill country prior to fertiliser inputs and cultivar introduction, and a high productivity pasture (high-legume content) to represent a more modern ryegrass-clover sward with associated fertiliser inputs. The different key parameters associated with these two crop type options are shown in Table 1.

Table 1: Key input parameters for two pasture crop type options and associated fertiliser and grazing options used in DayCent simulations at Ballantrae and Whatawhata.

Input file	Parameter	Low productivity pasture	High productivity pasture
CROP.100	PRDX(1) [1]	0.40	0.50
	PPDF(1) [2]	17.0	22.0
	PPDF(2) [3]	30.0	35.0
	SNFXMX(1) [4]	0.01	0.04
FERT.100	FERAMT(2) [5]	N/A	2.25
GRAZ.100	FLGREM[6]	0.4	0.6

[1] site productivity (gC/m^2), [2] optimal growth temperature (ºC), [3] maximum growth temperature (ºC), [4] N fixation rate (gN/gC), [5] P added (g/m^2), [6] proportional utilisation of standing herbage.

At Ballantrae, the schedule file for the pastoral phase began with 52 years (1921-1972) of low productivity pasture, followed by 2 years of high productivity pasture with fertiliser inputs of 24 kgP ha^{-1} y^{-1}. From 1975 the two fertiliser input rate treatments were simulated: the low fertiliser (LF) treatment included 32 years (1975-2006) of high productivity pasture with fertiliser inputs of 12 kgP ha^{-1} y^{-1}; and the high fertiliser (HF) treatment included 5 years (1975-1979) of developed pasture with fertiliser inputs of 60 kgP ha^{-1} y^{-1}, followed by 27 years (1980-2006) of developed pasture with fertiliser inputs of 36 kgP ha^{-1} y^{-1}. These simulations were regarded as representing easy slopes at the Ballantrae site, thus no erosion was included and the validation involved data collected from the easy slope class only.

At Whatawhata, an adjustment to the soil texture data in the SOILS.IN and <site>.100 files were made to reflect the allophanic soil type. This soil type is recognised as stabilising more soil carbon than expected based on texture alone (), a property not explicitly included in the DayCent model (W. Parton, pers. comm.). Accordingly the clay fraction was increased by 15% and the silt fraction decreased by 15% to increase the steady state levels in the passive soil C pool. The schedule file for the pastoral phase at Whatawhata began with 50 years (1920-1970) of low productivity pasture, followed by 12 years of high productivity pasture with fertiliser inputs of 36 kgP ha^{-1} y^{-1}. From 1980 two fertiliser input rate treatments were simulated: the low fertiliser (LF) treatment included 37 years (1980-2006) of high productivity pasture with fertiliser inputs of 30 kgP ha^{-1} y^{-1}; and the high fertiliser (HF) treatment included 37 years (1980-2006) of high productivity pasture with fertiliser inputs of 100 kgP ha^{-1} y^{-1}. These simulations were regarded as representing easy slopes at the Whatawhata site, thus no erosion was included and the validation involved data collected from the easy slope class only.

The daily weather data required to run the model (rainfall, minimum air temperature, maximum air temperature, 5 cm soil temperature, relative humidity, vapour pressure, solar radiation, and windspeed from 1972-2006) were obtained for both sites using the AgResearch interface for the Virtual Climate Station (VCS) application. The derivation of data from the VCS is described by (Tait and Woods, 2007).

Since the soil data output from the DayCent model is aggregated to a depth of 200 mm, we applied a scaling factor to convert these data to amounts in the 0-75 mm depth, corresponding to field sampling depths at the Whatawhata and Ballantrae sites. The scaling factor was chosen as 0.65. This was based on observations of the ratio of soil C contents between 0-75 mm and 0-200 mm in a number of profiles in the national soils database ranging between 0.6 – 0.7.

4.2.2 EcoMod

EcoMod simulations were conducted with v4.5.4, with the default settings for all parameters except those in Table 2, where input parameters for the soils at the two sites were obtained from various literature and unpublished data sources. The simulations at both sites began with a "spin-up" period of ~50 years, using the 35-year VCS weather records in series, during which no fertiliser was applied.

Table 2: Input parameters for EcoMod simulations specific to Whatawhata and Ballantrae

Parameter	**Whatawhata**	**Ballantrae**
Soil profile (mm)	500	500
K_{sat} (cm/d)	25[1]	167[4]
Bulk density (kg/m^3)	770[2]	840[5]
Saturated water content (%v)	45[1]	47[4]
Field capacity (%v)	32[1]	24[4]
Wilting point (%v)	13[1]	10[4]
Air dry water content (%v)	8	6
Initial labile surface C (%)	5.0[3]	5.0
Initial inert surface C (%)	0.8	0.8
Initial surface P (mg/kg)	15[3]	15
Fast OM pool decay efficiency	0.60	0.45

[1] based on calculations from soil texture measurements at Whatawhata (K. Mueller, *unpubl. data*) using equations in (Cosby et al., 1984)

[2] based on measurements at Whatawhata (Schipper et al., 2009)

[3] based on soil C and P measurements in forest at Whatawhata (Stevenson, 2004)

[4] based on calculations from soil texture measurements at Ballantrae (DA Costall, *unpubl. data*) using equations in (Cosby et al., 1984)

[5] Based on measurements at Ballantrae (DA Costall *unpubl. data*)

The Ballantrae site was simulated as a ryegrass + white clover sward, set stocked with ewes at 15 SU ha^{-1} with numbers adjusted to achieve target pasture cover of 1200 kgDM ha^{-1}. The option to include a cage-cutting simulation was used. Two different fertiliser input rate treatments were simulated, i.e. for the LF farmlets: 12 kgP ha^{-1} y^{-1} from 1975-2006, and for the HF farmlets: 45 kgP ha^{-1} y^{-1} from 1975-1980 and 36 kgP ha^{-1} y^{-1} from 1981-2006.

The Whatawhata site was simulated as a ryegrass + white clover sward, rotationally grazed with ewes at 300 SU in a 1 ha paddock according to target pre- and post-graze pasture masses, which were based on those measured at the site during the 1980s (S. Richardson, *unpubl. data*). The fertiliser inputs were 30 kgP ha^{-1} y^{-1} from 1970 and from 1985-2004 the two different fertiliser input rate treatments were simulated: 30 and 100 kgP ha^{-1} y^{-1}. These simulations were regarded as representing easy slopes at the Whatawhata site, thus the validation involved data collected from the easy slope class only.

5. Results

5.1 DayCent @ Ballantrae

After 2500 years of the native forest simulation, forest above-ground net primary production (ANPP) at the site ranged between 700–900 gC m^{-2} y^{-1}, above-ground biomass was 247 tC ha^{-1}, soil C was at 7600 gC m^{-2} and soil mineral P was 5.6 gP m^{-2} (in the top 200 mm).

After 50 years of low productivity pasture, the DayCent-simulated ANPP of the pasture had stabilised at ~ 320 gC m^{-2} y^{-1} (~6400 kgDM ha^{-1} y^{-1}, Fig. 1), very close to the levels of net herbage accumulation measured at the site in cutting trials in the first two years of fertiliser addition. During the subsequent phase of fertiliser application, the ANPP of the pasture increased to 400-520 gC m^{-2} y^{-1} (8000-10400 kgDM ha^{-1} y^{-1}, Fig. 1). Between 1975-1988, levels of net herbage accumulation (NHA) measured under the LF treatment at the site ranged between 6300-10200 kgDM ha^{-1} y^{-1}.

Under the high P input scenario, the model did not simulate any response in pasture growth despite increases in soil P fertility (by 2006, mineral P in the surface layer was 30 g m^{-2} in the low fertility scenario vs. 90 g m^{-2} in the high fertility scenario) hence these data are not presented in Fig. 1. However, from 1975-1988 levels of NHA measured under the HF treatment ranged between 10000-15500 kgDM ha^{-1} y^{-1}.

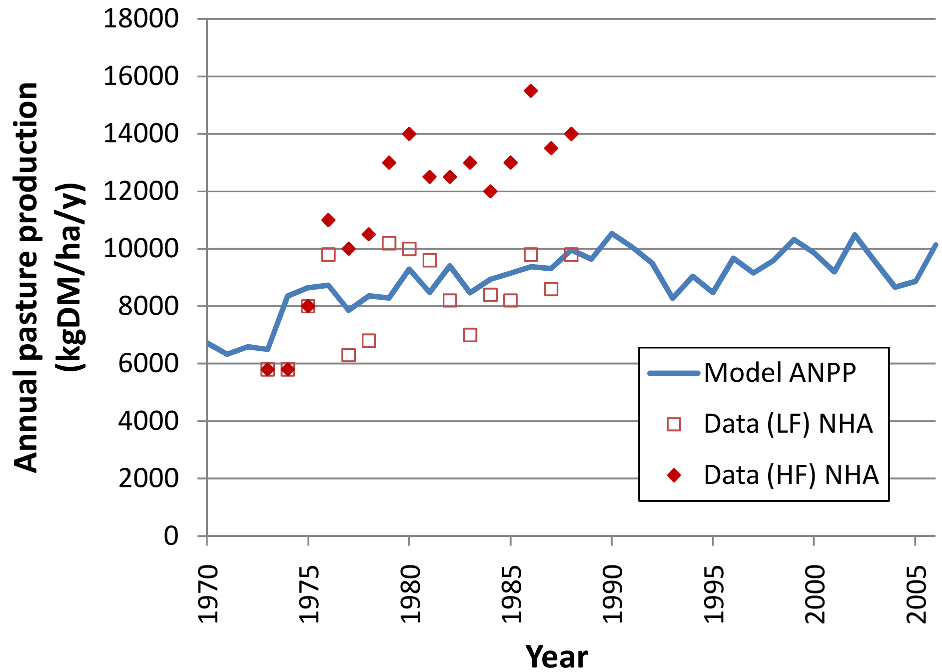

Figure 1: Annual pasture production (kgDM ha^{-1} y^{-1}) estimates for easy slopes on the low fertiliser (LF) treatment of the long-term fertiliser trial at Ballantrae, derived from a) DayCent-simulations of ANPP over 37 years and b) field measurements of NHA on the LF and HF treatments.

During the first 50 years of low productivity pasture, the DayCent-simulated soil C had declined from the levels under forest to 5400 gC m^{-2} in the top 200 mm (i.e. 35000 kgC ha^{-1} or ~5.65% in the top 75 mm) and appeared to have almost stabilised at that level (Fig. 2a). Under the subsequent low fertiliser input pasture treatment, SOC increased slightly to 36700 kgC ha^{-1} (~5.8%) in the top 75 mm and stabilised at that level after about 20 years. While these levels of soil C were broadly comparable with the data collected from the site, the model did not simulate the observed decline between 1972-1987.

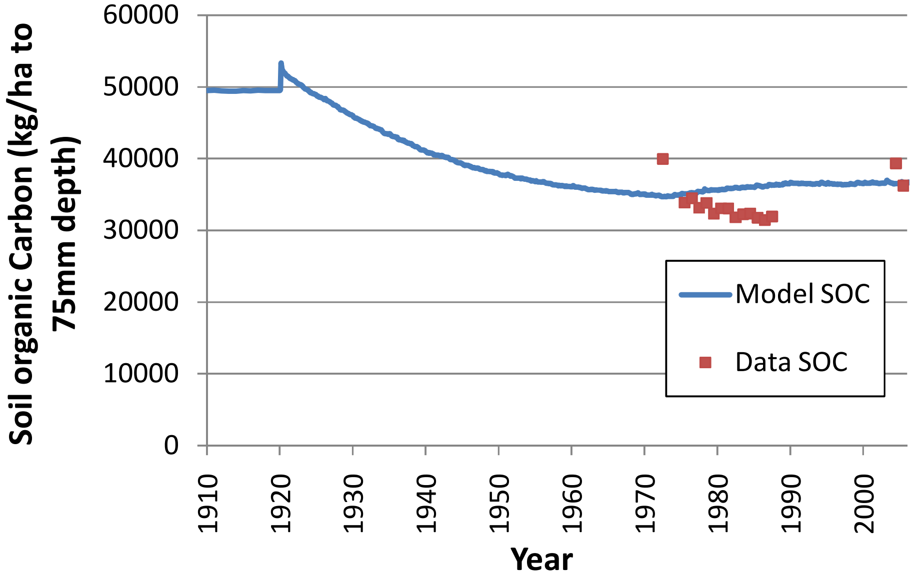

Figure 2a: DayCent-simulated changes in soil carbon (kgC ha^{-1} to 75 mm depth) on easy slopes over 87 years for grazed pasture (LF) after native forest at Ballantrae, compared with soil C data.

Over the same period, the simulation of soil N followed a similar pattern to that of soil C (Fig. 2b), with the exception that the decline in soil N from 1920 slightly lagged the decline in soil C. The simulated soil N declined to ~2850 kgN ha^{-1} (~0.45%) in the top 75 mm under low producing pasture. Subsequently during the period of fertiliser input, soil N increased to ~ 3000 kgN ha^{-1} (~0.48%) by 1990, after which it stabilised. These levels were very similar to measurements made at the site between 1972-87 and 2004-06, but the model did not simulate the observed decline in soil N between 1972 and 1975.

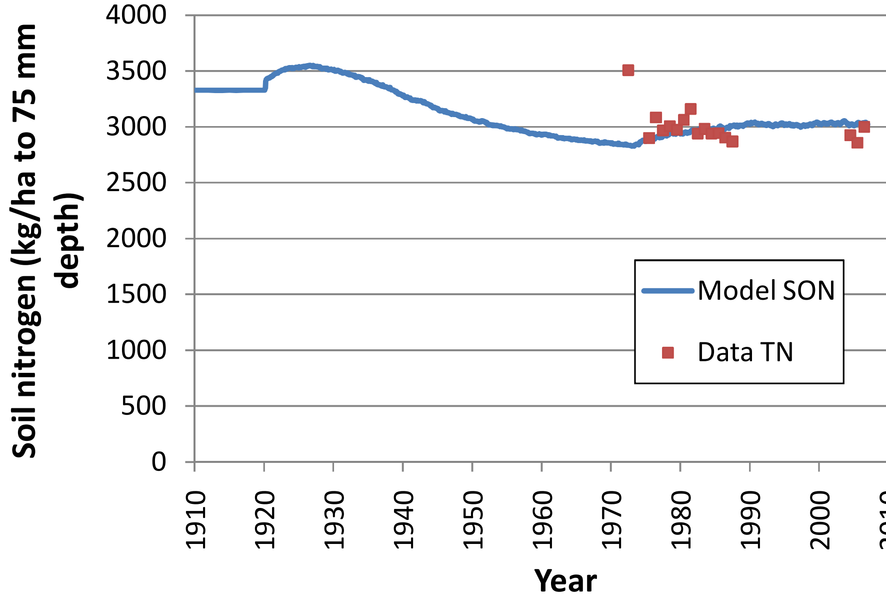

Figure 2b: DayCent-simulated changes in soil nitrogen (kgN ha^{-1} to 75 mm depth) on easy slopes over 87 years for grazed pasture (LF) after native forest at Ballantrae, compared with total soil N data.

5.2 DayCent @ Whatawhata

After 2500 years of the forest simulation, forest ANPP at the site ranged between 700–900 gC m^{-2} y^{-1}, above-ground biomass was 247 tC ha^{-1}, soil C was at 9300 gC m^{-2} and soil P was 5.0 gP m^{-2} (in the top 200 mm). In terms of the soil C pools, the texture adjustment at this site had the effect of increasing the passive soil C by ~1800 gC m^{-2}.

After 50 years of low productivity pasture, the DayCent-simulated ANPP of the pasture had stabilised at ~430 gC m^{-2} y^{-1} (~8600 kgDM ha^{-1} y^{-1}, Fig. 3). During the subsequent phase of fertiliser application, the ANPP of the pasture increased to 500-640 gC m^{-2} y^{-1} (10000-12800 kgDM ha^{-1} y^{-1}, Fig 3). Between 1981-2004, levels of net herbage accumulation measured at the site ranged between 8400-14400 kgDM ha^{-1} y^{-1}.

Under the high P input scenario, the model did not simulate any response in pasture growth hence these data are not presented.

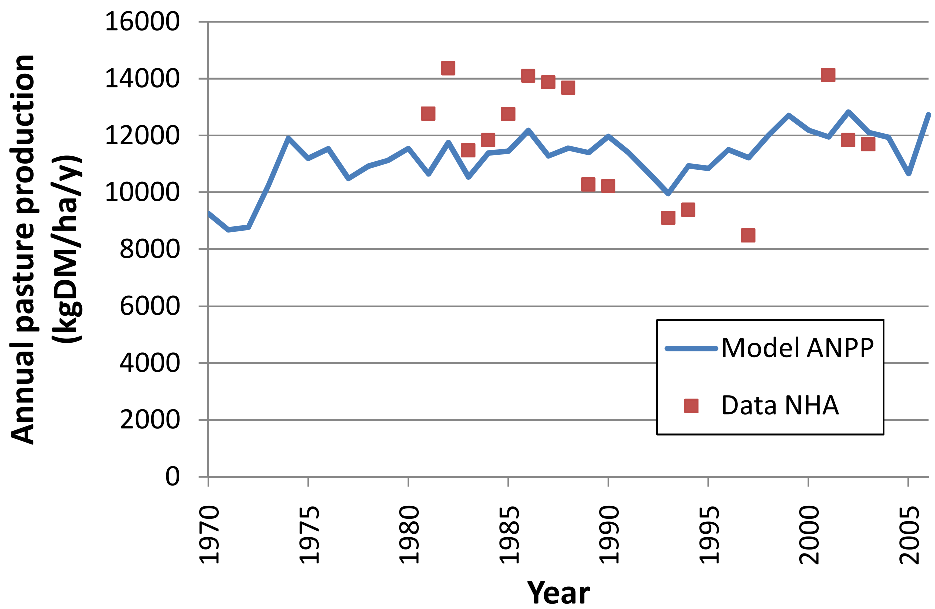

Figure 3: Annual pasture production (kgDM ha^{-1} y^{-1}) estimates for easy slopes on the long-term fertiliser trial at Whatawhata, derived from a) DayCent-simulations of ANPP over 32 years and b) field measurements of NHA on the LF treatment.

During the first 50 years of low productivity pasture, the DayCent-simulated soil C had declined from the levels under forest to 7400 gC m^{-2} in the top 200 mm (i.e. 48300 kgC ha^{-1} or ~8.4% in the top 75 mm) and appeared to have almost stabilised at that level (Fig. 4a). Under the subsequent low fertiliser input pasture treatment, SOC increased marginally (~600 kgC ha^{-1} in the top 75 mm). There was no difference between the low and high fertiliser input treatments in terms of soil C levels. While these levels of soil C were broadly comparable with the data collected from the site, the model did not simulate the magnitude of the observed increase and decline between 1983-2006.

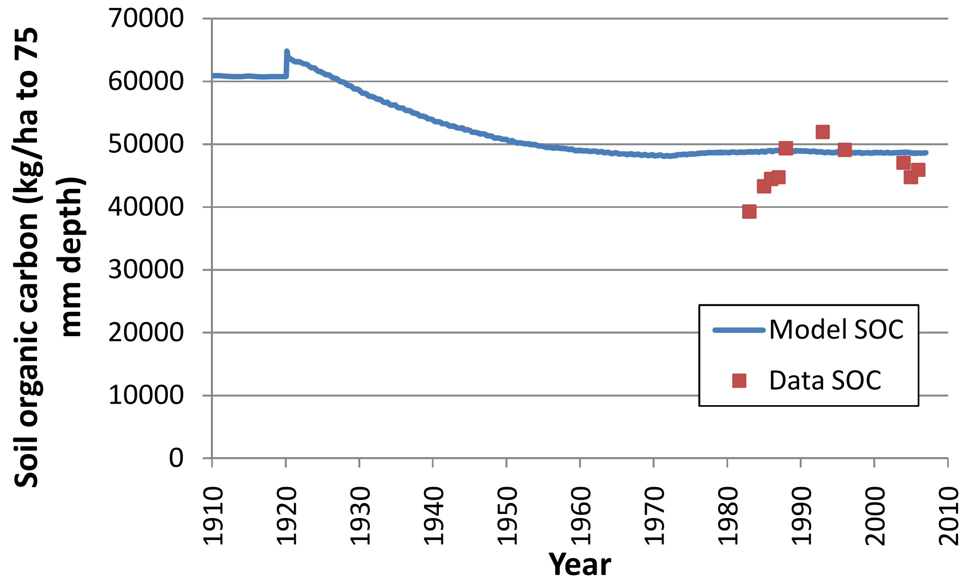

Figure 4a: DayCent-simulated changes in soil carbon (kgC ha^{-1} to 75 mm depth) on easy slopes over 87 years for grazed pasture (LF) after native forest at Whatawhata, compared with soil C data.

Over the same period, the simulation of soil N followed a similar pattern to that of soil C (Fig. 4b), with the exception that the decline in soil N from 1920 slightly lagged the decline in soil C. The simulated soil N stabilised at ~4000 kgN ha^{-1} (0.7%) in the top 75 mm during the period of low productivity pasture, and increased only marginally (~80 kgN ha^{-1}) during the subsequent period of fertiliser input.

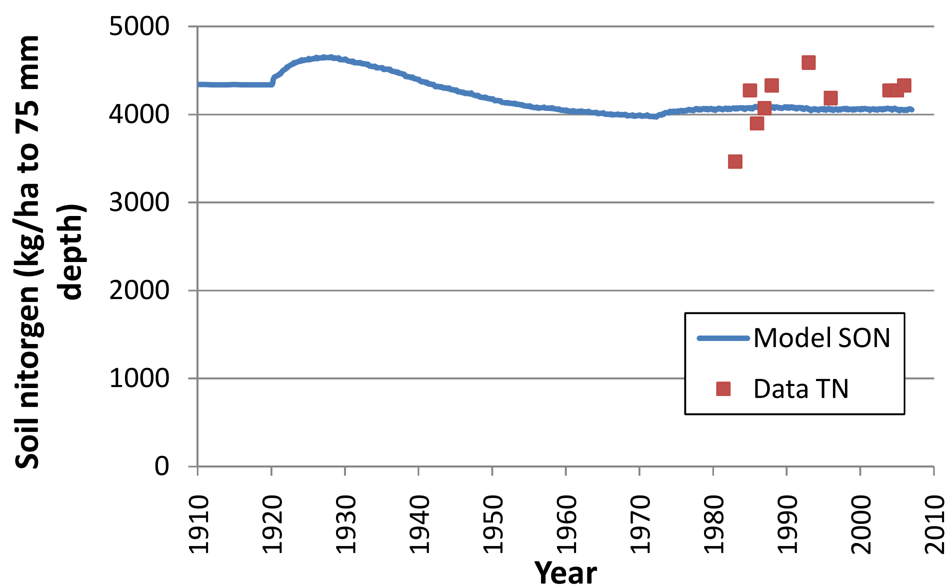

Figure 4b: DayCent-simulated changes in soil nitrogen (kgN ha^{-1} to 75 mm depth) on easy slopes over 87 years for grazed pasture (LF) after native forest at Whatawhata, compared with total soil N data.

5.3 EcoMod @ Ballantrae

The model simulated relatively low annual pasture production (NHA using the cage-cutting option) of between 4500-7500 kgDM ha^{-1} y^{-1} from 1970-1973 prior to fertiliser application (Fig. 5). Under the low fertiliser (LF) scenario this was followed by an increase in production from 1974 onwards and thereafter production generally ranged between 10000-14000 kgDM ha^{-1} y^{-1}. The difference between the simulated pasture growth rates between the low and high fertiliser scenarios was negligible, usually amounting to < 1 kgDM ha^{-1} day^{-1}. In comparison with the field measurements, the pattern of annual pasture production appeared to be more aligned with the data from the HF treatment – the mean difference between the annual figures for the LF simulation vs. the HF data was ~700 kgDM ha^{-1} less, compared to the LF simulation vs. the LF data which was ~2400 kgDM ha^{-1} greater.

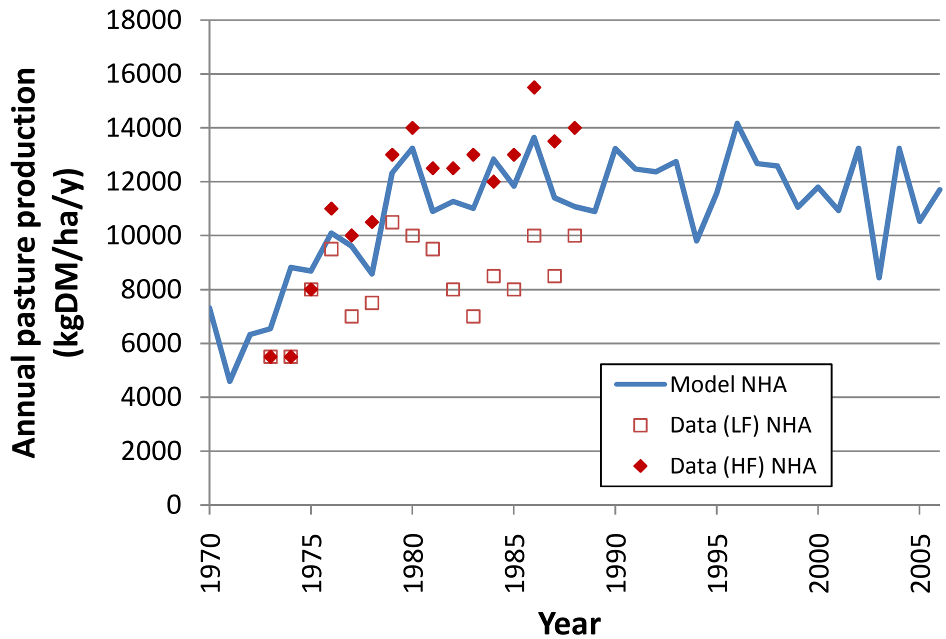

Figure 5: Annual pasture production (kgDM ha^{-1} y^{-1}) estimates for easy slopes on the long-term fertiliser trial at Ballantrae, derived from EcoMod-simulations over 37 years for a ryegrass + white clover pasture under continuous sheep grazing and field measurements of NHA in the low (LF) and high (HF) fertiliser input treatments.

The model simulated little change in the level of soil carbon under unfertilised sheep grazed pasture, assuming a SOC level of ~5% coming out of native forest (Fig. 6a). There did appear to be a slight increase over the 10 years following the commencement of fertiliser, in the order of ~10 kgC ha^{-1} y^{-1}. There was no difference in SOC levels between the low and high fertiliser scenarios, hence the latter data are not presented here. In comparison with the field data, the model has predicted vales within the range observed between 1972-1987, but was unable to simulate the observed decline in soil C in the order of 200 kgC/ha/y (~1.2 percentage points over those 15 years). More recent data from this site has indicated a recovery in soil C to levels similar to those observed in 1972, but the model has also not simulated this increase.

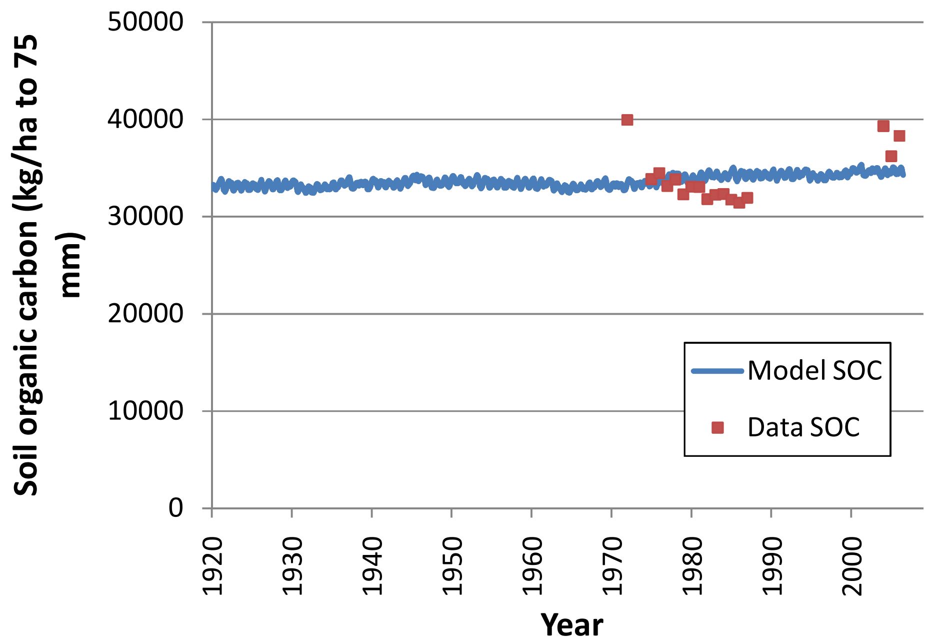

Figure 6a: EcoMod-simulated changes in soil carbon (kgC ha^{-1} to 75 mm depth) on easy slopes over 87 years for a ryegrass + white clover pasture under continuous sheep grazing at Ballantrae, compared with total soil C data.

The model also simulated a very stable pattern of soil N, deviating very little from 4000 kgN ha^{-1} (Fig. 6b). However, the levels simulated by the model were much higher than those observed in the field between 1972-2004 (2500-3000 kgN ha^{-1}), and the model did not simulate the observed loss in soil N of ~300 kgN ha^{-1} between 1972 and 1975.

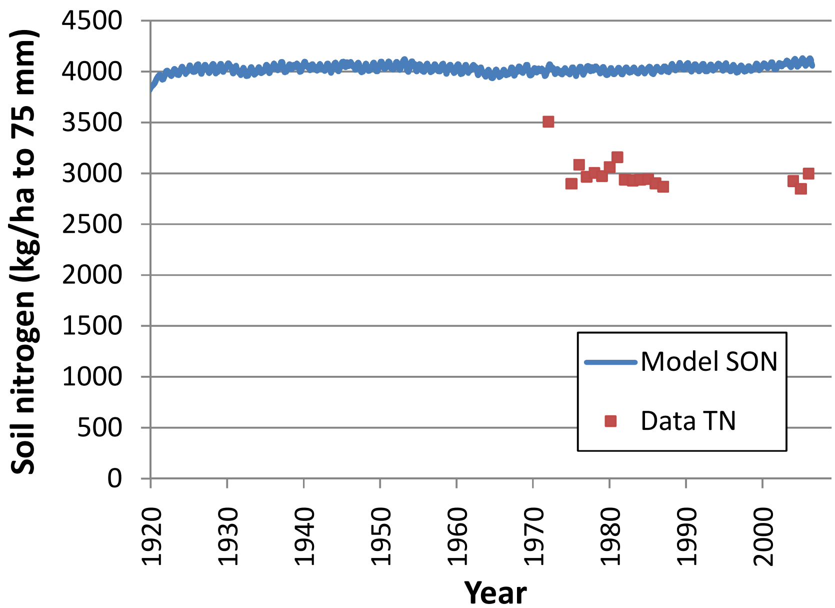

Figure 6b: EcoMod-simulated changes in soil nitrogen (kgN ha^{-1} to 75 mm depth) on easy slopes over 87 years for a ryegrass + white clover pasture under sheep grazing at Ballantrae, compared with total soil N data.

5.4 EcoMod @ Whatawhata

Ecomod simulated annual pasture production (the annual sum of positive daily net growth rates) of typically between 3000-6000 kgDM ha^{-1} y^{-1} prior to fertiliser addition, which gradually increased during the 1970s to levels of 8000-14000 kgDM ha^{-1} y^{-1} during the period of the fertiliser trial under the lower fertiliser input scenario (Fig. 7). The notable exception was a 4-year period of relatively low pasture productivity 4000-6000 kgDM ha^{-1} y^{-1} from 1990-1993. Pasture production did not increase in the higher fertiliser input scenario, hence these data are not shown. Annual pasture production measured at the Whatawhata site covered a similar range to the model simulation - between 8400-14400 kgDM ha^{-1} y^{-1} (Fig. 7). The average annual pasture production over the measured years was 11800 kgDM ha^{-1} y^{-1}, compared to an average of 10200 kgDM ha^{-1} y^{-1} for the same years as simulated by the model.

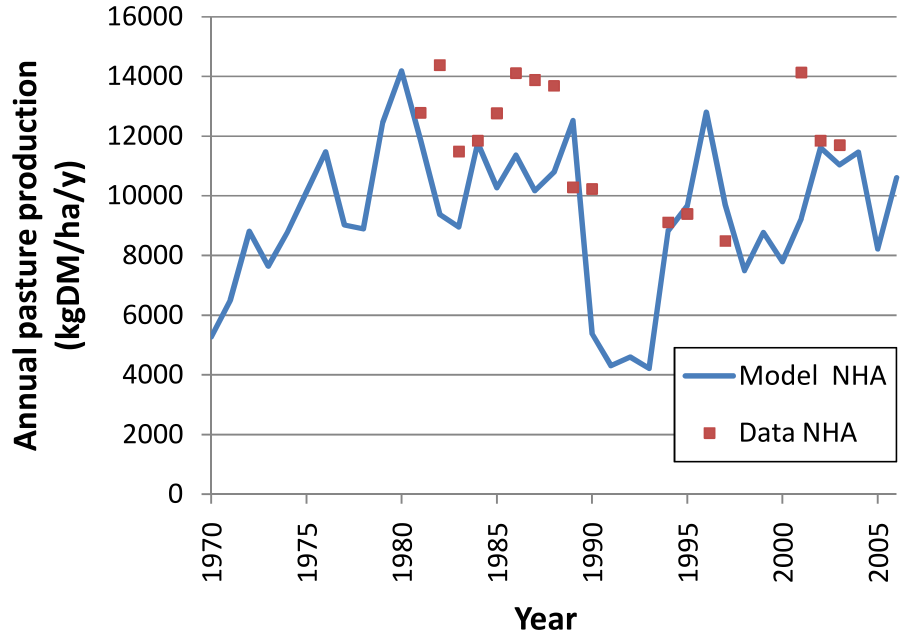

Figure 7: Annual pasture production (kgDM ha^{-1} y^{-1}) estimates on easy slopes for the long-term fertiliser trial at Whatawhata, derived from EcoMod-simulations over 32 years for a ryegrass + white clover pasture under rotational sheep grazing and field measurements of NHA on the LF treatment.

Under both fertiliser input scenarios, EcoMod simulated a long-term increase in the level of soil carbon under sheep grazed pasture, based on an initial value of ~5% soil C coming out of native forest (Fig. 8a). However, there was no substantive difference in the pattern of soil C over time between the two scenarios, hence Fig. 8a presents the data for the lower P input scenario (30 kgP ha^{-1} y^{-1} from 1985). The simulation also showed changes in the rate of soil carbon increase over the 87-year simulation period. For example, the model projected an increase in the order of 330 kgC ha^{-1} y^{-1} in the 33 year period from 1920-1952, followed by a period of relative stability until 1967, then an increase in the order of 350 kgC ha^{-1} y^{-1} in the 20-year period between 1967-1986 followed by another period of relative stability. In comparison with the field data for the period 1985-2006, where the data indicated an increase of 1560 kgC ha^{-1} y^{-1} between 1984-1990 and a non-significant decline between 1990-2006, the magnitude of the changes in soil C projected by the model was much smaller and unidirectional (Fig. 8a).

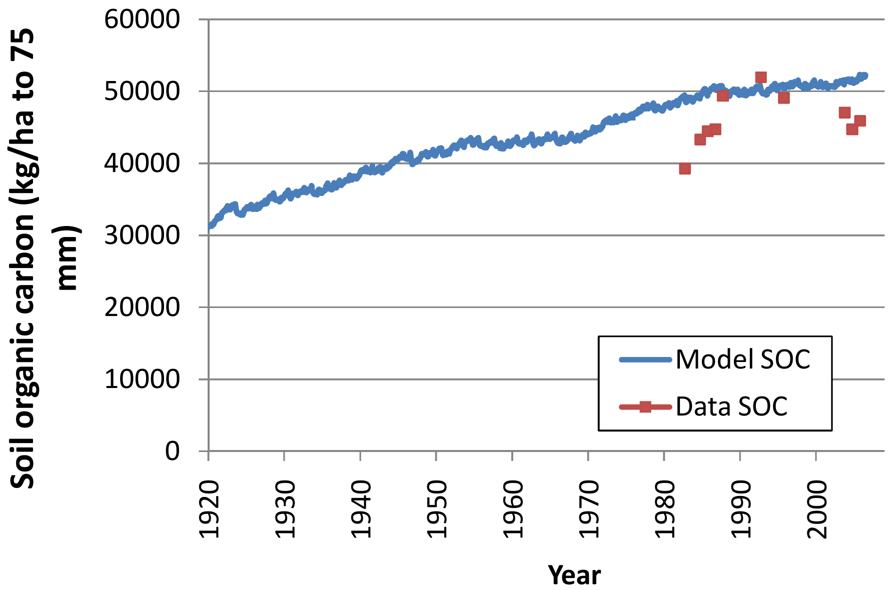

Figure 8a: EcoMod-simulated changes in soil organic carbon (kgC ha^{-1} to 75 mm depth) on easy slopes over 87 years for a ryegrass + white clover pasture under rotational sheep grazing at Whatawhata, compared with total soil C data.

The model also simulated a long-term increase in soil organic N (Fig. 8b), again with no difference between the two fertiliser input scenarios and with changes in the rate of N accumulation over time reflecting those observed for soil C (Fig. 8a). In comparison with the field data for the period 1985-2006, the model simulated much higher levels of soil N (note that the contribution of inorganic N to total N is relatively insignificant at <0.5%). In addition, where the data indicated an increase of 144 kgN ha^{-1} y^{-1} between 1984-1990 and a non-significant decline between 1990-2006, the magnitude of the changes in soil C simulated by the model was much smaller (30 kgN ha^{-1} y^{-1} between 1970-1990) and unidirectional.

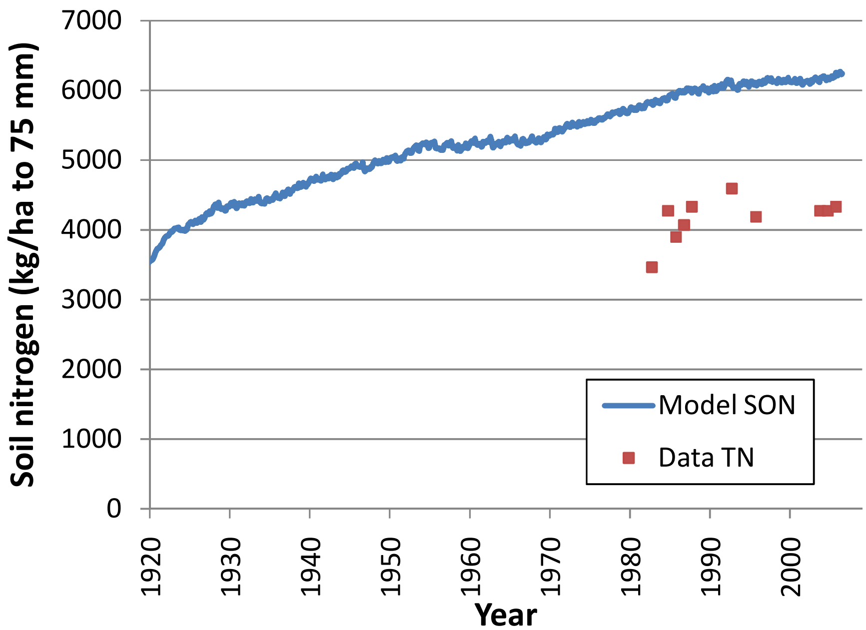

Figure 8b: EcoMod-simulated changes in soil organic nitrogen (kgN ha^{-1} to 75 mm depth) on easy slopes over 87 years for a ryegrass + white clover pasture under rotational sheep grazing at Whatawhata, compared with total soil N data.

6. Discussion

6.1 Primary productivity

A realistic simulation of net primary production is a key first step for any model in attempting to simulate soil carbon levels and dynamics. Both the DayCent and EcoMod simulation models performed adequately in this respect, that is to say they simulated levels of ANPP within the range of the relevant field data. However, there are some caveats in this comparison. With regard to the DayCent model, the output generated is aboveground net primary production, of which net herbage accumulation as measured by trim cuts is an (under) estimation. The comparison is limited by such factors as the cutting height and the occurrence of 'unmanaged herbivory'. With regard to EcoMod, at Ballantrae we were able to activate the cage cutting simulation in the model and hence the output should be directly comparable to the data, but at Whatawhata we used an annual summation of the daily net positive growth rate as the pasture production output data, which is not strictly comparable to the data from field measurements. It should also be noted that the data from Whatawhata was derived over a number of years from different datasets collected by different operators using different techniques – thus the empirical data is not internally consistent. Hence the most sensible approach is to simply ensure that the models predictions are within a similar range to the data, as indeed they largely were.

DayCent simulations of the original forest vegetation at both sites appeared to give reasonable results relative to the very limited published data. Aboveground forest productivity of 700-900 gC m^{-2} y^{-1} was broadly in line with an estimates for broadleaf/podocarp forest in the Central North Island (total NPP of 8.9 tC ha^{-1} y^{-1} in (Tate et al., 1995). Aboveground standing biomass of 247 tC ha^{-1} is within the range quoted by (Hall, 2001) (i.e. 180-350 tC ha^{-1}). Hence there is good reason to believe that the DayCent model was establishing a realistic forest simulation prior to the pastoral phase at these sites.

In terms of grassland productivity, the results produced by DayCent tended to be less variable than the data indicated, perhaps reflecting the nature of the plant production sub-model, which does not account for grazing management effects on pasture production. However this is not necessarily problematic, given our interest in decadal-scale patterns in soil carbon, rather than accurate annual estimates of pasture production. The more mechanistic plant production sub-model in EcoMod, perhaps not surprisingly was more responsive to climate variability and reflected the variation in the data better. EcoMod did appear to be simulating higher pasture production at Ballantrae (where the only reasonable comparison between model output and field data could be made on an annual basis). Fine tuning of the model would likely overcome this to some extent (White et al., 2008) but was beyond the scope of this study.

The lack of a response in ANPP to increased P input in the simulations of both models does require some attention, since it is at odds with measurements from the original fertiliser rate trials (e.g. Fig. 5). At Whatawhata, Gillingham (1990) reported a mean difference in annual pasture production between the 30 and 100 kgP ha^{-1} y^{-1} input rates of 2300 kgDM ha^{-1} y^{-1}. Examination of the output from both models indicated that at the low (supposedly 'maintenance') rate of 30 kgDM ha^{-1} y^{-1}, soil inorganic P was increasing substantially over the 1985-2006 period. Soil P was almost never activated as a growth limiting factor in the models, explaining their lack of response. The use of a low-productivity and high-productivity pasture (crop type) option in DayCent, with associated differences in N-fixation (Table 1), appears able to overcome this problem in a somewhat artificial way, based on the effect on ANPP at both sites (Figs. 1,3). Some further attention to the parameterisation of soil P and of plant P responses in the models seems advisable, but was also beyond the scope of this study. For example a fairly rudimentary manipulation of the ratio of available to total inorganic P in EcoMod did lead to a plant growth response to the P input levels at Whatawhata.

6.2 Soil Carbon

The prediction of DayCent for SOC coming out of native forest is somewhat difficult to validate for these sites, as there is little if any empirical data available. The data that were available for the Whatawhata site (Stevenson, 2004) should be treated with caution, since they appear to have been sampled from steep slopes, which at this site are typically sedimentary soils, in comparison to the ash-based soils on easy slopes where the fertiliser trial is located. These allophanic soils tend to store more soil carbon than their texture would predict (Saggar et al., 1996), and this relationship is not currently explicitly incorporated into either model. Manipulation of silt and clay fractions in DayCent (without altering hydrological parameters) was able to simulate this effect, but without reliable field data to validate the model such an exercise remains exploratory. For Ecomod, the allophanic soil effect was incorporated in the adjustment of the Fast OM pool decay efficiency, which is the retention rate of soil carbon in that pool (i.e. higher for the Whatawhata allophanic soil at 0.6 vs. 0.45 at Ballantrae).

At both sites, DayCent simulated a decline in soil C during 50 years of pastoral farming without fertiliser inputs (Fig. 2a, 4a). Data from South Island Pallic and Brown soils supports lower SOC under pasture compared with adjacent forest reserves (McIntosh et al., 1997), but the reverse is shown in North Island Pumice soils (Parfitt et al., 2003) and indeed in the sedimentary soil sampled at Whatawhata by (Stevenson, 2004). Analysis of national soils data indicates a negligible effect of indigenous forest vs. pastoral land use on soil organic C (Tate et al., 2005) and hence the long-term soil C dynamics simulated by DayCent remains unverified.

During the more detailed comparison of the period of fertiliser application at Ballantrae (1975-2006), there was a discrepancy in terms of the timing and magnitude of the shift from soil C decline to soil C accumulation that appeared in both the DayCent model and data. The data indicate that soil C was declining even with fertiliser application during the 70s-80s, and imply that some other factor drove the increase in soil C between 1987 and 2004. This has been suggested as being due to less rigorous alignment of stock numbers to pasture production, thus implicating lower pasture utilisation (A.D. Mackay, *pers. comm.*), in line with expectations based on the relationship between stocking rate and soil C (Clark et al., 2001) (Hoglund, 1985).

Meanwhile at Whatawhata, soil C appear to have declined to a greater degree under unfertilised pasture than the DayCent model would predict, and conversely soil C responded to fertiliser application and associated increase in pasture production to a much greater degree than the model during the period of fertiliser application. As with the simulation of ANPP, the model appears to be overly conservative in terms of annual-decadal dynamics.

At Whatawhata, the EcoMod simulation appeared to follow two phases of increasing then stable soil C that coincided with implementation of the fertiliser policy. From 1920-1970 (no fertiliser), soil C appeared to increase steadily to a steady state (~7.5%), then once P inputs were introduced from 1970, the pattern repeated to find a new (higher) steady state level of soil C (~8.5%). In the (Schipper et al., 2009) paper that discussed the data for 1984-2006 period, the pattern of increasing then stable/decreasing soil C was attributed to climate-driven shifts in pasture production. This was somewhat evident in the simulated pasture production output (relatively low from 1990-94, Fig. 7), but the longer-term view emphasised by the modelling here suggests that climate drivers would have been insufficient to lead to the magnitude of variation seen, and introduces the possibility that the introduction of fertiliser P input was also an important driver. In any case, the EcoMod model was also more conservative than the data in terms of the magnitude of soil C changes at decadal scales.

6.3 Soil nitrogen

Given that the dynamics of soil N broadly reflected those for soil C in both the model simulations and the data, the conclusions are similar.

DayCent simulated broad soil N levels over the period of fertiliser application at both sites that was consistent with the data, but only at Whatawhata did the direction of the simulated changes (increasing then stable) coincide with the data (Fig. 4b). Even in this case, the magnitude of the simulated changes over time was less than the data indicated. In addition, prior to modifying the default pool C:N ratios the model substantially over-estimated soil N.

Similarly, EcoMod was able to simulate the direction of soil N changes consistent with the data at Whatawhata (Fig. 8b), but at both sites over-estimated soil N by ~1500 kg ha^{-1}. This seems unlikely to be related to inputs of N, since both clover growth (~2000 kgDM ha^{-1} y^{-1}) and N-fixation rates (80-90 kgN ha^{-1} y^{-1}) in the simulations were consistent with experimental data for the sites (Ledgard et al., 1987). Some attention to the C:N ratios in the soil organic matter pools (as was the case with DayCent) would also be warranted for this model.

7. Conclusions

Both models did a good job of simulating the levels of primary productivity at both sites, an important prerequisite for valid simulations of soil carbon dynamics. However they were unable to respond to higher levels of P input in terms of increased ANPP, as shown in the original fertiliser rate trials. This is an important limitation that should be addressed, particularly in EcoMod with its more mechanistic treatment of pasture growth dynamics.

With the appropriate coarse level of parameterisation (e.g. Fast OM pool efficiency in EcoMod), both models also simulated levels of soil carbon consistent with the range of data observations. However they were unable to simulate the medium-term (decadal-scale) dynamics, in terms of the magnitude of changes observed n the data. This is an important limitation for their use in predicting soil C dynamics at the scale most relevant for “C farming”.

It seems clear that some fundamental data (i.e. ANPP, total C & N) needs to be collected for each site to which these models are applied, in order to have some confidence that the simulation outputs are within the expected range.

At this point it seems inadvisable to use these models for predicting the medium-term soil C and N dynamics at particular sites, in the context of either establishing baseline trends for net-net soil C accounting or predicting the impact of management on soil C sequestration into the future. While EcoMod is clearly the more dynamic (in terms of responsiveness to climate and management), flexible (in terms of examining relevant pastoral management) and user-friendly (in terms of the user interface), further development is required, at the very least in terms of refining parameters.

8. Acknowledgements

Thanks to Louis Schipper, Jacinta Parenzee, Ian Power, Bridget Wise and Bill Carlson for Whatawhata data; Greg Lambert and Roger Parfitt for Ballantrae data; Roger Parfitt, Alister Metherell, Bill Parton and Cindy Keough for assistance with DayCent; Mark Lieffering, Val Snow and Jeremy Bryant for assistance with EcoMod.

9. References

Bellamy, P.H.; Loveland, P.J.; Bradley, R.I.; Lark, R.M.; Kirk, G.J.D. 2005. Carbon losses from all soils across England and Wales 1978-2003. *Nature 437*: 245-248.

Bruce, J.G. 1976. Soil Map of part Raglan County, South Auckland, New Zealand. *New Zealand Soil Bureau*. DSIR, Wellington.

Clark, H.; De Klein, C.; Newton, P. 2001. Potential management practises and technlogies to reduce nitrous oxide, methane and carbon dioxide emissions form New Zealand agriculture. AgResearch Ltd.

Coleman, K.; Jenkinson, D.S. 1995. RothC-26.3 - a model for the turnover of carbon in soil: Model description and users guide. Lawes Agricultural Trust, Harpenden.

Cosby, B.J.; Hornberger, G.M.; Clapp, R.B.; Ginn, T.R. 1984. A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resources Research 20*: 682-690.

Cowie, J.D. 1983. The soils of Ballantrae Farm, Woodville. p 51. DSIR Soil Bureau, Palmerston North.

Gillingham, A.G.; Richardson, S.; Power, I.L.; Riley, J. 1990. Long term effects of withholding phosphate application on North Island hill country: Whatawhata Research Centre. *Proceedings of the New Zealand Grassland Association 51*: 11-16.

Hall, G.M.J. 2001. Mitigating an organisation's future net carbon emissions by native forest restoration. *Ecological Applications 11*: 1622-1633.

Haynes, R.J.; Williams, P.H.; Donald, L.S. 1993. Nutrient Cycling and Soil Fertility in the Grazed Pasture Ecosystem. *Advances in Agronomy*, pp 119-199. Academic Press.

Hewitt, A.E. 1998. *New Zealand Soil Classification*. Manaaki Whenua Press, Landcare Research, Lincoln.

Hoglund, J.H. 1985. Grazing intensity and soil nitrogen accumulation. *Proceedings of the New Zealand Grassland Association 46*: 65-69.

Hutchinson, J.; Campbell, C.; Desjardins, R. 2007. Some perspectives on carbon sequestration in agriculture. *Agricultural and Forest Meteorology 142*: 288-302.

Johnson, I.R.; Chapman, D.F.; Snow, V.O.; Eckard, R.J.; Parsons, A.J.; Lambert, M.G.; Cullen, B.R. 2008. DairyMod and EcoMod: biophysical pasture-simulation models for Australia and new Zealand. *Australian Journal of Experimental Agriculture 48*: 621-631.

Lal, R. 2003. Global potential of soil carbon sequestration to mitigate the greenhouse effect. *Critical Reviews in Plant Sciences 22*: 151-184.

Lambert, M.G.; Clark, D.A.; Mackay, A.D. 1990. Long term effects of withholding phosphate application on North Island hill country: Ballantrae. *Proceedings of the New Zealand Grassland Association 51*: 25-28.

Lambert, M.G.; Clark, D.A.; Mackay, A.D.; Costall, D.A. 2000. Effects of fertiliser application on nutrient status and organic matter content of hill soils. *New Zealand Journal of Agricultural Research 43*: 127-138.

Ledgard, S.F.; Brier, G.J.; Littler, R.A. 1987. Legume production and nitrogen fixation in hill pasture communities. *New Zealand Journal of Agricultural Research 30*: 413-421.

McIntosh, P.D.; Hewitt, A.E.; Giddens, K.; Taylor, M.D. 1997. Benchmark sites for assessing the chemical impacts of pastoral farming on loessial soils in southern New Zealand. *Agriculture, Ecosystems & Environment 65*: 267-280.

Metherell, A.K. 2003. Management effects on soil carbon storage in New Zealand pastures. *Proceedings of the New Zealand Grassland Association 65*: 259-264.

Parfitt, R.; Arnold, G.; Baisden, T.; Claydon, J.; Dodd, M.; Ross, C.; Schipper, L. 2007. Changes of C and N from New Zealand soil profiles under pasture over 20 years. *3rd International conference on mechanisms for organic matter stabilization and destabilization in soils and sediments*, Adelaide.

Parfitt, R.L.; Scott, N.A.; Ross, D.J.; Salt, G.J.; Tate, K.R. 2003. Land-use change effects on soil C and N transformations in soils of high N status: comparisons under indigenous forest, pasture and pine plantation. *Biogeochemistry 66*: 203-221.

Parton, W.J.; Hartman, M.; Ojima, D.; Schimel, D. 1998. DAYCENT and its land surface submodel: description and testing. *Global and Planetary Change 19*: 35-48.

Parton, W.J.; Stewart, J.W.B.; Cole, C.V. 1988. Dynamics of C, N, P and S in grassland soils: a model. *Biogeochemistry 5*: 109-131.

Saggar, S.; Parshotam, A.; Sparling, G.P.; Feltham, C.W.; Hart, P.B.S. 1996. 14C-labelled ryegrass turnover and residence times in soils varying in clay content and mineralogy. *Soil Biology and Biochemistry 28*: 1677-1686.

Schipper, L.; Dodd, M.; Fisk, L.; Power, I.; Parenzee, J.; Arnold, G. 2009. Trends in soil carbon and nutrients of hill-country pastures receiving different phosphorus fertilizer loadings for 20 years. *Biogeochemistry in press.*

Schipper, L.A.; Baisden, W.T.; Parfitt, R.L.; Ross, C.; Claydon, J.J.; 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.

Six, J.; Conant, R.T.; Paul, E.A.; Paustian, K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil 241*: 155-176.

Smith, P.; Smith, J.U.; Powlson, D.S.; McGill, W.B.; Arah, J.R.M.; Chertov, O.G.; Coleman, K.; Franko, U.; Frolking, S.; Jenkinson, D.S.; Jensen, L.S.; Kelly, R.H.; Klein-Gunnewiek, H.; Komarov, A.S.; Li, C.; Molina, J.A.E.; Mueller, T.; Parton, W.J.; Thornley, J.H.M.; Whitmore, A.P. 1997. A comparison of the performance of nine soil organic matter models using datasets from seven long-term experiments. *Geoderma 81*: 153-225.

Sparling, G.; Parfitt, R.L.; Hewitt, A.E.; Schipper, L.A. 2003. Three approaches to define desired soil organic matter contents. *Journal of Environmental Quality 32*: 760-766.

Stevenson, B.A. 2004. Changes in phosphorus availability and nutrient status of indigenous forest fragments in Pastoral New Zealand Hill country. *Plant and Soil 262*: 317-325.

Stewart, D.P.C.; Metherell, A.K. 1999. Carbon (13C) uptake and allocation in pasture plants following field pulse-labelling. *Plant & Soil 210*: 61-73.

Tait, A.; Woods, R. 2007. Spatial interpolation of daily potential evapotranspiration for New Zealand using a spline model. *Journal of Hydrometeorology 8*: 430-438.

Tate, K.R.; Giltrap, D.J.; Claydon, J.J.; Newsome, P.F.; Atkinson, I.A.E.; Taylor, M.D.; Lee, R. 1997. Organic carbon stocks in New Zealand's terrestrial ecosystems. *Journal of the Royal Society of New Zealand 27*: 315-335.

Tate, K.R.; Parshotam, A.; Ross, D.J. 1995. Soil carbon storage and turnover in temperate forests and grasslands - a New Zealand perspective *Journal of Biogeography 22*: 695-700.

Tate, K.R.; Wilde, R.H.; Giltrap, D.J.; Baisden, W.T.; Saggar, S.; Trustrum, N.A.; Scott, N.A.; Barton, J.P. 2005. Soil organic carbon stocks and flows in New Zealand: System development, measurement and modelling. *Canadian Journal of Soil Science 85*: 481-489.

White, T.A.; Johnson, I.R.; Snow, V.O. 2008. Comparison of outputs of a biophysical simulation model for pasture growth and composition with measured data under dryland and irrigated conditions in New Zealand. *Grass and Forage Science 63*: 339-349.

10. Appendices

10.1 Abbreviations

ANPP Above-ground net primary production

NHA Net herbage accumulation

OM (soil) Organic matter

SOC Soil organic carbon

SON Soil organic nitrogen

SU Stock units

VCS Virtual Climate Station

10.2 TREE.100 input parameters for DayCent simulations

Parameter	Definition	Value
PRDX(2)	max monthly site productivity (g m^{-2})	0.30
PPDF(1)	optimal growth temperature	17.0
PPDF(2)	maximum growth temperature	30.0
FCFRAC(1,2)	allocation to leaf	0.35
FCFRAC(2,2)	allocation to fine root	0.15
FCFRAC(3,2)	allocation to branch	0.10
FCFRAC(4,2)	allocation to large wood	0.35
FCFRAC(5,2)	allocation to coarse root	0.05
WOODDR(1)	monthly leaf death rate	0.04
WOODDR(2)	monthly fine root death rate	0.04
WOODDR(3)	monthly fine branch death rate	0.014
WOODDR(4)	monthly large wood death rate	0.002
WOODDR(5)	monthly coarse root death rate	0.002

10.3 FIX.100 input parameters for DayCent simulations

Parameter	Definition	Value
VARAT1(1,1)	max C:N ratio for flow to active SOM pool	14
VARAT1(2,1)	min C:N ratio for flow to active SOM pool	4
VARAT2(1,1)	max C:N ratio for flow to slow SOM pool	20
VARAT2(2,1)	min C:N ratio for flow to active SOM pool	14
VARAT3(1,1)	max C:N ratio for flow to passive SOM pool	12
VARAT3(2,1)	min C:N ratio for flow to passive SOM pool	10