Modelled soil carbon changes after reforestation

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Abstract

One of the approaches towards managing atmospheric CO_2 concentration is the planting of trees on former agricultural land, but it is uncertain whether soil carbon stocks will increase or decrease after reforestation. A modelling analysis was carried out to assess what changes in soil organic carbon are possible upon reforesting former grassland. It was based on runs with the whole-system model CenW which allowed explicit modelling of both carbon and nitrogen pools and fluxes. The key findings were:

1) In nitrogen-limited systems without excessive rainfall, total system nitrogen stocks are expected to remain similar to values before replanting trees. There can be small leaching losses for a few years after planting trees, but little change thereafter. Total losses or gains should not normally exceed a few percent of total nitrogen stocks in the system. However, up to several hundred kgN ha^{-1} are transferred from the soil to plant pools after planting trees.

2) With the change in litter quality from grass litter that is low in lignin to needle litter with higher lignin concentration, soil C:N ratios are likely to increase. This is likely to become even more pronounced when branch and bark litter adds to the litter pool. C:N ratios could increase from 16 to 20. Simulations in which each soil layer was modelled separately suggested that it can take many decades for that change in the C:N ratio to fully affect the soil because the most dramatic changes occur in the litter layer.

3) If there are only minor changes in nitrogen stocks, but more significant increases in C:N ratios, it should increase site carbon stocks. Various simulations were tried, with parameters changed that corresponded to changes in productivity, enhancing organic-matter turn-over or making the system more leaky with respect to nitrogen losses. None of these had any significant effect on soil-carbon stocks. Being nitrogen-limited, the system was forced to carbon stocks being controlled by nitrogen stocks multiplied by soil C:N ratios.

4) Productivity could affect soil-carbon stocks in a system where fertility was not limiting. Conversely, carbon stocks in the nitrogen-limited system could be changed by adding extra nitrogen. Other factors can play a role in systems where more significant gains and losses of nitrogen are possible, such as systems with fire, significant deep drainage or top-soil erosion.

These simulations show that explicit modelling of possible changes in the nitrogen cycle can put important constraints on likely changes in carbon stocks upon land-use change.

Key Words

Greenhouse, soil carbon, land-use change, reforestation, nitrogen budget, mitigation.

Introduction

When forests are cleared for agriculture, soil carbon is usually lost if the land is subsequently used for cultivated agriculture, but there are no consistent changes if the subsequent land use is uncultivated pasture (Murty et al 2002). These losses of soil carbon are not easily reversed when land is reforested, and often, there are even further losses of soil carbon after reforestation (Guo and Gifford 2002).

A modelling paper has recently been published by Halliday et al. (2003) that used the G'Day model and applied it to reforestation stands in New Zealand. It came to the conclusions that carbon losses after reforestation are only likely to occur if there are substantial losses of nitrogen stocks. Such losses are often observed after reforestation under New Zealand's wet conditions. In the present work, it was further

explored under what conditions soil carbon losses can occur in a drier Australian systems in which there is less potential for large gains or losses of nitrogen.

The overall aim of the present simulations was to gain a better understanding of the possible changes of soil carbon after land-use change, and the overall reasons why changes may go in certain directions. Specifically, the aim of these simulations was to simulate the change in soil carbon following reforestation, to explore the extent to which soil carbon is controlled by changes in soil nitrogen, and under what conditions, or with what assumptions, that control could be broken.

Methods

Modelling approach
This work used the model CenW 2.1.0 (Kirschbaum 1999), a generic growth model that simulates the fluxes of carbon and water, the interception of solar radiation and the dynamics of nitrogen cycling through plant and soil organic matter pools (Figure 1). The model has been tested against data from the fertilisation and irrigation experiments with *Pinus radiata* at the Biology of Forest Growth (BFG) experimental site near Canberra, Australia (Kirschbaum 1999). Only a brief description is presented here.
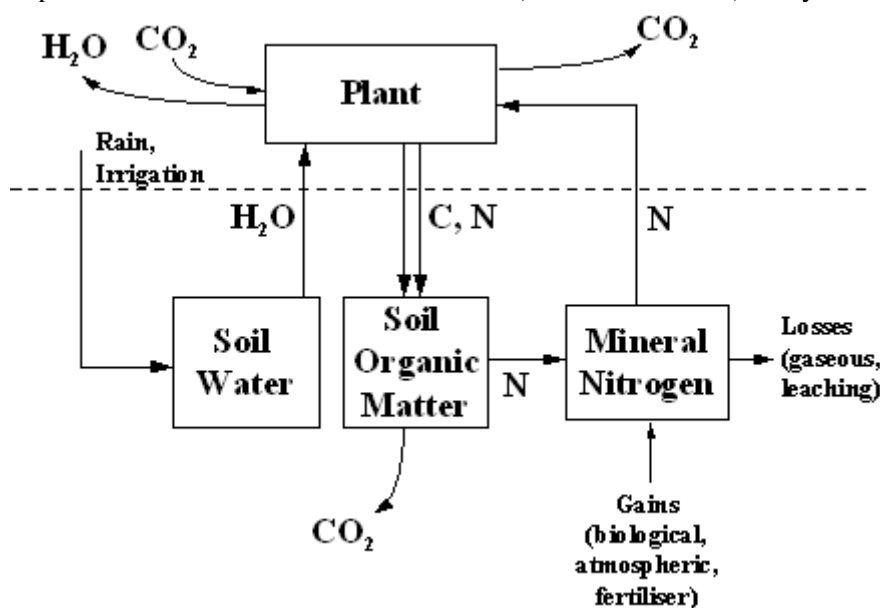
Figure 1. The basic modelling outline showing the key pools and fluxes of carbon, nitrogen and water between these pools and the external environment.

The model runs on a daily time step, with carbon gain calculated from light absorption, modified by temperature, soil water status and foliar nitrogen concentration. Respiration rate is calculated as a constant fraction of photosynthetic carbon gain. Allocation of carbon and nitrogen to different organs is determined by plant nutrition, tree height and plant allocation factors. Water use is calculated with the Penman-Monteith equation, with canopy resistance given by the inverse of stomatal conductance, which is correlated with photosynthetic carbon gain. Water can be lost by transpiration, soil evaporation and deep drainage.

Nitrogen is supplied through atmospheric deposition, fertiliser addition or mineralisation during the decomposition of soil organic matter. The model is run here without symbiotic nitrogen fixation because it used to simulate a pine stand. Decomposition rate is determined by temperature, soil water status and soil organic matter quality in a modified formulation of the CENTURY model (Kirschbaum and Paul 2002). Nitrogen enters the soil through litter production by the shedding of plant parts, such as roots, branches and foliage. Litter production is assumed to be proportional to live biomass. Foliage is also shed during drought, or when self shading in dense canopies induces leaf senescence. Litter is then added to the organic matter pools from which carbon is eventually lost and nitrogen becomes available as inorganic mineral nitrogen.

Some soil nitrogen is lost through volatilisation during the mineralisation of organic nitrogen, with the loss taken as a constant fraction of mineralised nitrogen (Parton et al. 1987; Kirschbaum and Paul 2002). Nitrogen mineralisation occurs when the C:N ratio of the active pool of organic matter falls below a threshold value of 10. The C:N ratio of other organic matter pools is not explicitly controlled but shifts with changes in the C:N ratios of donor pools, which is ultimately based on the C:N ratio in fresh litter and that in the active pool. All mineralised nitrogen is assumed to be taken up by plants apart from that lost through volatilisation and a fraction that may be leached when the soil is saturated with water.

The model was run with observed daily weather for Canberra. Fertility was determined by the amount of soil organic matter and weather-dependent rates of decomposition. For the runs shown below, the model was initialised with soil-organic matter amounts that corresponded to different fertilities as specified in respective simulations below. It was first run to equilibrium for a tree cover, then for 50 years as a grassland (Kirschbaum et al. 2003) before being replanted with *P. radiata* (Kirschbaum 1999) at time 0 for the simulations below.

Results

The modelled pattern of plant growth and key aspects of the soils under standard conditions is shown in Figure 2. When a new plantation was established, plant biomass increased. There was a slight delay for a few years until a new canopy was established, but thereafter the increase in total biomass was fairly linear (Fig. 2a), while stem growth showed a more typical sigmoidal growth pattern (data not shown). Biomass initially comprised mainly foliage and fine roots, but over time, stems and coarse roots became more dominant.
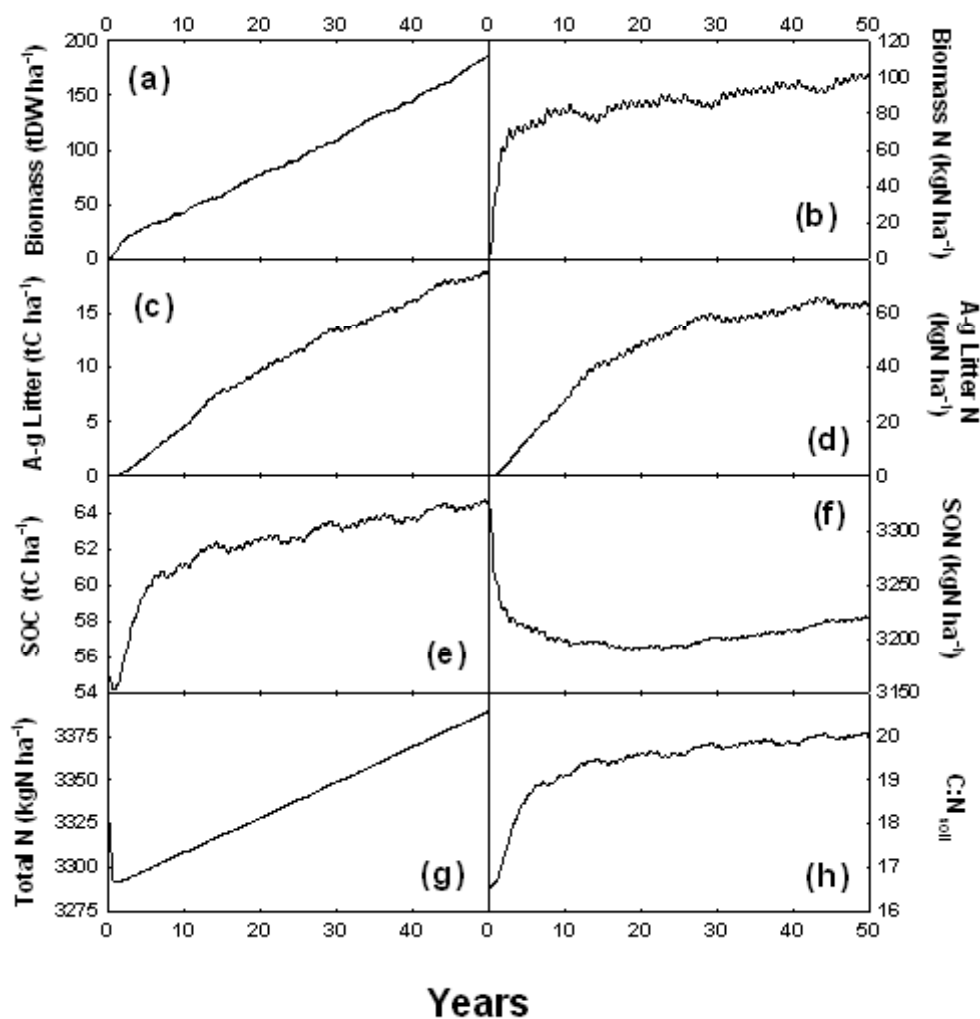
Figure 2. Changes in various pools and ratios after planting *Pinus radiata* on a low-fertility grassland. Shown are total living biomass carbon (a) and nitrogen (b), above-ground litter carbon (c) and nitrogen (d), soil organic carbon minus fresh litter (e), the corresponding nitrogen pools (f) total site nitrogen in all pools (g) and the C:N ratio of soil organic matter minus fresh litter (h).

Biomass nitrogen also increased (Fig. 2b), but followed a very different pattern compared to carbon increases, with a steep increase in biomass nitrogen over the first few years, corresponding to the increase in foliage and fine-root pools, but only slighter on-going increases thereafter as the high-nitrogen pools were saturated, and on-going stem growth required little additional nitrogen.

Changes in litter pools (Figs. 2c, d) followed the increase in biomass pools, with litter initially comprising nitrogen-rich foliage litter, but thereafter changed towards more nutrient-poorer and longer-lasting branch litter. Hence, carbon litter increased linearly over time (Fig. 2c), whereas litter nitrogen increased strongly over the first 20 years and more slowly thereafter (Fig. 2d). After 5 years, there were about 100 kgN ha^{-1} in plant biomass and above-ground litter and about 180 kgN ha^{-1} after 50 years.

Because the system gained nitrogen only through atmospheric deposition, the increase in plant and litter nitrogen had to come at the expense of decreasing soil organic nitrogen, which fell by about 100 kgN ha^{-1} over 50 years (Fig. 2f). Total site nitrogen fell by almost 30 kgN ha^{-1} over the first few years (Fig. 2g) as water and mineralised nitrogen were in excess of the requirements of the initially small tree seedlings so that some nitrogen could be leached out of the system.

After the initial nitrogen loss, nitrogen stocks increased again as atmospheric inputs (2.5 kgN ha^{-1} yr^{-1}) added nitrogen, as there were no further leaching losses, because volatilisation losses were small (at 2% of nitrogen turn-over) and there were no other losses from the system. Hence, the system's total nitrogen stocks remained fairly constant, with the change over 50 years being within 2% of initial stocks.

Soil C:N ratios increased from about 16.5 to 20 (Fig. 2h), with the change from more decomposable grass litter to more resistant litter from pine needles and woody plant components. Multiplying the total amount of nitrogen in soil organic matter (Fig. 2f) by the C:N ratio (Fig. 2h), constrained possible changes in the amount in soil organic carbon (Fig. 2e), which showed an increase from about 55 to 64 tC ha^{-1}.

This system was tightly constrained by the nitrogen budget. Total system nitrogen stocks could not change much because there were no major losses as deep-water drainage was rare. Even with deep drainage, losses
would have been small because other than shortly after tree planting, the pool of mineral nitrogen was likely
to remain small in such a nutrient deficient system. Gains were also small because there was assumed to be no biological fixation, no fertiliser addition and atmospheric inputs were regular but small.

Significant nitrogen inputs could come from dung or fertiliser addition, which is explored further below. Greater nitrogen movements could occur in systems subject to soil erosion, or through burning cut-offs or if litter were removed for animal bedding and the like.

Changed productivity
In the following Sections, various changes to assumptions or contributing processes are explored for their possible effects on the patterns described above. First, the effect of changing growth rate is explored by either doubling CO_2 concentration or reducing rainfall to 75%. Reducing rainfall reduced plant production and decomposition rates. Increasing CO_2 increased productivity and had indirect effects due to the resultant different plant sizes, litter-fall rates and water-use regimes.

The key observations were that total biomass productivity changed as expected, with increases under doubled CO_2 concentration and reductions under reduced rainfall (Fig. 3a). Changes were not large, however, because the system was strongly affected by nitrogen limitation so that water availability was not always limiting, and hence the response to further shortening of water supply was not as great as might have been expected. The compensating effect of nitrogen dynamics could also be seen in the increased biomass nitrogen content under decreased rainfall (Fig. 3b) even though biomass carbon decreased.

Above-ground litter was quite similar under the three conditions (Fig. 3c) which was due to a combination of decreased litter input (in the reduced-rainfall simulation), compensated by reduced

decomposition rate under the drier condition. The opposite case pertained under the high-CO_2 condition which remained more moist because of reduced water use by trees.

Soil organic nitrogen (Fig. 3f) and total nitrogen (Fig. 3g) differed slightly between these simulations, but more importantly, they differed by only small amounts. The C:N ratio of soil organic matter was somewhat lower under reduced rainfall (Fig. 3h), which was due to the higher nitrogen concentration in fresh litter which led to the production of less structural litter and thereby overall to a lower C:N ratio.

Because of the relative constancy in total soil nitrogen and a slight reduction in the C:N ratio, total soil organic matter was somewhat lower by 1-2 tC ha^{-1} in the reduced-rain simulation (Fig. 3e), but even under that simulation, soil carbon increased over the 50 years of the stand's growth. These simulations indicate that even fairly drastic changes in productivity had little effect on soil-carbon amounts because of the strong, and over-riding control by the amounts of nitrogen in the system and the fairly conservative C:N ratios in organic-matter pools.
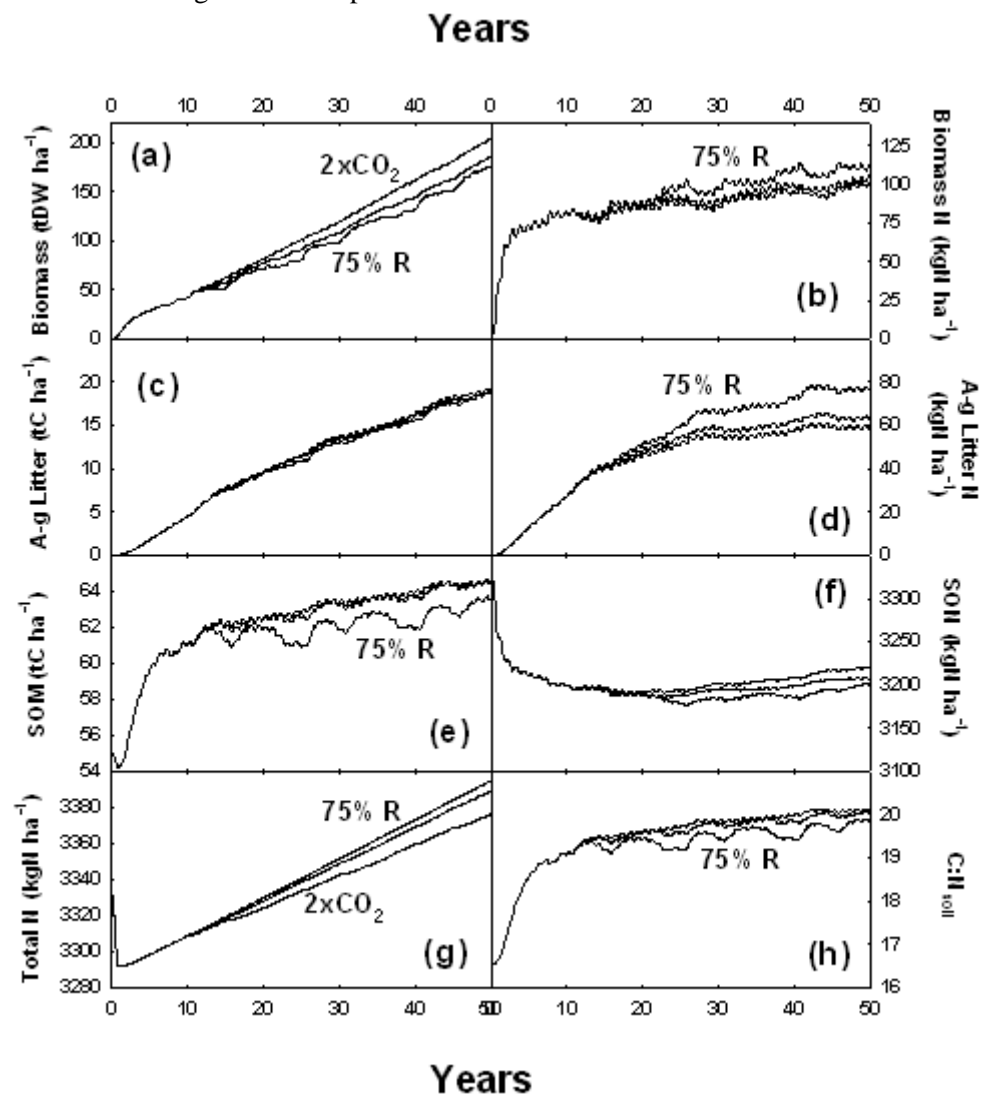
Figure 3. The effect of changing productivity on pools and ratios after reforestation. Pools and ratios as for Fig. 2. Productivity was changed by reducing rainfall to 75% or doubling CO_2 concentration from year 10 onwards.

*Changed productivity in a high-fertility system*
Next, the simulations were repeated for a system set to high fertility, and a simulation under standard conditions is compared with one under reduced rainfall. A stand initialised to high fertility achieved much higher productivity than in the low-fertility simulation (cf. Figs. 2a, 4a), which was also reflected in higher litter dry weight (Fig. 4c) and associated higher amounts of nitrogen in biomass and litter (Figs. 4b, d).

Importantly, soil carbon in the high-fertility case was affected by reduced productivity (Fig. 4e), with soil organic carbon decreasing by almost 10 tC ha^{-1} (or 10%) in the low-rainfall case over 40 years. Soil nitrogen (Fig. 4f) or total site nitrogen (Fig. 4g) did not differ much between the simulations with high and low productivity, which implied that the C:N ratio of soil organic matter was lower when productivity was reduced (Fig. 4h). Even though soil nitrogen exerted little controlling influence under these particular simulation conditions, conservation of mass still had to be obeyed and ratios had to remain within biologically meaningful bounds.

These simulations showed that the finding of soil carbon amounts being controlled by the site's nutrient budget was restricted to low-nutrient systems. In high-fertility systems, soil carbon was not controlled by nitrogen stocks, and other factors could have a controlling effect.

Nitrogen addition to low-fertility system
While there are generally few natural means for nitrogen gains and losses of pine plantations, nitrogen can be gained through fertiliser addition or the movement of animal dung by animals that may shelter under trees rather than on adjoining pasture. This additional input of nitrogen into the system was simulated here as an additional input of 10 kgN ha^{-1} yr^{-1}.
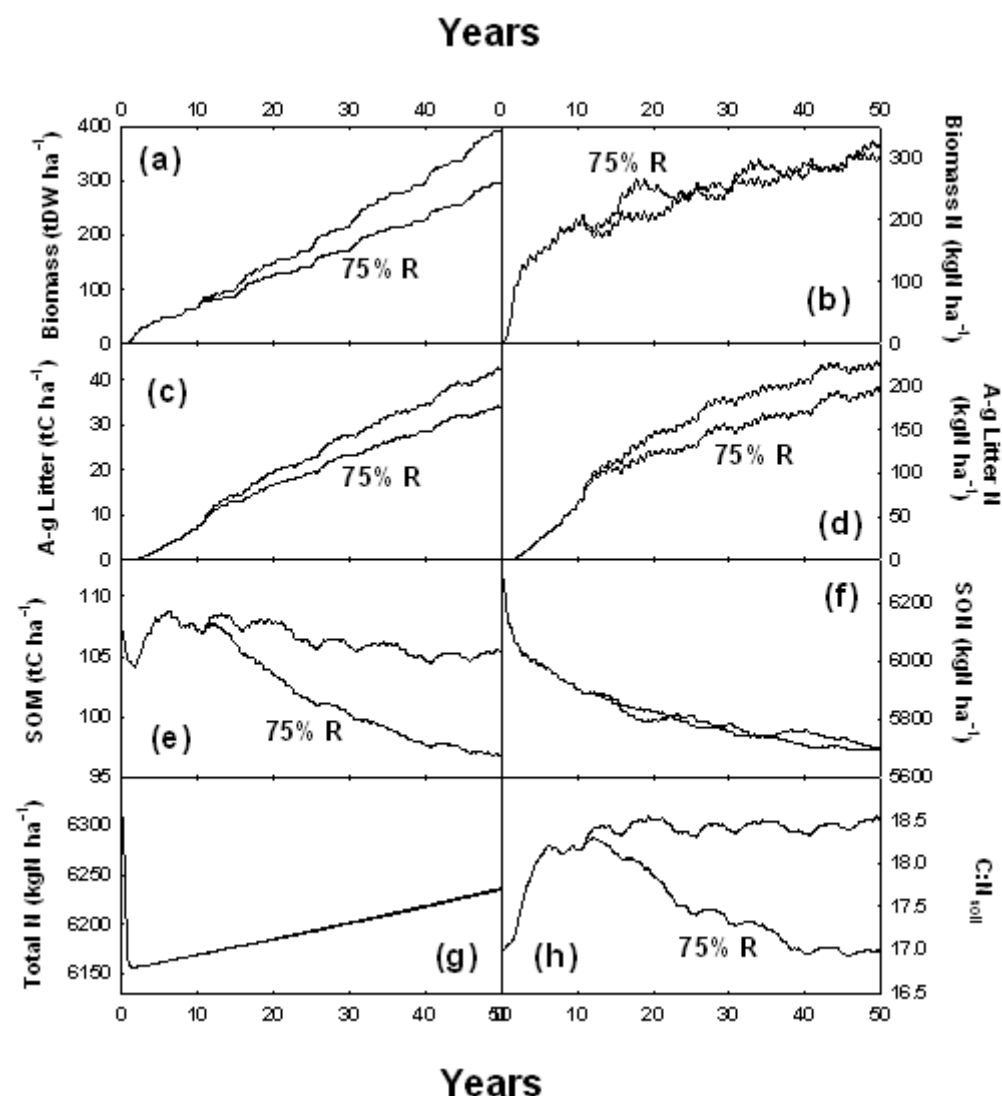
Figure 4. The effect of changing productivity on pools and ratios after reforestation in a highly fertile system. Pools and ratios as for Figure 2. Productivity was changed by reducing rainfall to 75% from year 10 onwards.

Adding extra nitrogen to the system, increased the carbon and nitrogen contents of every pool in the system (Fig. 5). With the C:N ratio of organic matter only marginally affected by nitrogen addition, the nitrogen addition increased soil carbon by about 8 tC ha^{-1} (Fig. 5e). Over 50 years, 500 kgN ha^{-1} had been

added to this system. Of that, about 200 kgN ha^{-1} were retained in biomass (Fig. 5b) and above-ground litter (Fig. 5d) pools, with organic nitrogen increased by about 300 kgN ha^{-1} (Fig. 5f). 300 kgN ha^{-1} multiplied by a C:N ratio of 20 led to an increase in soil carbon by about 6 tC ha^{-1}. The actual increase was even slightly larger because the C:N ratio also increased slightly.

Additional simulations
Space consideration prevent the complete list of simulations to be given here, but additional runs were carried out to simulate the effect of enhanced decomposition rate through soil cultivation and increasing the proportional loss of nitrogen from the system. Both of those changes increased the nitrogen loss from the system and thereby reduce soil carbon stocks, but effects on soil carbon were only slight.

The model was also modified to simulate soil-carbon dynamics separately for the litter layer and separately for each soil layers. The explicit inclusion of separate layers into the soil organic-matter model could simulate a range of observed properties of soils, such as a decrease of amounts of organic matter and C:N ratios with depth. The spatial separation of different organic-matter pools with very different properties slowed changes in C:N ratio in response to changing litter quality. However, the introduced changes were merely in the matter of degree rather than constituting fundamental changes. This had the effect of slowing the effect of different litter quality in its effect on soil C:N ratios, but that effect, too, was only moderate in its overall effect on soil-carbon dynamics.
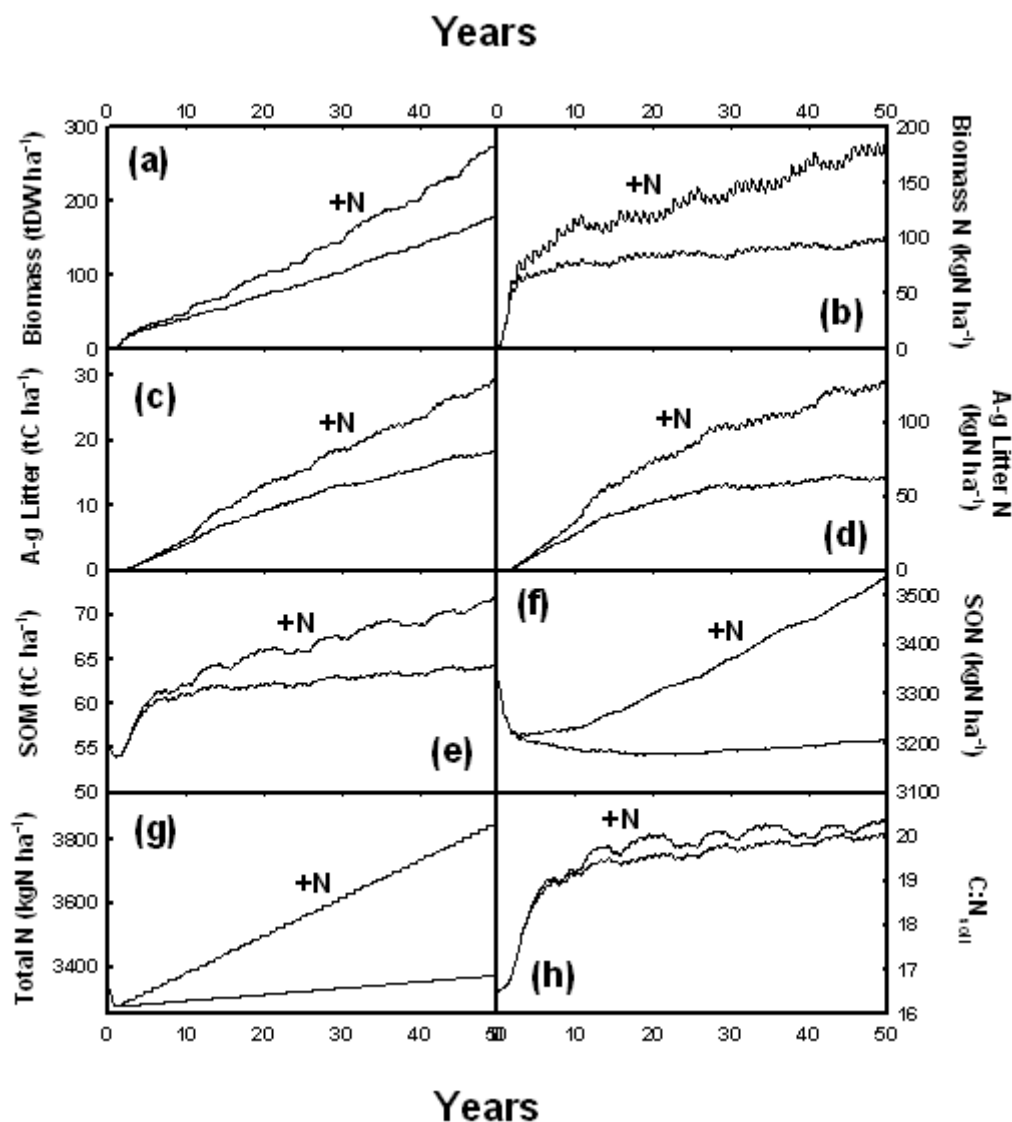
Figure 5. The effect of nitrogen addition on various pools and ratios after reforestation in a low-fertility system. Pools and ratios as for Figure 2. Nitrogen was added at the rate of 10 kgN ha^{-1} yr^{-1} from year 1.

Discussion

The simulations shown here indicate that it is difficult to see how systems limited by nitrogen nutritioncould lose soil carbon upon reforestation provided that there are no possibilities for significant losses of soil nitrogen from the system. If soil nitrogen stocks remain similar (apart from some transfer to plant pools), and C:N ratios increase in line with changes in litter quality, it must be expected that soil carbon stocks would increase upon reforestation. Reductions in soil carbon are possible in systems that are either not limited by nitrogen nutrition, or where significant losses are possible, such as in systems with large deep drainage, or where erosion may remove top soil. Consistent with that, losses of soil carbon after conversion of pastures to forests have generally been restricted to environments that receive large amounts of rainfall (Guo and Gifford 2002).

Observations also indicate that upon deforestation, C:N ratios tend to decrease (Murty et al. 2002). If the reverse applies under reforestation, C:N ratios should increase. That is consistent with the observation that soils under forest systems usually have higher, and often much higher, C:N ratios than grasslands, and consistent with the observation that critical C:N ratios (for the start of nitrogen mineralisation) are lower with more decomposable than more recalcitrant fresh litters (Kirschbaum and Paul 2002). This change in C:N ratio after reforestation could be slowed by modelling the different soil layers separately (data not shown).

So, if nitrogen stocks remain the same, and C:N ratios increase, then soil carbon stocks should increase. That simple logic was consistent with the various detailed simulations shown above, which generally showed an increase in soil carbon after reforestation. This is similar to the conclusions of Halliday et al. (2003) apart from the fact that in the New Zealand soils that they studied, there was greater scope for nitrogen losses through leaching than under the more water-limited Australian conditions.

This leads to the question whether large amounts of nitrogen could be lost from the system. Some nitrogen is simply transferred from the soil to plants and litter pools, and that needs to be explicitly accounted for in these considerations. This may amount to 100-200 kgN ha^{-1}, and, taking a C:N ratio of 15, could explain a carbon loss of about 2-3 tC ha^{-1}. However, an increase in the C:N ratio by just one unit or less would generally have the same numeric effect on increasing soil carbon.

In principle, large amounts of nitrogen could be lost through erosion, frequent litter removal, including burning, harvesting, especially if plant components other than the wood of the stem are removed, or if the early establishment phase is much more extensive than assumed in the model here so that larger amounts of nitrogen could be leached over a longer time.

This worked highlighted the importance of critical assessment of nitrogen budgets as part of studying carbon management in biospheric systems. Because of the generally tight linkage between carbon and nitrogen in soil organic matter pools, any changes in soil carbon, especially, increases in soil carbon are constrained by the need to satisfy the associated nitrogen budgets as well.

References

Guo LB, Gifford RM (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* **8**, 345-360.

Halliday JC, Tate KR, McMurtrie RE, Scott NA (2003). Mechanisms for changes in soil carbon storage with pasture to *Pinus radiata* land-use change. *Global Change Biology* **4**, 1294-1308.

Kirschbaum MUF (1999). CenW, a forest growth model with linked carbon, energy, nutrient and water cycles. *Ecological Modelling* **181**, 17-59.

Kirschbaum MUF, Paul KI (2002). Modelling carbon and nitrogen dynamics in forest soils with a modified version of the CENTURY model. *Soil Biology & Biochemistry* **34**, 341-354.

Kirschbaum MUF, Simioni G, Medlyn BE, McMurtrie RE (2003). On the importance of including soil nutrient feed-back effects for predicting ecosystem carbon exchange. *Functional Plant Biology* **30**, 223-237.

Murty D, Kirschbaum MUF, McMurtrie RE, McGilvray H (2002). Does forest conversion to agricultural land change soil organic carbon and nitrogen? A review of the literature. *Global Change Biology* **8,** 105-123.

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.