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Modelling the carbon cycle of grassland in the Netherlands under various management strategies and environmental conditions

A. VAN DEN POL VAN DASSELAAR[1] AND E.A. LANTINGA

Department of Theoretical Production Ecology, Wageningen Agricultural University,
P.O. Box 430, NL-6700 AK Wageningen, The Netherlands
[1] Present address: Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, P.O. Box 8005, NL-6700 EC Wageningen, The Netherlands

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Abstract

A simulation model of the carbon cycle of grassland (CCGRASS) was developed to evaluate the long-term effects of different management strategies and various environmental conditions on carbon sequestration in the soil. The results presented here refer to permanent grassland on a young sedimentary loam soil in the Netherlands.

The model predicted that the rate of increase in the amount of soil organic carbon will be highest at low to moderate application rates of nitrogen (100 – 250 kg N ha^{-1} yr^{-1}). This is due to the fact that the annual gross photosynthetic uptake of CO_2 in permanent grassland is hardly influenced by the level of N supply. Since N shortage stimulates the growth of the unharvested plant parts (roots and stubble) the carbon supply to the soil is highest at low to moderate N application rates. The rate of increase in the amount of soil organic carbon will be higher under grazing than under mowing as a result of a greater amount of carbon added to the soil.

Increase of atmospheric CO_2 concentration may induce an increase in decomposition rate of soil organic matter due to simultaneously increased temperatures. At the same time, plant productivity and thus carbon supply to the soil will be stimulated due to the CO_2-fertilization effect. Under the assumption of a temperature increase of 3 °C if the present atmospheric CO_2 concentration doubles, the model predicted that the combined effect of elevated CO_2 and temperature will slightly reduce the rate of increase in the amount of organic carbon in grassland soils compared to that under unchanged environmental conditions. There was 2% less carbon sequestration by grassland at the end of a period of 100 years as a result of these changes in environmental conditions. The separate effects of increased temperature or elevated CO_2 were 10% less and 10% more carbon storage at the end of a period of 100 years, respectively.

Keywords: model, carbon balance, carbon sequestration, grassland, management, atmospheric CO_2 concentration, temperature, The Netherlands

Introduction

Greenhouse gases such as CO_2, CH_4 and N_2O are absorbing the long-wave radiation re-emitted from the surface of the earth. The atmospheric concentration of these greenhouse gases is increasing, for example CO_2 is increasing at a rate of 0.5% annually (Bolin, 1986). This will stimulate plant growth (Goudriaan & Unsworth, 1990), but can also induce a global warming. The share of CO_2 in the total increase of greenhouse gases (about 50%) puts an emphasis on the need for accurate estimates of the global carbon cycle.

Grasslands play an important role in the cycling of CO_2. They account for about 20% of the terrestrial CO_2 fluxes of the global carbon cycle, and have a similar share in global soil organic carbon (Minami *et al.*, 1994). Grasslands may contribute to a global biotic carbon sequestration, reducing the rate of increase of atmospheric CO_2. The objective of the study presented here is to predict the long-term effects of grassland management and expected climatic changes on carbon sequestration by grassland. For this purpose, a mechanistic dynamic simulation model of the carbon cycle of grassland was developed. It incorporates the influence of management (mowing, grazing, fertilizer N input level) and environment (temperature, atmospheric CO_2 concentration). Mechanistic dynamic simulation models have proven to be useful for the study of soil organic matter dynamics; they help to integrate the fragmentary knowledge about the processes involved and therefore to develop a better understanding of the behaviour of the soil system as a whole. They are useful in formulating and testing hypotheses and in establishing the relative importance of parameters (Verberne *et al.*, 1990). The results presented here refer to permanent grassland on a young sedimentary loam soil in the Netherlands.

Carbon cycle of grassland

Photosynthesis is the basic process of the carbon cycle. CO_2 and H_2O are transformed into assimilates, and subsequently used for formation of biomass. After death, plant material turns to litter and soil organic matter. Excreta of grazing animals and spreading of animal manure also add carbon to the soil.

Figure 1 shows the annual carbon balance of mown grass swards at a fertilizer N input range of 100 to 700 kg N ha^{-1} yr^{-1}. Figure 1 is based on experimental results collected on loam and clay grassland soils in the Netherlands (Van de Ven, 1983; Lantinga, 1985; Schapendonk & Lantinga, 1990). The annual gross crop CO_2 assimilation of grass is, under good water supply, on average 22 t C ha^{-1} yr^{-1} at fertilizer N levels ranging from 250 to 700 kg N ha^{-1} yr^{-1}. At a fertilizer N level of 100 kg N ha^{-1} yr^{-1} the annual gross crop CO_2 assimilation is about 10% lower. At increasing rates of N application a smaller part of the assimilated carbon is translocated to the roots and stubble. The proportion of gross photosynthetic uptake lost by shoot respiration equals about 30%, independent of the rate of N application.

The carbon balance of grazed grassland is more extensive. The stubble production of grazed grassland is estimated to be about 5% higher than the stubble production of mown grassland (Lantinga, unpublished measurements). Grazing losses account for about 15% of the harvestable fraction above a 4-cm stubble (Anonymous, 1993). The magnitude of carbon in faeces and urine of grazing animals depends on the stocking density, herbage intake per animal and herbage digestibility.

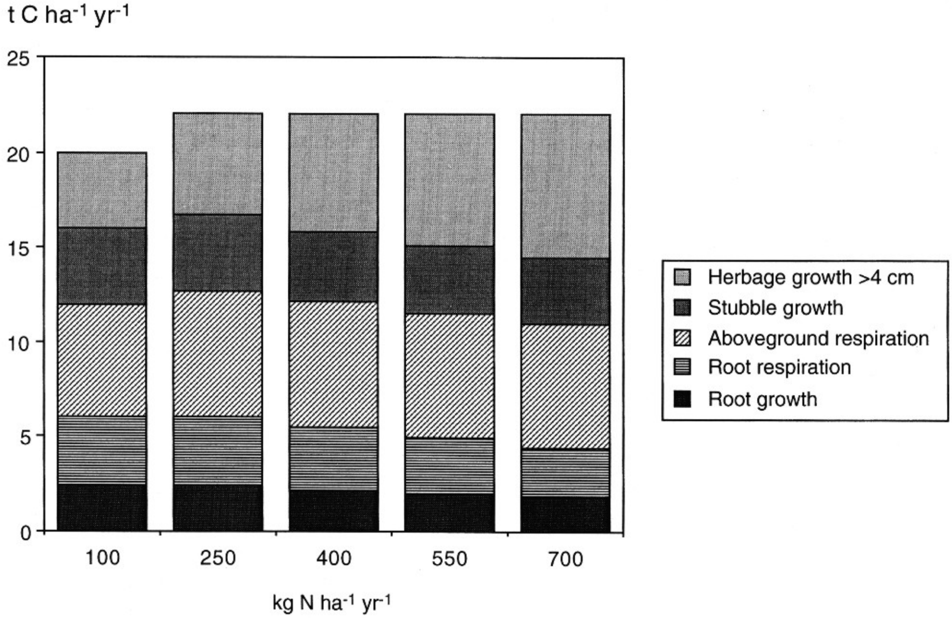

Figure 1. Annual carbon balance of mown grass swards at a fertilizer N range of 100 to 700 kg N ha^{-1} yr^{-1}.

The annual amounts of carbon added to a mown and a grazed grassland soil are shown in Table 1. Under mowing, only carbon from crop residues is added to the soil. Since the harvestable crop fraction is higher at high N rates compared to low N rates and the annual gross crop CO_2 assimilation is independent of the rate of N application at N rates above 250 kg ha^{-1} yr^{-1}, less carbon is supplied to the soil at high N rates. The amount of carbon added to the soil is higher for grazing than for mowing due to extra amounts of carbon in grazing losses, faeces and urine, and more stubble production. The C/N ratio of the added organic material is lower at high N rates compared to low N rates due to a higher N content of this material (Table 1). The C and N contents are derived from Whitehead (1986) and Whitehead *et al.* (1990).

Table 1. Annual amounts of carbon (kg C ha^{-1}) supplied to a mown and a grazed grassland soil, and C/N ratios (C/N) of the added organic material, at fertilizer N rates of 100 to 700 kg N ha^{-1} yr^{-1} (Sources: Figure 1 and data in text).

Fertilizer rate kg N ha^{-1} yr^{-1}	Mowing		Grazing			
	grass	C/N	grass	excreta	total	C/N
100	6400	38.9	7170	969	8139	30.0
250	6490	30.3	7455	1295	8750	24.1
400	5940	24.8	7023	1523	8546	20.3
700	5280	21.6	6552	1863	8415	17.8

Decomposition, resulting in the release of CO_2, is influenced by the C/N ratio of the decomposable material, soil type and climate (Bouwman, 1990). Material with a low C/N ratio is more easily decomposed than material with a high C/N ratio (Van Veen & Paul, 1981; Janzen & Kucey, 1988). Soils with a high clay content generally have a higher organic matter content and exhibit a lower decomposition rate than sandy soils (Kortleven, 1963). Soil temperature and precipitation are the most important climatic factors influencing the decomposition rate. The decomposition rate is highest at a high temperature and an intermediate moisture content of the soil (Jenny, 1965; Van der Linden *et al.*, 1987).

Model description

The model CCGRASS (Carbon Cycle GRASSland) simulates the carbon cycle of grassland soils. The subroutine SOM forms the heart of the model. It simulates the dynamics of soil organic matter and is based on a mechanistic dynamic simulation model of Verberne (Verberne *et al.*, 1990; Verberne, 1992). In this model, the organic matter in the soil is divided into recently added organic material (subdivided into decomposable material, structural material and resistant material) and native soil organic matter (subdivided into microbial biomass, active organic matter and stabilized organic matter). All transformations are considered to be first-order reactions. The decomposition rate is assumed to be dependent on soil temperature and soil moisture content and on the C/N ratio of the decomposable material. Some modifications have been made to the model of Verberne. The relationship between soil moisture content and decomposition rate has been changed (see below). Subroutines GRASS, WATER and RNGEN have been added. Possible effects of an increasing atmospheric CO_2 concentration have been included. Both in the model of Verberne and in CCGRASS the relationship between soil temperature and decomposition rate according to Van der Linden *et al.* (1987) is used (Figure 2). Soil temperature is calculated by linear interpolation between average monthly soil temperatures at 10 cm depth. To study the effects of grassland management and climate change for a particular site, site specific data are necessary. They are incorporated in the model via several data files.

Subroutine GRASS calculates the amounts of carbon added to the soil under mowing and grazing for a fertilizer N application range of 100 to 700 kg N ha^{-1} yr^{-1}, and the C/N ratios of the added organic material. GRASS is based on the experimental results presented in Figure 1. Annual amounts are being split up to daily amounts by superimposing a seasonal pattern of herbage production according to Lantinga (1985) (not shown). The subroutine WATER calculates the actual soil moisture content. This subroutine is taken from a simulation model of crop growth for water-limited production situations (Van Keulen *et al.*, 1992). The annual rainfall pattern is simulated by using a rain generator in the subroutine RNGEN (De Ruijter, 1990). The same rainfall pattern is used each year to avoid fluctuations in the simulated time course of soil organic carbon.

Due to the increasing atmospheric concentration of CO_2 and other greenhouse gases, temperature on earth could be rising, which might lead to less carbon storage

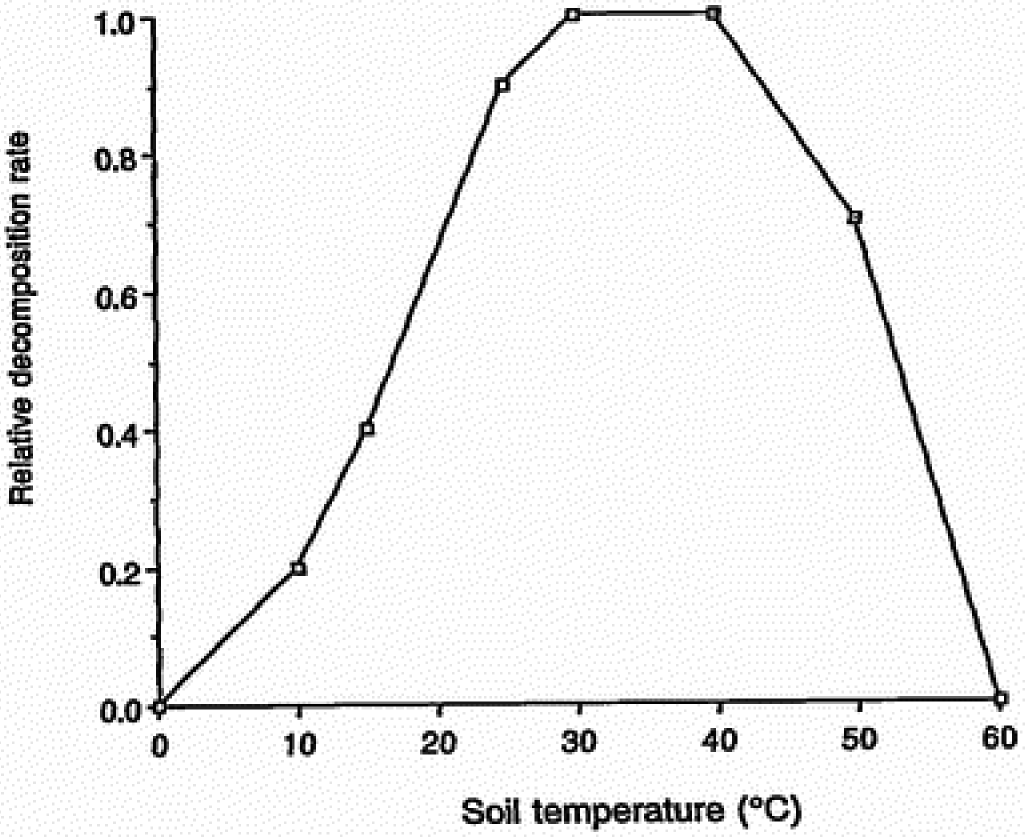

Figure 2. Relationship between soil temperature and decomposition rate (Van der Linden, 1987).

in the soil as the decomposition rate increases with increasing temperature (Figure 2). CCGRASS assumes that temperature rises with 3 °C if the present atmospheric CO_2 concentration doubles (derived from Bouwman, 1989). An increasing CO_2 concentration can induce a larger plant production, the so-called CO_2-fertilization effect (Goudriaan & Unsworth, 1990; Goudriaan, 1992). An annual growth rate of the atmospheric CO_2 concentration of 0.5% could be translated into an annual increase in plant production of 0.25% (Goudriaan, 1992). This is included in the model. A number of other possible implications of an increasing CO_2 concentration or temperature are not included in the model:

1. According to Farrar & Williams (1991) root:shoot ratios tend to increase for CO_2-enriched herbaceous plants, but decrease at elevated temperatures. Therefore the model assumes that assimilate partitioning is not changed under simultaneous increases in atmospheric CO_2 concentration and temperature.
2. As the atmospheric CO_2 concentration rises the N concentration of foliage and roots will decrease, irrespective of availability of N in the soil (Conroy, 1992). A higher C/N ratio at elevated CO_2 suggests that plant material would decompose more slowly. However, this is likely to be counteracted by the effects of an increased concentration of soluble sugars and starch (Polglase & Wang, 1992) and lower lignin:N and lignin:P ratios (Conroy, 1992).
3. Effects of increasing temperature on total plant production are not taken into account, since they are of minor importance compared to the CO_2-fertilization effect (Taylor, 1993; Wolf & Van Diepen, 1993).
4. Effects of an increasing CO_2 concentration on weather variables like rainfall are not included, as the impact is not yet predictable (e.g. Tinker & Ineson, 1990).

Relationship between soil moisture content and decomposition rate

The relationship between soil moisture content (SMC) and decomposition rate is not fully understood. In situations of shortage or surplus of water, decomposition of organic material is slower than at an intermediate SMC. In simulation models, the relationship between SMC and decomposition rate is often characterized by a relative SMC, e.g. relative to the SMC at saturation (Beek & Frissel, 1973) or at field capacity (Van Keulen & Seligman, 1987). As each soil has its own characteristics, it may be better to describe the relationship between SMC and decomposition rate by the four characteristic moisture contents of a soil: air dry (AD), wilting point (WP), field capacity (FC) and saturation (ST). Figure 3 shows a possible relationship between SMC and decomposition rate, which is used in the model CCGRASS. It is based on a review of the available literature (Stanford & Epstein, 1974; Stott *et al.*, 1986; Van Keulen & Seligman, 1987; Beek & Frissel, 1973).

Results

The results presented here refer to a young sedimentary loam soil at Swifterbant in Oostelijk Fleveland. At this site, Hassink & Neeteson (1991) have studied the effect of grassland management on the amount of soil organic carbon. On such a soil with a very good water supply, there is hardly any limitation of grass growth by water shortage in an average year. Therefore the data of Figure 1 and Table 1 were used as

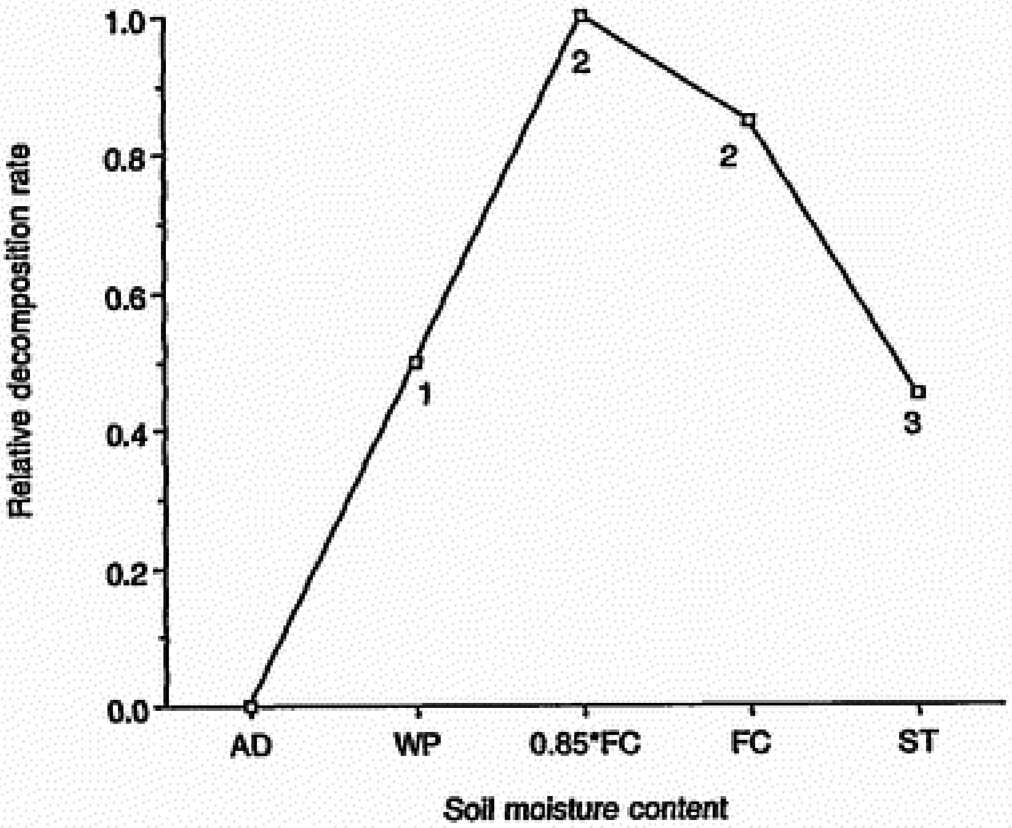

Figure 3. Relationship between soil moisture content and decomposition rate, based on a review of the available literature (1 = Stott *et al.*, 1986; 2 = Van Keulen & Seligman, 1987; 3 = Beek & Frissel, 1973).

input for the model. The initial amount of soil organic carbon is set at 55 t C ha^{-1} in the upper layer of 30 cm. The soil moisture content in spring of year 1, the start of the simulation, is set at 0.435, which is the soil moisture content at field capacity. The equilibrium amount of soil organic carbon is independent of the initial conditions (results not shown).

Influence of management strategies

Figure 4 shows the simulated time course of soil organic carbon in an unchanged climate under mowing and grazing at fertilizer N inputs of 100, 250, 400 and 700 kg N ha^{-1} yr^{-1}. The rate of increase of soil organic carbon appeared to be higher for grazing than for mowing and higher at low rates of N application than at high rates. However, during the first years, especially under grazing, there was hardly any effect of fertilizer N level.

Influence of environmental conditions

Figure 5 shows the influence of soil temperature on the simulated time course of soil organic carbon at a constant atmospheric CO_2 concentration, i.e. without effects on total grass production. To examine the influence of temperature year-round, daily soil temperatures in the Netherlands were decreased or increased with a constant value. The rate of increase of soil organic carbon appeared to be higher at low temperatures than at high temperatures.

The possible effects of an increased atmospheric CO_2 concentration and/or temperature on soil organic carbon over a period of 100 years are shown in Figure 6. In the model, atmospheric CO_2 concentration increases at a rate of 0.5% annually (Bolin, 1986). Plant production increases then at a rate of 0.25% annually

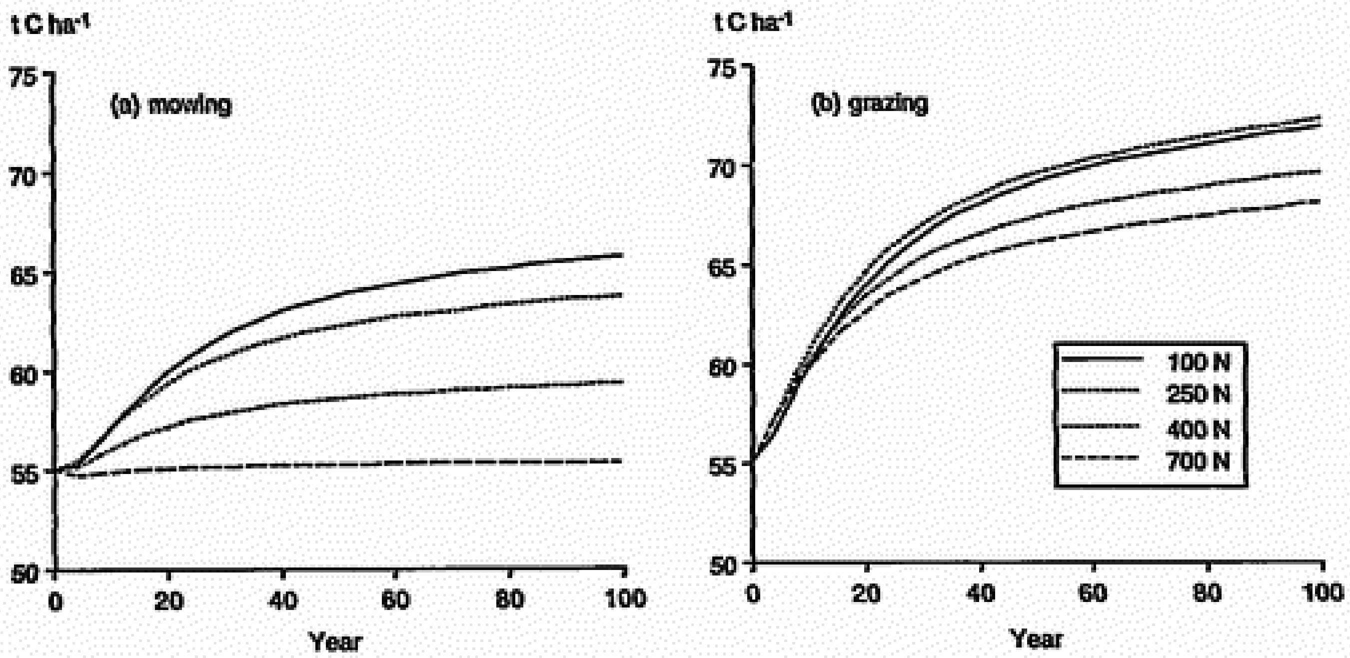

Figure 4. Simulated time course of soil organic carbon (t C ha^{-1}) in an unchanged climate under (a) mowing and (b) grazing at four rates of N application (100, 250, 400 and 700 kg N ha^{-1} yr^{-1}).

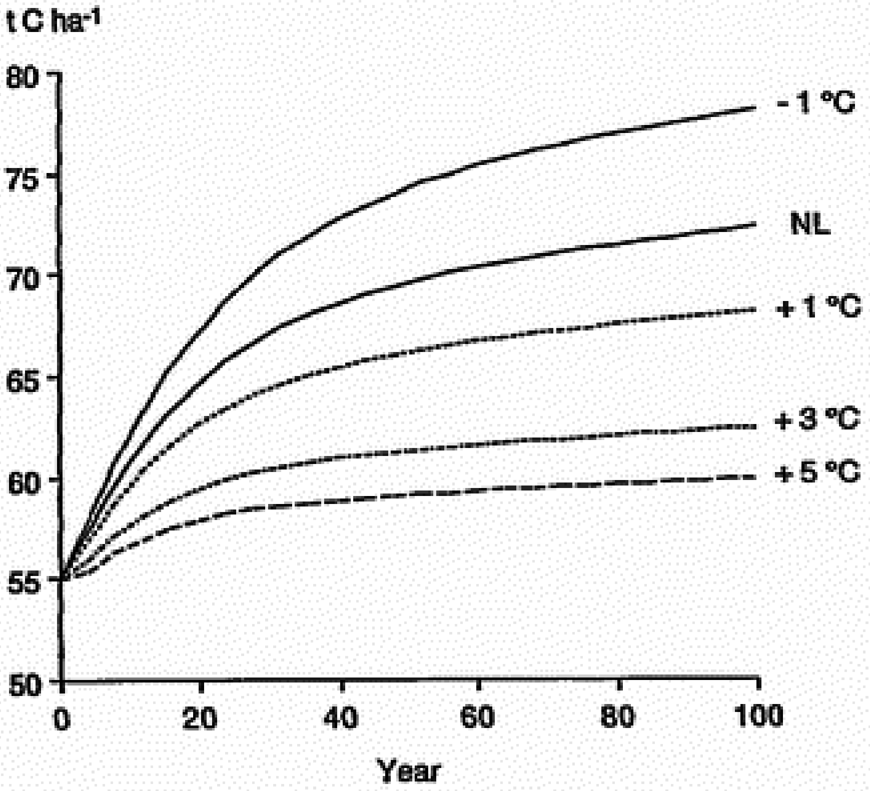

Figure 5. Influence of soil temperature (°C, NL = current soil temperature in the Netherlands) on the simulated time course of soil organic carbon (t C ha^{-1}) under grazing at a constant atmposheric CO_2 concentration and a fertilizer N rate of 250 kg N ha^{-1} yr^{-1}.

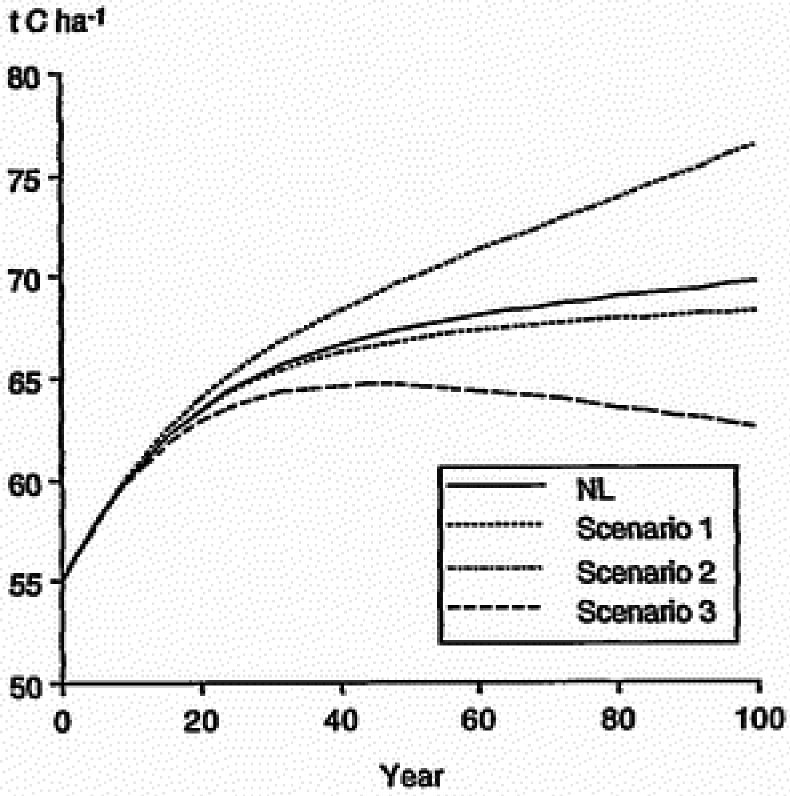

Figure 6. Influence of different environmental scenarios on the simulated time course of soil organic carbon (t C ha^{-1}) under grazing at a fertilizer N rate of 400 kg N ha^{-1} yr^{-1} (NL = the Netherlands at present; scenario 1 = atmospheric CO_2 concentration, plant production and temperature increase annually with 0.5%, 0.25% and 0.18%, respectively; scenario 2 = atmospheric CO_2 concentration, plant production and temperature increase annually with 0.5%, 0.25% and 0%, respectively; scenario 3 = atmospheric CO_2 concentration, plant production and temperature increase annually with 0.5%, 0% and 0.18%, respectively).

(Goudriaan, 1992). Temperature increases at a rate of 0.18% annually, leading to an increase of 3 °C (present annual mean temperature of 10.5 °C) if the present atmospheric CO_2 concentration doubles (derived from Bouwman, 1989). Under the assumptions of the model the combined effect of elevated CO_2 and temperature will slightly reduce the rate of increase in the amount of organic carbon in grassland soils compared to that under unchanged environmental conditions. There was 2% less carbon sequestration by grassland at the end of a period of 100 years as a result of these changes in environmental conditions. The separate effects of increased temperature or elevated CO_2 were 10% less and 10% more carbon storage at the end of a period of 100 years, respectively.

Discussion

The carbon cycle in agro-ecosystems comprises many various processes. It is therefore not possible to forecast with a simple model the time course of soil organic carbon accurately. However, the effects of, for example, grassland management and changes in environmental conditions on carbon sequestration in the soil may be evaluated with a feasibility study, like the present one. Especially because there is a lack of experimental data, a model like CCGRASS is a useful tool to study those effects. The few available data from long-term experiments at ambient CO_2 do not include fertilizer N levels up to 700 kg ha^{-1} yr^{-1}. For example, in the Park Grass experiment at Rothamsted (Warren & Johnston, 1964) the highest level was 145 kg N ha^{-1} yr^{-1}. The only available reference material comes from Hassink & Neeteson (1991). They studied the effects of grassland management on the amount of soil organic carbon, three years after the start of their experiments (Table 2). At the beginning of their experiments the amount of soil organic carbon was assumed to be the same for every treatment (Hassink, pers. comm.), since no initial soil carbon measurements were done. After about three years, the amount of soil carbon was considerably higher under grazing than under mowing. This effect was reproduced with the model (Figure 4), but differences between grazing and mowing were smaller than those reported by Hassink & Neeteson (4870 vs. 8949 kg C ha^{-1}, averaged over the N levels). Other experiments by Hassink (pers. comm.) showed no significant short-term effect of

Table 2. Amounts of organic carbon (kg ha^{-1}) in loamy grassland soils (0–25 cm) at different fertilizer N levels (kg ha^{-1} yr^{-1}) under mowing and grazing in March 1989, i.e. three years after the start of the treatments (Hassink & Neeteson, 1991).

Fertilizer rate kg N ha^{-1} yr^{-1}	Mowing		Grazing
250	55620		63306
400	53466		61537
550	51668		65729
700	58105		64084
average	54715		63664
difference		8949	

grazing or mowing on the amount of soil organic carbon. Hassink & Neeteson (1991) found no significant short-term effect of fertilizer N level on the amount of soil organic carbon. The model showed the highest net increase of soil organic carbon at low to moderate rates of N application (Figure 4), but note that during the first years of simulation there were no clear differences between rates of N application.

The difference between grazing and mowing is a consequence of the higher amount of organic material that is added to the soil (Table 1). Although the influence of the rate of N application is not quite clear from short-term experiments, a higher net increase of soil organic carbon at low to moderate application rates of N compared to high application rates seems to be realistic. At low to moderate rates of N application more organic material is added to the soil with a higher C/N ratio (Table 1); a high C/N ratio decreases the decomposition rate (Van Veen & Paul, 1981; Janzen & Kucey, 1988).

The effect of clover was not studied. Hatch *et al.* (1991) observed that the accumulation rate of soil organic matter was greater under a fertilized (420 kg N ha^{-1} yr^{-1}) perennial ryegrass sward than under an unfertilized ryegrass/white clover sward. Both swards were grazed rotationally by young beef cattle. Total carbon content of the soil under the ryegrass sward rose from 34 t C ha^{-1} in 1976 (sowing) to 68 t C ha^{-1} in 1988, and to only 51 t C ha^{-1} under the grass/clover sward. This large difference in accumulation rate may have been caused by a lower dry matter production of the grass/clover sward, and also by a faster decomposition rate of clover residues, due to a lower C/N ratio.

Increase of atmospheric CO_2 concentration may induce a temperature rise. At increasing temperatures, the decomposition rate of organic material increases (Van der Linden *et al.*, 1987). As a consequence carbon storage in the soil will be less (Figure 5). On the other hand, increased plant productivity due to the CO_2-fertilization effect will increase carbon storage in the soil. At present it is not quite clear which effect will be dominating, either the increase in decomposition rate or the increase in plant production. This depends on both the absolute changes in environmental conditions and the effects of these changes on the processes considered. Under the assumptions of the model, carbon storage in the soil was slightly less (only 2% after 100 years) at elevated CO_2 and increased temperature compared to that under unchanged environmental conditions (Figure 6). Various authors have hypothesized on carbon storage in the soil at elevated atmospheric CO_2 and increased temperature. According to Franz (1990) there are several lines of evidence that the increase in decomposition rate will dominate the increase in plant productivity, and may have already been detected (see also Houghton & Woodwell, 1989). This means less carbon storage in the soil and a higher release of CO_2 to the atmosphere. However, potential changes in long-term carbon storage remain unclear, as evidence to support contradictory hypotheses can be found (Wood *et al.*, 1994). For example, hypotheses of Bazzaz (1990) and Hunt *et al.* (1991) result in an increased carbon storage in the soil, while hypotheses of Strain & Cure (1985) result in a decreased carbon storage in the soil. More research on C and N cycling patterns after long-term exposure to elevated CO_2 is therefore needed to answer the long-term carbon storage question (Wood *et al.*, 1994).

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