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Evaluation of Models (PaSim, RothC, CENTURY and DNDC) for Simulation of Grassland Carbon Cycling at Plot, Field and Regional Scale

STRIVE

Environmental Protection Agency Programme

2007-2013

SSTI
Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government

Environmental Protection Agency

The Environmental Protection Agency (EPA) is a statutory body responsible for protecting the environment in Ireland. We regulate and police activities that might otherwise cause pollution. We ensure there is solid information on environmental trends so that necessary actions are taken. Our priorities are protecting the Irish environment and ensuring that development is sustainable.

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Evaluation of Models (PaSim, RothC, CENTURY and DNDC) for Simulation of Grassland Carbon Cycling at Plot, Field and Regional Scale

(2005-FS-32-M1)

STRIVE Report

Prepared for the Environmental Protection Agency

by

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Executive Summary

Biogeochemical models are increasingly used to simulate greenhouse gas (GHG) exchange and carbon (C) cycling in terrestrial ecosystems. Models enable the integration of processes and can be upscaled from plot to field and regional scale. In addition, such models are becoming increasingly important in the development of GHG accounting systems. There is a need to investigate the applicability of such models to the major ecosystem types in Ireland.

A literature review was carried out to evaluate the use of the RothC, CENTURY, DNDC and PaSim models for modelling soil organic carbon (SOC) stock changes in Irish grasslands (Chapter 2). RothC, CENTURY and DNDC have simulated SOC stock changes in mineral soils under grassland, arable and forest cover. PaSim has not been used similarly. Based on this review, CENTURY and RothC are the most suitable models for simulating SOC stock changes in grassland soils in Ireland. Where assessments of nitrous oxide (N_2O) emissions are to be carried out in tandem with SOC stock change investigations, the DNDC model should be considered.

The potential response to climate change of SOC stocks in two grassland sites in Ireland with contrasting soil and climatic conditions was assessed using the RothC, CENTURY and DNDC models (Section 3). The future climate was simulated using regionally downscaled datasets for the period 2021–2060 for a range of Intergovernmental Panel on Climate Change (IPCC) emission scenarios. All three models predicted a reduction in SOC stocks at the Cork site, with variation between models and scenarios. The range of reduction of SOC was 1.9 to 7.4 t C ha^{-1}, equivalent to a per cent loss range of 1.4 to 5.4%. At the Wexford site, the CENTURY and DNDC models predicted small changes in SOC, while RothC predicted losses of 2.3 to 4.4 t C ha^{-1}, equivalent to a per cent loss range of 2.9 to 5.7%. Although these models should be tested at more sites, RothC and CENTURY appear to be more suitable than DNDC for simulating future changes in SOC stocks in Irish soils.

There is an urgent need to establish experiments which will provide data on long-term changes in SOC stocks, and provide a sound basis for further model comparisons and regional- and national-scale assessments. Suitable datasets relating to climate, soils and land management should be collated and harmonised so that a geographic information system (GIS)-based platform for model upscaling can be developed and information gaps identified.

1 Introduction

Anthropogenic activity is driving the enrichment of greenhouse gases (GHGs) in the atmosphere, with fossil fuel usage and land-use change being the principal agents for CO_2, and agriculture being the principal source of methane (CH_4) and nitrous oxide (N_2O). It is now widely accepted that this is causing climate change which could result in more extreme weather events, with severe implications for ecosystems, health, infrastructure and property. The terrestrial biosphere is a key component of the global carbon (C) cycle, with soils being estimated to contain 2011 Pg (1 Pg = 1 Gt = 10^{15}g) of organic C to 1 m depth. This is about four times the amount of C in vegetation and twice the amount in the atmosphere (Bolin et al. 2000). Although estimates of human emissions are relatively well understood, less is known about how GHGs are cycled between ecosystems and the atmosphere, and how climate change could perturb these cycles. In addition to this there is a need for scientific tools to account for GHG balances in different land-use systems and to support national GHG reporting requirements pursuant to the United Nations Framework Convention on Climate Change and its Kyoto Protocol.

Grasslands are one of the Earth's most abundant land cover types and account for approximately 40.5% of the terrestrial land area (White et al. 2000). There is a growing body of knowledge about CO_2 exchange at field and landscape level (e.g. Flanagan et al. 2002; Gilmanov et al. 2007; Novick et al. 2004) which shows that grassland can act as both a source and a sink of CO_2. Grassland is the dominant land use in Ireland. Eaton et al. (in press) estimated that, in 2000, grasslands accounted for 53.3% of the land area of Ireland and 25% of soil organic carbon (SOC) stocks to 1 m depth. Studies using eddy covariance (Jaksic et al. 2006a) and chamber techniques (Byrne et al. 2005) suggest that Irish grasslands are moderate sinks for CO_2.

Biogeochemical models are increasingly used to simulate GHG exchange and carbon cycling in terrestrial ecosystems. Models enable the integration of processes and can be upscaled from plot to field and regional scale. In addition, such models are becoming increasingly important in the development of GHG accounting systems. There is a need to investigate the applicability of models to simulate and predict carbon stocks and GHG exchange in Irish grasslands. Given this background, this study had the following objectives.

1 To conduct a literature review of the RothC, CENTURY, DNDC and PaSim models, and to evaluate their use for modelling SOC stock changes in Irish grasslands (Section 2).

2 To use the RothC, CENTURY and DNDC models to investigate the potential response to climate change of SOC stocks in two grassland sites in Ireland with contrasting soil and climatic conditions.

2 Use of the RothC, CENTURY, DNDC and PaSim Models for Modelling Soil Organic Carbon Stock Changes in Grasslands

2. 1 Background

Biogeochemical models are an increasingly used tool in studies of biosphere–atmosphere exchange of GHGs. There are a number of reasons for this. The carbon cycle is very complex and multilayered and it is therefore not possible to measure experimentally all of its components across the range of temporal and spatial scales necessary. For example, measuring changes in SOC stocks in extremely difficult because soils are highly variable and models are frequently used to estimate current and future stock changes. While models are not a substitute for measurements, they do allow integration of processes and advance the understanding of same. In addition, once models are adequately calibrated, they can be used to investigate the effect of changes in management and climate, as well as providing a research tool which can be used to upscale from plot to field and regional level.

2.2 Objective

The objective of this chapter is to review the relevant literature in relation to the existing models RothC, CENTURY, DNDC and PaSim and to evaluate their application to SOC stock changes in grasslands at plot, field and regional scales.

2.3 Description of Models

2.3.1 RothC

The Rothamsted Carbon model (RothC) is a process-based model of carbon turnover in non-waterlogged soils. It was developed at Rothamsted Research in the UK using data from the Rothamsted long-term experiments (Hart 1984; Jenkinson et al. 1987; Jenkinson and Rayner 1977). It was originally developed for and parameterised to model the turnover of organic carbon in arable soils at plot level under a range of soil and climatic conditions (Coleman and Jenkinson 1996). It has been extended to model turnover at plot level in grassland (Coleman et al. 1997) and forest sites (Falloon and Smith 2002; Smith et al. 2006). It models the effects of soil type, temperature, moisture content and plant cover on carbon turnover in non-waterlogged soils. It uses a monthly time step to calculate total organic carbon (t ha^{-1}), microbial biomass carbon (t ha^{-1}) and 14°C (from which the radiocarbon age of the soil can be calculated) on a year to centuries timescale (Jenkinson 1990; Jenkinson et al. 1991; Jenkinson and Coleman 1994; Jenkinson et al. 1992). The model calculates the SOC stock on an annual basis from which the rate of change can be inferred. The RothC website is at http://www.rothamsted.bbsrc.ac.uk/aen/carbon/rothc.htm. As RothC does not work well for organic soils, a new model, ECOSSE, has been developed as an alternative (Smith et al. 2007b).

2.3.1.1 Structure of RothC

At the start of the RothC simulation, SOC (t C ha^{-1}) is divided into decomposable plant material (DPM) and resistant plant material (RPM), both of which decompose by first-order kinetics to give CO_2 (which is lost from the system), microbial biomass (BIO) and humified organic matter (HUM). SOC is split into four active compartments and a small amount of inert organic matter (IOM). The four active compartments are DPM, RPM, BIO and HUM. Each compartment decomposes by a first-order process with its own characteristic rate. The IOM compartment is resistant to decomposition. The structure of the model is shown in Figure 2.1.

Incoming plant carbon is split between DPM and RPM, depending on the DPM/RPM ratio of the particular incoming plant material. For example, for most agricultural and improved grassland, RothC uses a DPM/RPM ratio of 1.44, i.e. 59% of the plant material is DPM and 41% is RPM. For deciduous or tropical woodland a DPM/RPM

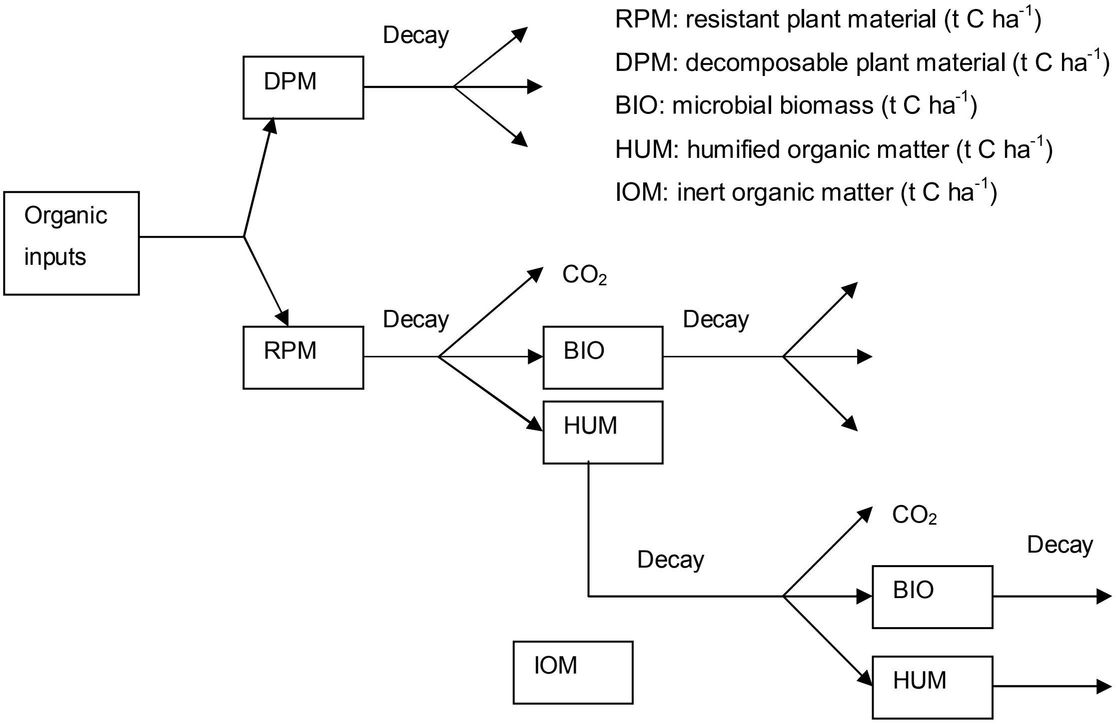

Figure 2.1 Partitioning of the basic components of organic matter in the soil in RothC (Coleman and Jenkinson 2005).

ratio of 0.25 is used, so 20% is DPM and 80% is RPM. All incoming plant material passes through these two compartments once.

Both DPM and RPM decompose to form CO_2 (which is emitted to the atmosphere), BIO and HUM. The proportion that goes to CO_2 and to BIO + HUM is determined by the clay content of the soil. The BIO + HUM is then split into 46% BIO and 54% HUM. BIO and HUM both decompose to form more CO_2, BIO and HUM. Farmyard manure (FYM) is assumed to be more decomposed than normal plant material. It is split in the following way: DPM 49%, RPM 49% and HUM 2%.

2.3.1.2 Inputs to RothC

RothC operates on a monthly time step and its major input variables are soil texture and weather data. These are listed in Table 2.1.

2.3.1.3 Outputs from RothC

The RothC model estimates the total SOC stock (t C ha^{-1}) at monthly or annual intervals and partitions it into the pools DPM, RPM, BIO and HUM. It also estimates the loss of CO_2 (t C ha^{-1}) due to decomposition of organic matter and can be used to assess the dynamics of ^{13}C.

2.3.1.4 Use and performance of RothC

As stated above, RothC was originally developed for arable soils but has been extended to other site types. It has been successfully applied to long-term, plot-level experiments across a range of soil and climatic conditions, including grassland, cropland and forest soils in the UK (Coleman et al. 1997); forest soils in the USA (Coleman et al. 1997); and arable soils in Germany (Coleman et al. 1997), Australia (Coleman et al. 1997), the Czech Republic (Coleman et al. 1997), China (Guo et al. 2007; Yang et al. 2003) and Kenya (Kamoni et al. 2007b) (Table 2.2). It has also been used to simulate SOC changes in various arable rotations, including sandy soils in Thailand (Wu et al. 1998) and calcareous clay soils in Syria (Jenkinson et al. 1999). Marked deviations from experimental data have been reported by Ludwig (2005) for maize cultivation on a silty soil in Germany, and by Lobe et al. (2005) for

Table 2.1 Summary inputs to RothC.

Time step	Meteorology	Soil and plant	Management
Month	Precipitation (mm) [1]Open-pan evaporation (mm) [2]Average air temperature (°C)	[3]Clay content (%) Depth of soil sample (cm)	[4]Estimate of decomposability of incoming plant material [5]Soil cover [6]Monthly input of plant residues (t C ha^{-1}) [7]Monthly input of farmyard manure (t C ha^{-1})

1 Rainfall and open-pan evaporation are used to calculate the topsoil moisture deficit (mm) (TSMD), as it is easier to obtain rainfall and pan evaporation data, from which the TSMD is calculated, rather than monthly measurements of the actual topsoil moisture deficit.

2 Air temperature is used rather than soil temperature because it is more easily obtainable for most sites. For the Rothamsted Research station, monthly air temperature satisfactorily represents the monthly mean soil temperature in the surface 20 cm, showing a difference of only +1°C of the annual minimum and –1°C of the annual maximum (Coleman and Jenkinson 2005).

3 Clay content is used to calculate how much plant-available water the topsoil can hold; it also affects the way organic matter decomposes. For a description of how decomposition rate constants and TSMD are calculated see Coleman and Jenkinson (2005).

4 An estimate of the decomposability of the incoming plant material – the DPM/RPM ratio (t C ha^{-1}/ t C ha^{-1}) (discussed above). Guideline values are given in the RothC manual (Coleman and Jenkinson 2005).

5 It is necessary to indicate whether or not the soil is vegetated because decomposition has been found to be faster in fallow soil than in cropped soil, even when the cropped soil is not allowed to dry out (Jenkinson et al. 1987; Sommers et al. 1981; Sparling et al. 1982). In the model input files the soil cover is classified as 'fallow' or 'covered' on a monthly basis.

6 The plant residue input is the amount of carbon that is put into the soil per month (t C ha^{-1}), including carbon released from roots during crop growth. As this input is rarely known, the model is most often run 'in reverse', generating input from known soil, site and weather data.

7 The amount of FYM (t C ha^{-1}) put on the soil, if any, is input separately, because FYM is treated slightly differently from inputs of fresh plant residues.

coarse textured arable soils in South Africa. Coleman and Jenkinson (2005) advise that it should be used cautiously on subsoils, soils developed on recent volcanic ash, and tundra and taiga soils, and not at all on soils that are permanently waterlogged. RothC has also been applied successfully in simulating changes in SOC stocks due to land-use change. Romanya et al. (2000) used a chronosequence approach to study changes in SOC after afforestation of Mediterranean agricultural soils and found that the changes in SOC were accurately simulated by RothC. Cerri et al. (2003; 2007a) used data from 11 site specific 'forest to pasture' chronosequences in the Brazilian Amazon and found that RothC accurately simulated the decline in SOC following clearance and conversion to grassland.

The RothC model has been linked to spatial databases (or GISs) to estimate changes in regional SOC stocks. This has a number of advantages in that it allows the local soil attributes, meteorological conditions and land use to be taken into account, enables dynamic estimates, facilitates scenario analysis and allows areas of particular SOC sequestration to be identified. The first such analysis was that carried out by Falloon et al. (1998b). The future SOC stock changes in an area of 24,804 km^2 in Hungary were predicted by combining RothC with soil data for 351 polygons with unique soil, land form, lithology, land use and meteorological data. Falloon et al. (2006) have combined RothC with 1 km × 1 km soils, land use and land-use change data with climatic data to develop a system which can be used to investigate the effects of changes in land use, land management and climate change on national SOC stocks in the UK (including Northern Ireland). Smith et al. (2006) have used a similar approach, at 18 km × 18 km resolution, to estimate the changes in mineral soils in European forests for the period 1990–2100. Using the same resolution, Smith (2005) estimated changes in SOC stocks of European croplands and grasslands during the period 1990–2080. More recently, Smith et al. (2007a) estimated changes in SOC stocks of cropland mineral soils of European Russia and the Ukraine during the period 1990–2070 (resolution not stated). RothC has also been combined with spatial data to predict SOC stock in Kenya between 1990 and 2030 (Cerri et al. 2007b), in the Brazilian Amazon between 2000 and 2030 (Kamoni et al. 2007a), and in Jordan between 2000 and 2030 (Al-Adamat et al. 2007).

Table 2.2 Synthesis of published studies using RothC to simulate changes in SOC in long-term experiments.

Country	Climate	Ecosystem	Site comments	Performance	Reference
Rothamsted, UK	Temperate	Forest	Geescroft Wilderness, naturally regenerated forest	Good reproduction of increase in soil C and radiocarbon content of soil C	Coleman et al. (1997)
Rothamsted, UK	Temperate	Fallow	Highfield Bare Fallow, grazed until 1959, fallow thereafter	Measured decline in soil C initially faster than RothC, but gap narrowed	Coleman et al. (1997)
Rothamsted, UK	Temperate	Grassland	Park-grass experiment, grassland for 300 years	Reasonable fit to changes in soil C in unmanured and fertilised plots. Poor reproduction in plots treated with FYM and fishmeal	Coleman et al. (1997)
Ruzynê, Czech Republic	Cool, temperate	Arable	Ruzynê experiment, continuous cultivation for 100s of years	Good agreement with measurements for fertilised plots. Poor agreement in plots receiving N and FYM due to variability in measurements	Coleman et al. (1997)
Tamworth, Australia	Temperate, subtropical	Arable	Tamworth experiment, cultivation for 130 years	Poor fit to measurements	Coleman et al. (1997)
Waite, Australia	Temperate, subtropical	Arable		Decline in soil C due to cultivation reproduced well	Coleman et al. (1997)
China	Cool, temperate	Arable	Long-term fertilisation trial	Accurate simulation of changes in soil C	Yang et al. (2003)
China	Cool, temperate	Arable	Long-term fertilisation trial	Accurate simulation of changes in soil C	Yang et al. (2003)
China	Cool, temperate	Arable	Long-term experiments set up in early 1980s	Accurate simulation of changes in soil C	Guo et al. (2007)
Kenya	Tropical	Arable	Two experiments, 26 and 13 years long	Good agreement with measurements, but poor for intercropping	Kamoni et al. (2007b)

2.3.2 CENTURY

CENTURY was originally developed for grassland soils (Parton et al. 1987) but has been widely used for arable (e.g. Falloon and Smith 2002) and forest soils (e.g. Kirschbaum and Paul 2002). Similarly to RothC it operates on a monthly time step and its major input variables are soil texture and weather data.

The CENTURY model simulates the long-term dynamics of C, nitrogen (N), phosphorus (P) and sulphur (S) for different plant–soil systems. The model can simulate the dynamics of grassland systems, agricultural crop systems, forest systems and savannah systems. The grassland/crop and forest systems have different plant production submodels that are linked to a common soil organic matter (SOM) submodel. The savannah submodel uses the grassland/crop and forest subsystems and allows for the two subsystems to interact through shading effects and nitrogen competition. The SOM submodel simulates the flow of C, N, P and S through plant litter and the different inorganic and organic pools in the soil. The model runs using a monthly time step. A detailed description of the model (CENTURY 4) and the user manual are available at http://www.nrel.colostate.edu/projects/century/nrel.htm. Model documentation is available in Parton et al. (1992).

2.3.2.1 Structure of CENTURY

The soil organic matter submodel is based on multiple compartments for SOM and is similar to other models of SOM dynamics (Jenkinson 1990; Jenkinson and Rayner 1977; van Veen and Paul 1981). Figure 2.2 illustrates the pools and flows of carbon in CENTURY. The model includes three soil organic matter pools (active, slow and passive) with different potential decomposition rates, above-ground and below-ground litter pools, and a surface microbial pool, which is associated with decomposing surface litter.

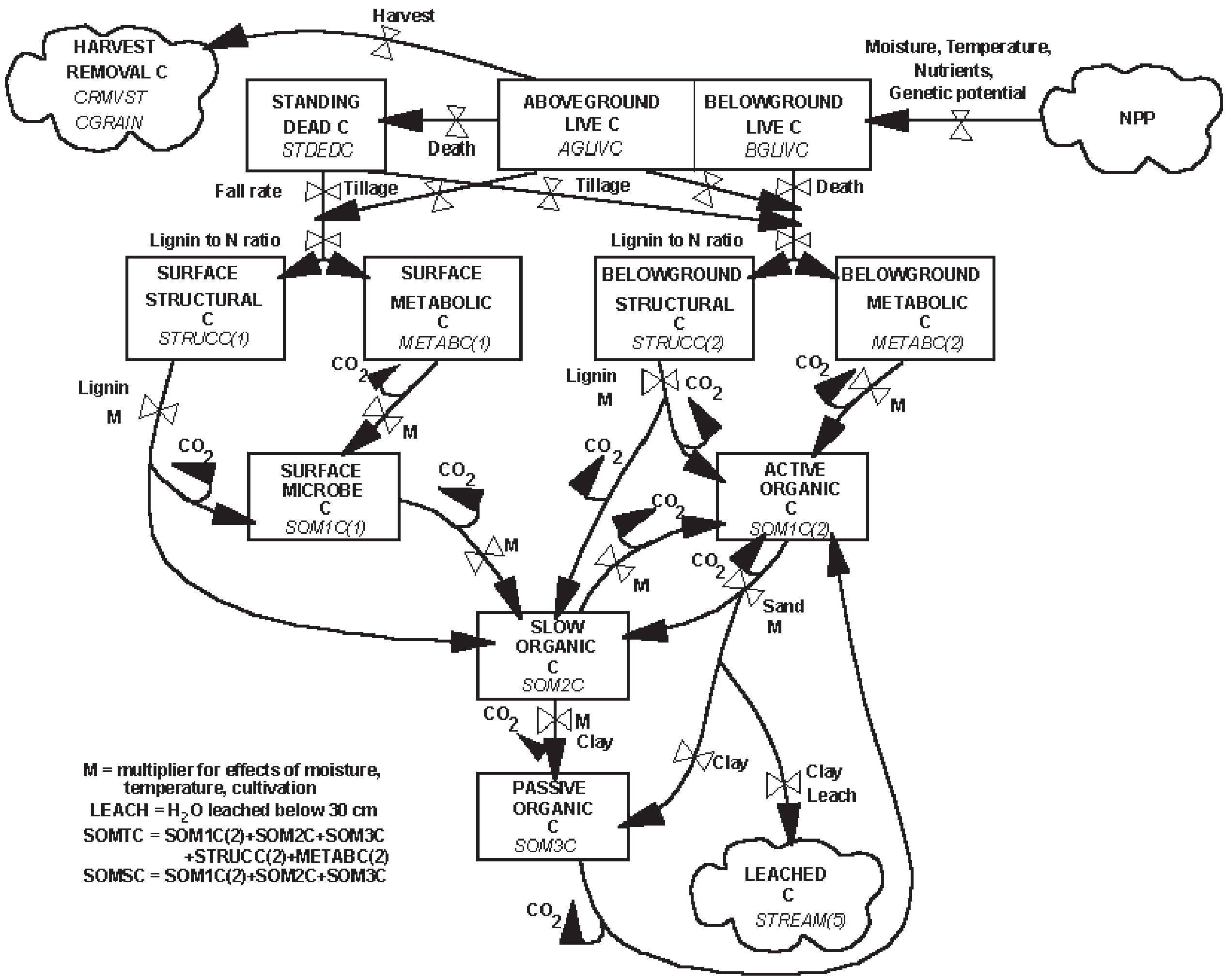

Figure 2.2 Structure of the soil carbon submodel in CENTURY (Parton et al. 1992).

Table 2.3 Summary inputs to CENTURY.

Time step	Meteorology	Soil and plant	Management
Month	Precipitation (mm) Average maximum and minimum air temperature (°C)	Clay content (%) Depth of soil sample (cm) [1]Initial soil C, N, P and S levels (g m^{-2})	[2]Lignin content of plant material [3]Atmospheric and soil N inputs (g N m^{-2} yr^{-1})

[1] The user can choose to run the model considering only C and N dynamics, or C, N and P, or C, N, P and S.

[2] This can generally be estimated from existing literature.

[3] Inputs of N in fertiliser and animal slurry or manure application should be available from management records. Atmospheric inputs of N can be estimated from literature.

2.3.2.2 Inputs to CENTURY

The CENTURY model operates on a monthly time step and its major input variables are soil texture and weather data. These are listed in Table 2.3.

2.3.2.3 Use and performance of CENTURY

As stated above, CENTURY was originally developed for pasture soils but has been extended to other site types. Parton et al. (1993) tested CENTURY using observed data from 11 temperate and tropical grasslands around the world. They found that soil C and N levels could be simulated to within ±25% of the observed values (100 and 75% of the time respectively) for a diverse set of soils. CENTURY has been successfully applied to long-term, plot-level experiments across a range of soil and climatic conditions (Table 2.4), including grassland, cropland and forest soils in the UK (Kelly et al. 1997); forest soils in the USA (Kelly et al. 1997); arable soils in Germany (Kelly et al. 1997), Denmark (Foereid and Høgh-Jensen 2004), Australia (Kelly et al. 1997), the Czech Republic (Kelly et al. 1997) and Kenya (Cerri et al. 2007b); grassland soils in Germany (Werth et al. 2005) and grassland converted to continuous fallow in Russia (Mikhailova et al. 2000). CENTURY has also been applied successfully to chronosequence-based experiments. Romanya et al. (2000) used a chronosequence approach to study changes in SOC after afforestation of Mediterranean agricultural soils, and found that the changes in SOC were accurately simulated by CENTURY. Cerri et al. (2004; 2007a) found that CENTURY was able to reproduce the change in SOC stocks following conversion of forest in the Brazilian Amazon to grassland.

The CENTURY model has also been linked to spatially defined datasets to make regional assessment of SOC stock changes with changing land use and management. Burke et al. (1990) combined CENTURY with climate and soil data to simulate spatial variability in carbon storage and fluxes within grassland ecosystems in Colorado at 2.5 km × 2.5 km resolution. Burke (1991) extended this work to cover the entire Great Plains and adjacent areas of the Central Lowlands in the USA. Ardö and Olson (2003) combined CENTURY with land use, climate and soil data to assess changes in SOC at 1 km × 1 km resolution over an area of 262,144 km^2 in Sudan. In a similar synthesis, Parton et al. (2004) estimated SOC stocks in Senegal during the period 1991–2001 at 10 km × 10 km resolution. It has been used to assess SOC stock changes in grassland soils in 16 states of the USA (Paustian et al. 2001) and in croplands of the USA (EPA 2006). In recent work it has been combined with spatial datasets to assess SOC stock changes in the Brazilian Amazon between 2000 and 2030 (Cerri et al. 2007b), in Kenya between 1990 and 2030 (Kamoni et al. 2007a), and in Jordan between 2000 and 2030 (Al-Adamat et al. 2007).

2.3.3 DNDC

The denitrification–decomposition (DNDC) model is a process-based computer simulation model of soil C and N biogeochemistry (Li 1996, 1992a, b, 1994). The model operates at a daily time step and consists of two components. The first component, consisting of the soil climate, crop growth and decomposition submodels, predicts soil temperature, moisture, pH, redox potential (Eh) and substrate concentration profiles driven by ecological drivers (e.g. climate, soil, vegetation and anthropogenic activity). The second component, consisting of the nitrification, denitrification and fermentation submodels, predicts NO, N_2O, N_2, CH_4 and NH_3 fluxes based on the modelled soil environmental factors. The entire model forms a bridge between C and N biogeochemical cycles and the basic ecological drivers. Further information on the model and the user manual are available at http://www.dndc.sr.unh.edu/.

2.3.3.1 Structure of DNDC

In DNDC, SOC resides in four major pools: plant residue (i.e. litter), microbial biomass, humads (i.e. active humus) and passive humus. Each pool consists of two or three subpools with different specific decomposition rates. The daily decomposition rate for each subpool is regulated by the pool size, the specific decomposition rate, soil clay content, N availability, soil temperature and soil moisture. When SOC in a pool decomposes, the decomposed carbon is partially allocated into other SOC pools, and partially lost as CO_2. Dissolved organic carbon (DOC) is produced as an intermediate during decomposition, and can be immediately consumed by the soil microbes. The structure of the model is shown in Figure 2.3.

Table 2.4 Synthesis of published studies using CENTURY to simulate changes in SOC in long-term experiments.

Country	Climate	Ecosystem	Site treatments	Performance	Reference
Halle, Germany	Temperate	Arable	Bad Lauchstädt long-term fertiliser experiment	Good agreement between model and observations of soil C	Kelly et al. (1997)
Rothamsted, UK	Temperate	Grassland	Park-grass experiment, grassland for 300 years	Good reproduction of increase of soil C due to addition of FYM	Kelly et al. (1997)
Ruzynê, Czech Republic	Cool, temperate	Arable	Ruzynê experiment, continuous cultivation for 100s of years	Good agreement with measurements for manured plots, poor agreement in control plots	Kelly et al. (1997)
Tamworth, Australia	Temperate, subtropical	Arable	Tamworth experiment, cultivation for 130 years	Good agreement with measurements	Kelly et al. (1997)
Waite, Australia	Temperate, subtropical	Arable		Decline in soil C due to cultivation reproduced well	Kelly et al. (1997)
Rothamsted, UK	Temperate	Forest	Geescroft Wilderness, naturally regenerated forest	Observations suggest increasing soil C while model levels off	Kelly et al. (1997)
Carolina, USA	Temperate, subtropical	Forest	Calhoun experimental Forest, plantation forest	Good reproduction of increase in soil C following conversion from arable to forest	Kelly et al. (1997)
Kursk, Russia	Continental	Arable	Grassland converted to arable	Successful simulation of soil C during 50 years of fallow	Mikhailova et al. (2000)
Asov, Denmark	Temperate	Arable	30-year experiment	Good relationship between model and observations	Foerid and Høgh-Jensen (2004)
Baden-Württemberg, Germany	Temperate	Grassland	27-year experiment	Good relationship between model and observations	Werth et al. (2005)
Kenya	Tropical	Arable	Two experiments, 26 and 13 years long	Good agreement with measurements	Kamoni et al. (2007b)

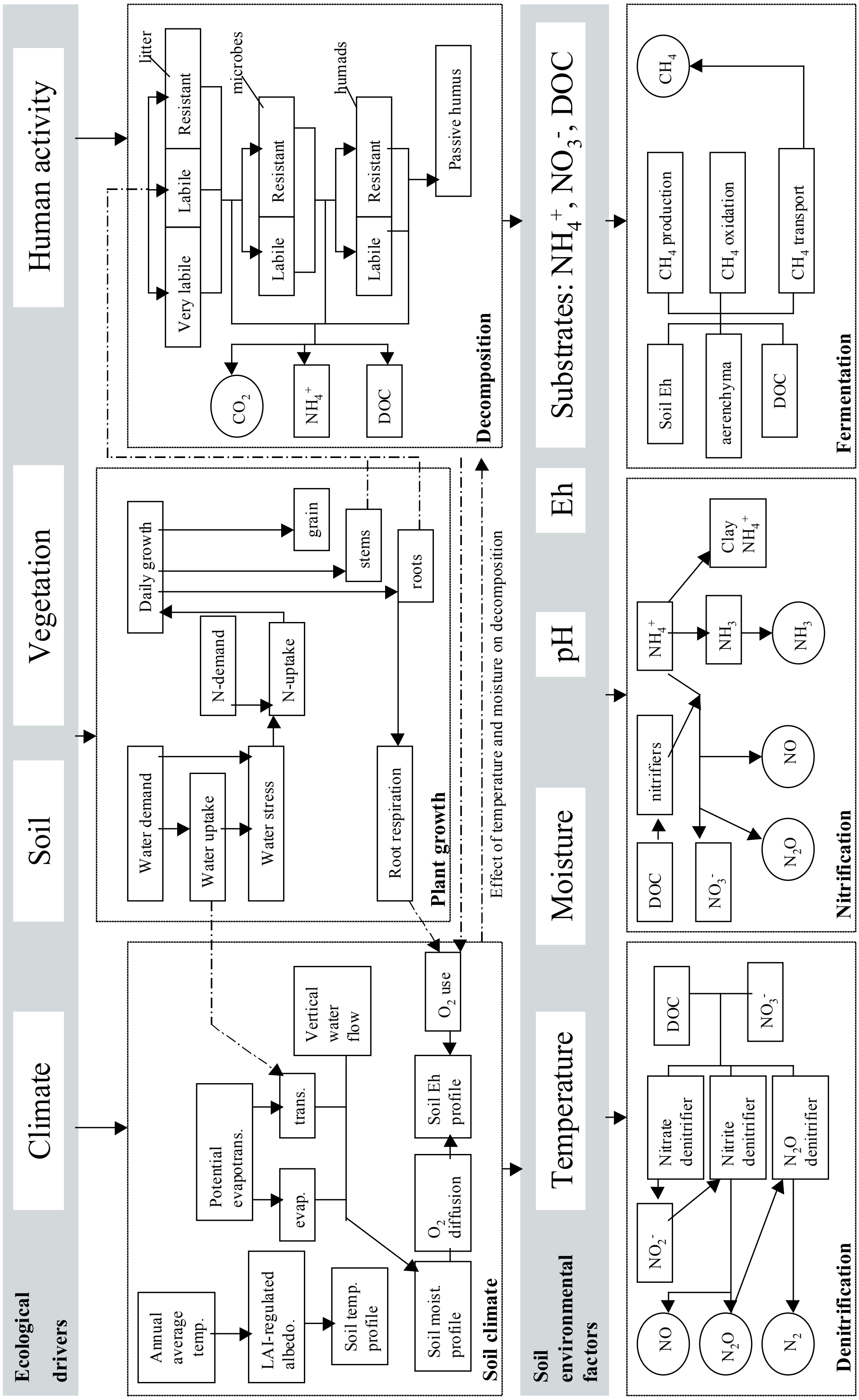

Figure 2.3 Structure of the DNDC model (Li et al. 1997).

Table 2.5 Summary inputs to DNDC.

Time step	Meteorology	Soil and plant	Management
Day	Precipitation (mm) Maximum air temperature (°C) Minimum air temperature (°C) [1]N concentration in rainfall (mg N l^{-1}) [2]Atmospheric background NH_3 conc. (µg N m^{-3}) [3]Atmospheric background CO_2 conc. (ppm)	[4]Soil texture Clay content (%) Bulk density (g cm^{-3}) pH [5]Field capacity (0–1) [6]Wilting point (0–1) Hydraulic conductivity (mm hr^{-1}) [7]Porosity (0–1) Slope (%) Carbon content of surface soil (kg C kg^{-1}) [8]Initial NO_3^- content of surface soil (mg N kg^{-1}) [9]Initial NH_4^+ content of surface soil (mg N kg^{-1})	[10]Crop physiological and phenological parameters Amount and type of fertiliser applied (kg ha^{-1}) Manure application (kg C ha^{-1}) Duration of grazing season (days) and number of animals (head ha^{-1}) Time and number of grass cuttings (kg C ha^{-1})

[1, 2] These can be determined from literature.
[2] These can be determined from literature. The default value is 0.06 µg N m^{-3}.
[3] This has a default value of 350 ppm.
[4] A range of soil texture classes are provided from which one can be chosen.
[5] Water-filled porosity at soil field capacity. When soil texture is selected a default value is provided. This can be changed by the user.
[6] Water-filled porosity at soil wilting point. When soil texture is selected a default value is provided. This can be changed by the user.
[7] The volume percentage of the total soil bulk not occupied by solid particles.
[8] Initial NO_3^- content of surface soil (mg N kg^{-1}).
[9] Initial NH_4^+ content of surface soil (mg N kg^{-1}).
[10] Default values for a range of crops are provided.

2.3.3.2 Inputs to DNDC

The DNDC model operates on a daily time step and its major input variables are listed in Table 2.5.

2.3.3.3 Use and performance of DNDC

The DNDC model has reproduced long and short-term changes in SOC across a range of soil types, land uses and climates, including bare soils with residue incorporation in Germany and Costa Rica (Li et al. 1997; 1994); grassland soils in Germany and the UK (Li et al. 1997; 1994); and arable soils in the USA (Li et al. 1994), Germany, the Czech Republic, Australia (Li et al. 1997; 1994) and China (Li et al. 2003) (Table 2.6).

The DNDC model has been widely used for regional-scale assessments. Tang et al. (2006) estimated SOC stocks in cropland soils in China by combining a GIS database (resolution not stated) of climate, soil properties, cropping systems and management practices with DNDC. Applying a similar approach, Sleutel et al. (2006a) estimated SOC stock changes in croplands in Flanders, northern Belgium, during 1990–2000 and, based on this, assessed the effect of management options of SOC stock changes during 2006–2012 (Sleutel et al. 2006b). Levy et al. (2007) simulated fluxes of CO_2 and N_2O from European grasslands at 50 km × 50 km resolution by combining DNDC with input datasets for grassland area, climate, soils and nitrogen deposition in each grid cell. The typical grassland-management regime within each grid cell was determined from a biogeographical classification of European grasslands and consultation with national experts in each biogeographical region.

Other applications of DNDC include simulation of N_2O fluxes in grasslands (Beheydt et al. 2007; Hsieh et al. 2005; Saggar et al. 2007) and arable soils (Beheydt et al. 2007; Farahbakhshazad et al. 2007; Tonitto et al. 2007), as well as CH_4 and N_2O fluxes in rice fields (Babu et al. 2006; Pathak et al. 2005). Li et al. (2000) linked DNDC to a forest physiological model (i.e. PnET developed by Aber and Federer (1992)) to form a forest biogeochemical model, PnET-N-DNDC. This model has been used to predict carbon sequestration (Miehle et al. 2006) and trace-gas emissions (Butterbach-Bahl et al. 2001) in forest ecosystems. A wetland version of the model has also

Table 2.6 Synthesis of published studies using DNDC to simulate changes in SOC in long- and short-term experiments.

Country	Climate	Ecosystem	Site treatments	Performance	Reference
Costa Rica	Tropical	Bare soil	Residue incorporation during 1 year	Observed and modelled decomposition rates very similar	Li et al. (1994)
Germany	Temperate	Bare soil	Residue incorporation during 9 years	Field and simulated results in good agreement	Li et al. (1994)
Germany	Temperate	Grassland	Soil CO_2 emissions measured for 1 year	Simulated annual CO_2 flux slightly lower than measured	Li et al. (1994)
Missouri, USA	Temperate	Arable	Soil CO_2 emissions measured for 1 year	Simulated annual CO_2 flux similar to measured	Li et al. (1994)
Illinois, USA	Temperate	Arable	Morrow plots, 86-year soil C dynamics	Decline of soil C in all treatments simulated well	Li et al. (1994)
Rothamsted, UK	Temperate	Grassland	Park-grass experiment, grassland for 300 years	Good reproduction of change of soil C in plots managed for hay	Li et al. (1997)
Waite, Australia	Temperate, subtropical	Arable		Decline in soil C due to cultivation reproduced well	Li et al. (1997)
Halle, Germany	Temperate	Arable	Bad Lauchstädt long-term fertiliser experiment	Good agreement between model and observations of increase in soil C	Li et al. (1997)
Tamworth, Australia	Temperate, subtropical	Arable	Tamworth experiment, cultivation for 130 years	Measurements variable but good agreement with model	Li et al. (1997)
Ruzynê, Czech Republic	Cool, temperate	Arable	Ruzynê experiment, continuous cultivation for 100s of years	Good agreement with measurements for control plots, poor agreement in manured plots	Li et al. (1997)
China	Temperate	Arable	Four-crop rotation experiments of 6–10 years duration	Modelled and observed changes in soil C agree well	Li et al. (2003)

been developed, Wetland-DNDC, to simulate C dynamics and CH_4 emissions in wetland ecosystems (Zhang et al. 2002). This version of DNDC has been further applied to forested wetlands (Cui et al. 2005a; b).

2.3.4 PaSim

The PaSim model is a process-based ecosystem model which simulates the carbon, nitrogen and water balances of the atmosphere–plant–soil system and can be used to predict dry-matter production of a fertilised and cut, mixed-perennial meadow (Riedo et al. 1998). Extensions to the model have been carried out by Schmid et al. (2001) in relation to the production and emission of N_2O from grassland, and by Riedo et al. (2002) in relation to the exchange of ammonia with the atmosphere. More recently, Vuichard et al. (2007b) have adapted the model in relation to water stress, senescence and the effects of diet quality on the emissions of CH_4 from grazing animals.

2.3.4.1 Structure of PaSim

The model has five submodels: soil physics, soil biology, plant, animal and microclimate (Figure 2.4). PaSim is driven with hourly meteorological input data for radiation, air temperature, vapour pressure, wind speed, precipitation, and atmospheric concentration of CO_2 and ammonia (NH_3). PaSim integrates the land-management practices of grass cutting, grazing and the application of fertiliser and slurry.

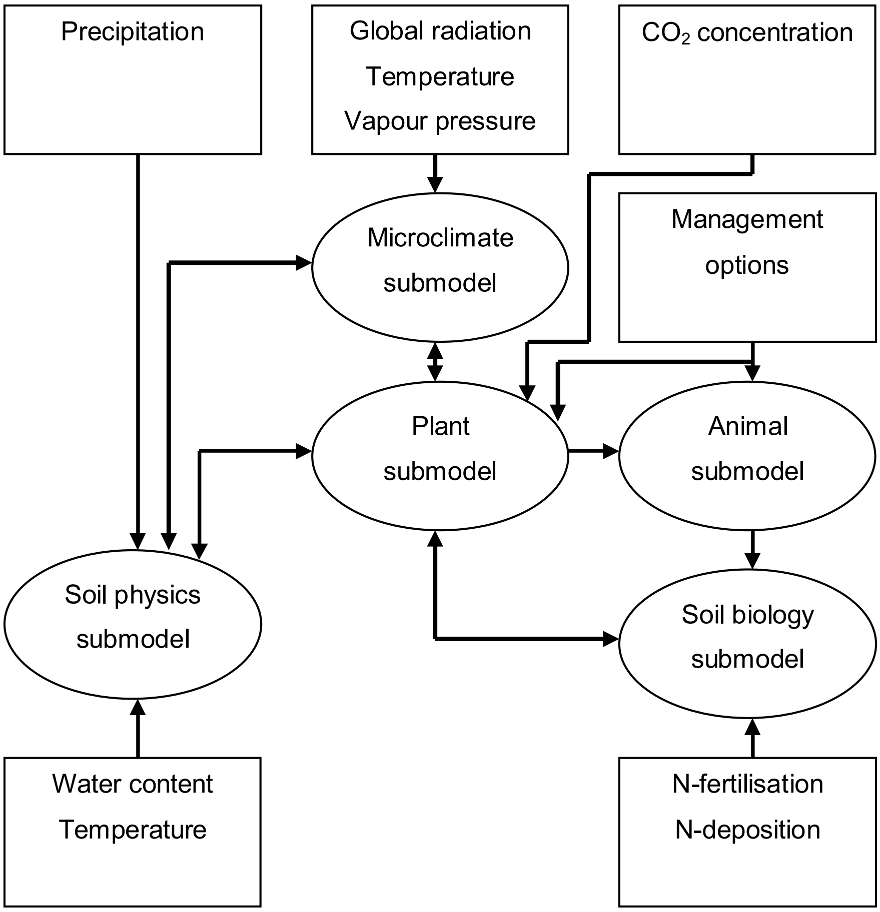

Figure 2.4 Submodels, driving variables and internal fluxes of carbon, nitrogen and water in the PaSim model (from Riedo et al. 1998).

The plant submodel was developed on the basis of the Hurley Pasture model (Thornley and Verbane 1989) and simulates shoot and root growth in relation to C and N uptake, energy fluxes and soil moisture conditions. The microclimate submodel is used to calculate the interception of radiation by the canopy, and the energy balances of the canopy and soil surface. Canopy development is divided into two distinct stages, a reproductive stage and a vegetative stage. A transition from reproductive to vegetative growth is triggered after a sustained period of air temperatures above a base level. In addition, after the second cut the canopy is automatically assumed to be in the vegetative state. The soil biology submodel calculates plant available soil C and N and is derived from the CENTURY model (Parton et al. 1987). The animal submodel allows the effects of grazing animals to be incorporated.

2.3.4.2 Inputs to PaSim

The PaSim model operates on an hourly time step and its major input variables are soil texture and weather data. These are listed in Table 2.7.

2.3.4.3 Use and performance of PaSim

The PaSim model has been evaluated at a wide range of grassland sites in Europe. Riedo et al. (1998) found that the difference between simulated and measured dry-matter production for two climatically different sites in Switzerland was between –6 and +21%. Riedo et al. (1999) combined the model with statistically downscaled climate change scenarios to investigate the effect of climate change on dry-matter production at two grassland sites. Working in the Swiss Alps, Riedo et al. (2000) used the model to quantify the effect of elevated CO_2 and climate change on net primary production and carbon stocks, and

Table 2.7 Summary inputs to PaSim.

Time step	Meteorology	Soil and plant	Management
Hourly	Air temperature (°C) Vapour pressure (Pa) Radiation (mol quanta m^{-2}) Precipitation (mm) Wind speed (m s^{-1}) [1]Atmospheric background NH_3 conc. (µg N m^{-3}) [2]Atmospheric background CO_2 conc. (ppm)	Soil pH [3]Soil texture Clay content (%) Bulk density (g cm^{-3}) Saturated-soil water content (m^3 m^{-3}) [4]Field capacity [5]Wilting point Saturated hydraulic conductivity (mm day^{-1}) [6]Depth of soil layers (m) Carbon content of soil (kg C kg^{-1})	Amount and time of fertiliser application (kg ha^{-1}) Manure application (kg C ha^{-1}) Duration of grazing season (days) and number of animals (head ha^{-1}) Time and number of grass cuttings (kg C ha^{-1})

[1,2] These can be determined from literature.

[3] Relative proportions of sand, silt and clay.

[4] Water-filled porosity at soil field capacity.

[5] Water-filled porosity at soil wilting point.

[6] Soil profile can be divided into three soil layers, the depths of which can be can be estimated when calibrating the model (Lawton et al. 2006).

found that in two out of three grassland sites there was a reduction in SOC stocks. Schmid et al. (2001) found that the model reproduced N_2O production and emissions for two field sites in Switzerland. Working at a grassland in Scotland, Riedo et al. (2002) found good agreement between PaSim and micrometeorological measurements of NH_4. Soussana et al. (2004) used PaSim to estimate the greenhouse gas balance of a pasture site in the French Massif Central under a range of grazing intensities and N fertiliser applications. In a study at a grassland site in south-west Ireland, Lawton et al. (2006) simulated net ecosystem CO_2 exchange at a grassland site and found good agreement between the model output and observed net ecosystem CO_2 exchange in the growing season but not so good in the winter period. Vuichard et al. (2007b) tested PaSim against in-situ measurements of biomass and CO_2 and CH_4 fluxes at five European grassland sites. They found good agreement between the observed seasonal cycle of biomass and CO_2 and CH_4 fluxes and the model output. However, the large uncertainties in biomass measurements and leaf-area index (LAI) made accurate simulation difficult. Calanca et al. (2007) used PaSim to simulate fluxes of CO_2 and N_2O at five grassland sites in Europe and found reasonable agreement between measured and modelled ecosystem respiration and net ecosystem CO_2 exchange. Modelled N_2O emissions were 2–10 times higher than observed.

To date, only one study has combined PaSim with spatial data to carry out a regional-scale assessment. Vuichard et al. (2007a) combined PaSim with remote-sensing data to map fluxes of CO_2, N_2O and CH_4 within European grasslands at ~108 km × 108 km resolution. Input data included climate and weather data, soil and land-cover information and grassland management (cutting or grazing only).

2.4 Discussion

A conceptual framework for upscaling SOC models from plot to region has been developed by Paustian et al. (1995) (Figure 2.5). The main components of this work are as follows.

1. The models are evaluated in order to assess and improve their performance in the conditions found in the study area. This will utilise long-term experimental datasets (where available) and results from relevant field and laboratory-based studies.
2. Information is collected on the spatial and temporal variation of driving variables across the region. This includes data on soils, climate, land use and management, and is managed in a GIS. This data is input to the simulation model to represent regional patterns and dynamics.
3. Assessment of changes in SOC stocks.

Models such as RothC, CENTURY, DNDC and PaSim were originally developed to study ecosystem behaviour at the site or plot level (e.g. a pasture or a forest stand). An inherent aspect of their development is the assumption that driving variables such as climate and soil properties are homogeneous across the site or plot. These models can be considered as one dimensional in that they consider only soil variation with depth and not spatial variation. They are structurally complex and account for variation in the decomposition of different organic compounds by considering multiple organic matter fractions. Decomposition follows first-order kinetics, i.e. a constant fractional loss per unit time, of different organic matter fractions, with the potential rate being modified by a variety of soil environmental conditions. In general, a relatively large number of rate controls representing soil environmental conditions are considered in these models, including soil temperature, soil moisture, soil pH, soil texture and nutrient concentrations, as well as other factors such as litter composition and disturbance or management regimes. Given that these models were developed for ecosystem-based investigations, they tend to be detailed and to be applied in relatively data-rich environments.

The RothC, CENTURY and DNDC models have simulated changes in SOC stocks in long-term, plot-scale experiments across a range of climatic, soil and land-use conditions. Although the PaSim model has not been evaluated in a similar fashion, the fact that the soil biology submodel is based on the CENTURY model suggests that it would perform well in long-term experiments in grassland. Smith et al. (1997b) compared nine soil organic matter models using data from seven long-term experiments. RothC produced low errors for all datasets except for some experimental treatments. Smith et al. (1997a) attributed this to the use of the same conditions to initialise the model for all treatments, whereas treatment specific initial conditions would have reduced the error. CENTURY produced low errors for all datasets and performed best for grassland and arable systems. DNDC produced consistently low errors for grassland and arable simulations and was not tested on forest soil data.

There is increasing interest in using SOC models to estimate SOC stock changes at regional level. While it may seem appropriate to first apply such models at field scale, this is not done. There are a number of reasons for this. Firstly, these models are one dimensional and do not consider spatial variation. Furthermore, for field-based experiments the input data required to run these models is usually available at a single point. For example, soil samples are usually taken at soil pits that are considered to be representative of the study area. Such experiments are generally not carried out at field level because the amount of soil and related analyses required would be prohibitively expensive. Furthermore there is less background variation in plot-based experiments compared to field-based experiments (due, for example, to spatial variation in soil properties) which permits statistical detection of treatment effects, etc. Similarly, meteorological data is normally collected at one location which is considered to be representative of the study area.

It is standard practice to upscale SOC models from plot to regional level. Regional analysis involves the subdivision of the study area into a number of spatial units (i.e. grid cells) for which unique sets of driving variables (e.g. climate, soils, land use and management) are derived and then supplied to the model. Each spatial unit is treated independently, i.e. there are no interacting processes between them. A limitation of this method is that exchanges between grid cells such as water and soil (i.e. erosion) are not included. Progress has been made in addressing this deficiency. For example, CENTURY has been incorporated in a new model (erosion–deposition–carbon model (EDCM)) developed by Liu et al. (2003), which simulates the effect of rainfall-induced soil erosion and deposition on SOC dynamics.

As stated above, these models assume spatial homogeneity, but when applied at coarser spatial scales this assumption may not hold. In general, aggregation errors are minimal when the relationship between the independent variable (to be aggregated) and dependent variable is linear (Paustian et al. 1997). In contrast, when the relationship is non-linear, aggregation error can be significant. For example, the relationship between SOC

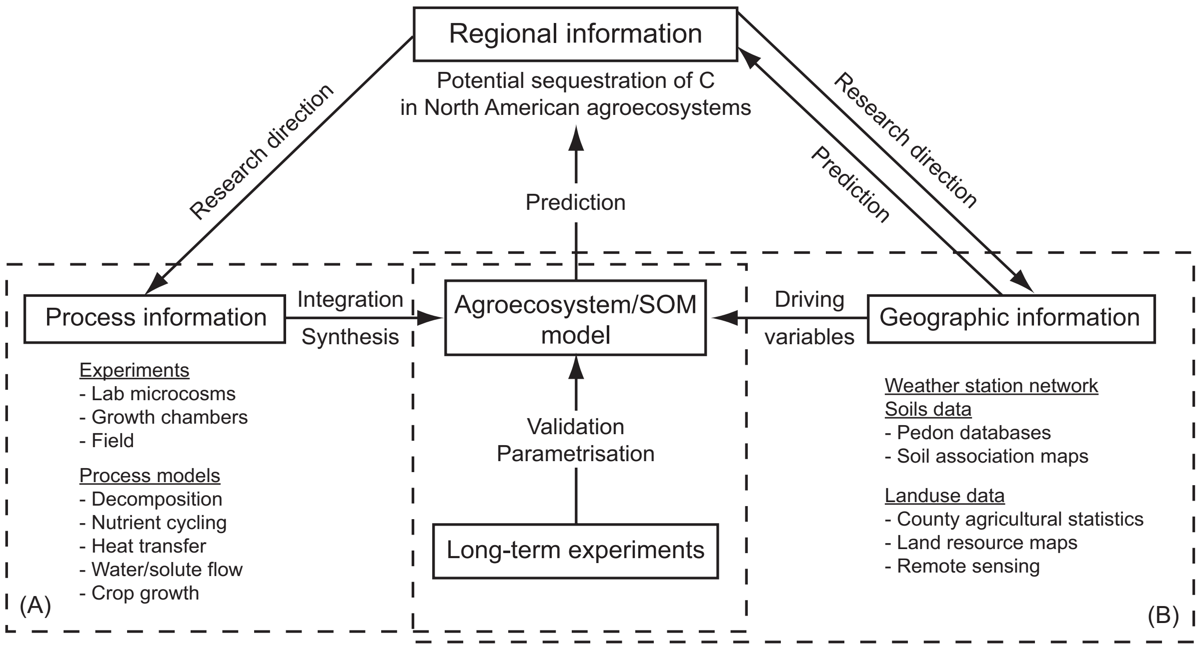

Figure 2.5 A conceptual diagram showing the integration of process information, long-term experiment data and site networks, simulation modelling and regional GIS databases. Box A denotes components which can be applied for local-scale analyses (i.e at a particular location) and Box B denotes components which are necessary for regional-scale analyses (from Paustian et al. 1995).

and soil texture is non-linear. Consequently, when two different soil textures are aggregated, there will be an error in the prediction of SOC. This was demonstrated in a simulation study by Burke et al. (1990) using CENTURY. They found that simulated primary production, which responds in a linear fashion to precipitation (Parton et al. 1987), was insensitive to increasing spatial aggregation. In contrast, SOC levels were more sensitive to the scale of spatial aggregation, primarily due to the effect of averaging soil texture. Decomposition and the seasonality of primary production are affected by climatic factors (i.e. temperature and precipitation), which vary spatially and temporally. Thus, the effects of both spatial and temporal averaging of climate data need to be considered. Ojima et al. (1991) demonstrated the effect of using either monthly or annually averaged output from a general circulation model to predict SOC change in the Great Plains of the USA. There were distinct differences in predicted patterns of SOC for the same mean annual temperature change, depending on whether temperature change was expressed on a monthly basis or if it was 'aggregated' over the year.

The choice of model for simulating and predicting SOC stocks in Irish grassland will be based on a number of criteria including: (i) Is the model appropriate to soil and climate conditions in Ireland? (ii) Are there suitable datasets available for testing the models? (iii) Are the model inputs available at a range of scales?

Three of the models (RothC, CENTURY and DNDC) have been used to simulate SOC stocks in temperate conditions. This suggests that they would be suitable for Irish conditions. Although PaSim has not been used specifically to model SOC stock changes, it has been used to simulate net ecosystem CO_2 exchange in a range of grasslands, including two sites in Ireland (Lawton et al. 2006; Vuichard et al. 2007b). As stated previously, the soil biology submodel of PaSim is based on CENTURY. Consequently it may act similarly in simulating SOC stock changes. RothC is the simplest of the models and is the least demanding in terms of data inputs. CENTURY is more complex and somewhat more demanding in terms of inputs. Both models operate on a monthly time step, which is sufficient to capture temporal dynamics in SOC. DNDC and PaSim are different in that they require more inputs (particularly PaSim) and operate at daily and hourly time steps respectively.

Although long-term, field-based experiments are a vital component of research into SOC dynamics (Richter et al. 2007), no such experiments exist in Ireland. The National Soils Database (Fay et al. 2007) provides baseline soil geochemistry data (including SOC) for the top 10 cm of Irish soils. The EPA-funded SoilC project (Eaton et al. 2007) will provide data on SOC stocks in a range of grassland sites which can be used to initialise SOC models. These sites should be developed as benchmark or reference sites which can be re-sampled at 5–10 year intervals. This would increase the capacity to calibrate and validate SOC models for Irish conditions. Results of site-specific studies can also provide valuable input to models (e.g. Byrne and Kiely 2006; Byrne et al. 2005; Jaksic et al. 2006b; Lawton et al. 2006).

When upscaling models to the regional or national scale, the grid resolution is a critical issue. If the grid is too coarse it may not adequately reflect spatial variation in soil and climatic conditions. For instance, Vuichard et al. (2007a) used a 108 km × 108 km grid for a European-wide assessment and suggest that, while this resolution may be sufficient to represent regional meteorological regimes, it would be too coarse to capture local spatial heterogeneities and their impact on grassland GHG fluxes. In contrast, Falloon et al. estimated changes in UK soils at 1 km × 1 km resolution. Using a regional climate model, the C4I project (McGrath et al. 2005) developed a 40-year simulation of the past climate (1961–2000) at 13 km × 13 km resolution for Ireland. The model was then used to simulate the future climate for a range of scenarios. Tomlinson estimated SOC stocks in the Republic of Ireland for 1990 and 2000 at 2 km × 2 km resolution.

When considering which models to use to assess changes in SOC stocks in grassland soils across a range of scales, RothC and CENTURY should be considered first. This is because they require fewer inputs than DNDC and PaSim, and have been more widely used to simulate and predict changes in SOC stocks. If other aspects of the carbon cycle (apart from SOC) are to be modelled, then DNDC and PaSim should be considered. For regional-scale studies there is a clear need to assemble in GIS format all potential data sources in relation to soils, climate and land use. A key issue in this is how data is aggregated (e.g. Is the soil modelled to a common depth across profiles or total depth for each profile?). As discussed earlier this may affect the results of any modelling exercise.

3 Effect of Future Climate Change on Soil Carbon Stocks in Irish Grasslands – A Model Comparison

3.1 Introduction

Soils are an integral component of the global carbon budget and are estimated to contain 2011 Pg (1 Pg = 1 Gt = 10^{15}g) of organic carbon to 1 m depth (Bolin et al. 2000). This is about four times the amount of carbon in vegetation and twice the amount in the atmosphere (Bolin et al. 2000). Consequently there is much scientific interest in soil carbon stocks and their potential feedback to climate change (Davidson and Janssens 2007). Grasslands occupy some 62.7 million ha in the EU 25 plus Norway and Switzerland (Janssens et al. 2005). Grassland is the dominant land use in Ireland. Eaton et al. (in press) estimated that, in 2000, grasslands accounted for 53.3% of the land area of Ireland and 25% of SOC stocks to 1 m depth. Despite this, the potential response of SOC in Irish grasslands to climate change has not been assessed.

Process-based models have been widely used to investigate the effect of land-use change, climatic change and different management practices on SOC (e.g. Kamoni et al. 2007a; Li et al. 2003; Smith et al. 2005). The RothC model was originally developed to model the turnover of organic carbon in arable soils at plot scale under a range of soil and climatic conditions (Coleman and Jenkinson 1996). It has been extended to model carbon turnover at plot scale in grassland (Coleman et al. 1997) and forest sites (Falloon and Smith 2002; Smith et al. 2006). It has also been combined with spatial databases to carry out regional assessments of changes in soil carbon stocks. For example, Smith et al. (2005) projected changes in soil carbon stocks in European grasslands under future climate and land-use change and estimated that soil carbon stocks (to 30 cm depth) will fall by between 5.9 and 9.3 t C ha^{-1} between 1990 and 2080. They found that these losses would be reduced by increased organic matter input to the soil as a result of enhanced productivity and projected changes in technology.

The CENTURY model was originally developed for grassland soils (Parton et al. 1987), and in addition to being applied to a range of grassland soils (e.g. Parton et al. 1993; Werth et al. 2005) has been widely used for arable (e.g. Falloon and Smith 2002) and forest soils (e.g. Kirschbaum and Paul 2002). Parton et al. (1995) modelled the impact of climate change and increasing atmospheric CO_2 for 31 temperate and tropical grassland sites using CENTURY. They found that climate change caused soil carbon to decrease overall, with a loss of 4 Pg from global grasslands after 50 years. CENTURY has also been linked to spatially defined datasets to make regional assessments of soil carbon stock changes with changing land use and management (e.g. Kamoni et al. 2007a; Paustian et al. 2001).

The DNDC model is a process-based simulation model of soil carbon and nitrogen biogeochemistry (Li et al. 1996; 1992a; b; 1994). It has reproduced long- and short-term changes in soil carbon across a range of soil types, land uses and climates (Li et al. 1997; 1994; 2003). It has been used to investigate the effect of future climate change on nitrous oxide emissions from soils (Hsieh et al. 2005) and has also been combined with spatial databases for regional-scale applications (Sleutel et al. 2006a, b; Tang et al. 2006).

In this chapter we use the three models RothC, CENTURY and DNDC to investigate the potential response to climate change of SOC stocks in two grassland sites in Ireland with contrasting soil and climatic conditions. Regionally downscaled datasets for the period 2021–2060 derived by McGrath et al. (2005) for a range of IPCC emission scenarios (Nakicenovic and Swart 2000) are used to simulate future climate. We compare the models in terms of data inputs, predicted change in SOC stocks and their potential for application at regional and national level.

3.2 Materials and Methods

3.2.1 *Site description*

Two sites were chosen for this study. The first site (Cork) was located in an area of intensively managed grassland 180 m above sea level in County Cork, southern Ireland (51° N, 8° W). The climate is temperate maritime with an average rainfall of 1470 mm yr^{-1} and an annual daily mean temperature of 6.2°C in January and 13.7°C in July. The dominant soil type is gleysol (FAO–UNESCO 1974) with 39% sand, 44% silt, 17% clay and a bulk density of 1.17 g cm^{-3}. The soil pH is 5.4 and the SOC content (0–10 cm) is 3.9–5.9% (Byrne et al. 2005). The dominant grass species is perennial ryegrass (*Lolium perenne* L.) with smaller amounts of meadow foxtail (*Alopecurus pratensis* L.) and Yorkshire fog (*Holcus lanatus* L.). Grass production rates are in the range 7.6–14 t dry matter ha^{-1} yr^{-1} (Byrne et al. 2005).

The second site (Wexford) is located at the Teagasc Wexford Castle Research Centre, Wexford Castle, Co. Wexford in south-east Ireland (52° N, 6° W) and is described by Hyde et al. (2006) as follows. The mean annual rainfall is 1014 mm and the mean annual temperature is 10ºC. The soil is a gleyic cambisol (FAO–UNESCO 1974) with 18% sand, 38% silt and 18% clay and a bulk density of 1.23 g cm^{-3}. The soil pH is 5.8 and the C and N content are 3.2% and 0.28% respectively. The pasture is perennial ryegrass (*Lolium perenne* L.).

3.2.2 *Description of models and model inputs*

For a full description of the RothC, CENTURY and DNDC models see Section 2 of this report.

The climatic inputs were derived from the work of McGrath et al. (2005) who used a regional climate model (RCM) to create a 40-year simulation of the past climate (1961–2000) on a grid of 13 km × 13 km over Ireland. Following verification of the RCM performance in recreating the recent past climate, McGrath et al. (2005) used the model to simulate the future climate for the period 2021–2060 for a range of IPCC emission scenarios (Nakicenovic and Swart 2000). The emission scenarios are described in Table 3.1. See McGrath et al. (2005) for a list of the

Table 3.1 Characteristics of the IPCC climate scenarios used by McGrath et al. (2005) to drive the RCM to generate the climate scenarios used in this study.

Scenario	Characteristics
A1B	Very rapid economic growth Global population that peaks in mid-century and declines Rapid introduction of new and more efficient technologies Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income Balance between fossil-intensive and non-fossil energy sources Medium–high emissions
A2	The world is very heterogeneous Underlying theme is self-reliance and preservation of local identities Fertility patterns across regions converge very slowly Continuously increasing population Economic development is primarily regionally oriented Per capita economic growth and technological change more fragmented and slower than other storylines
B1	Same global population, that peaks in mid-century and declines thereafter, as in the A1 storyline, rapid change in economic structures toward a service and information economy Reductions in material intensity and the introduction of clean and resource-efficient technologies Emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives

meteorological products simulated. Average monthly climatic data for 1961–2000 and for the A2, A1B and B1 emission scenarios were bilinearly interpolated from the four nearest grid points of the 13 km × 13 km grid to the locations of the study sites (McGrath, personal communication). Differences in topography were not taken into account. These monthly climatic data formed the basis of the climatic inputs to the RothC, CENTURY and DNDC models. For RothC the climatic inputs were average monthly air temperature (°C), total monthly precipitation (mm) and total monthly open-pan evaporation (mm). Average monthly air temperature (°C) and total monthly

Table 3.2 Climate and soil properties used as inputs for RothC, CENTURY and DNDC at the Cork site.

Input	RothC	CENTURY	DNDC
Climate properties			
	Average monthly air temperature (°C) Total monthly precipitation (mm) Total monthly open-pan evaporation (mm)	Minimum monthly air temperature (°C) Maximum monthly air temperature (°C) Total monthly precipitation (mm)	Maximum daily air temperature (°C) Minimum daily air temperature (°C) Total daily precipitation (cm)
Soil			
Land-use type	–	–	[15]Moist grassland
Soil-texture class	–	–	[16]Silt loam/loam
Depth (cm)	[1]20	[3]20	[17]20
Sand fraction	–	[4]0.39	–
Silt fraction	–	[5]0.44	–
Clay fraction	[2]0.17	[6]0.17	[18]0.17
Bulk density	–	[7]1.17 g cm^{-3}	[19]1.17 g cm^{-3}
Wilting point	–	[8]0.11 (VSMC*, 0–1)	[20]0.20 (WFPS†, 0–1)
Field capacity	–	[9]0.25 (VSMC*, 0–1)	[21]0.40 (WFPS†, 0–1)
Saturated hydraulic conductivity	–	–	[22]0.025 m hr^{-1}
Porosity	–	–	[23]0.45 (0–1)
Depth of water retention layer (cm)	–	–	[24]100
pH	–	[10]5.4	[25]5.4
C in surface organic matter with fast turnover	–	[11]50 g C m^{-2}	–
C in SOM with fast turnover	–	[12]409 g C m^{-2}	–
C in SOM with intermediate turnover	–	[13]5997 g C m^{-2}	–
C in SOM with slow turnover	–	[14]7224 g C m^{-2}	–
Initial SOC content in surface soil (0–5 cm)	–	–	[26]0.072 kg C kg^{-1}
Initial NO_3^- concentration in surface soil	–	–	[27]21.6 mg N kg^{-1}
Initial NH_4^+ concentration in surface soil	–	–	[28]2.16 mg N kg^{-1},

* Volumetric soil moisture content.

† Water-filled porosity.

[1, 3, 17] Soil depth set at 20 cm to allow comparison between model outputs.

[2, 4, 5, 6, 7, 10, 18, 19, 25] Byrne et al. (2005).

[8,9] Saxton et al. (1986).

[11, 12, 13, 14, 24] Best estimate.

[15, 16, 20, 21, 22, 23, 26, 27, 28] Model default.

precipitation (mm) were derived from the work of McGrath et al. (2005) as described above. Total monthly open-pan evaporation is required for RothC and this was calculated using the method of Penman (1948). The climatic inputs for CENTURY were minimum monthly air temperature (°C), maximum monthly air temperature (°C) and total monthly precipitation (mm). The DNDC model operates at a daily time step and it was therefore necessary to construct daily time series of maximum air temperature (°C), minimum air temperature (°C) and total precipitation (cm) for 1961–2000 and for each of the three emission scenarios. This was done as follows. Daily time series of maximum air temperature, minimum air temperature and precipitation were collated using meteorological measurements made at the study sites during 2004. These were then adjusted so that their mean minimum and maximum monthly temperatures and total monthly precipitation values were the same as the monthly values produced by the RCM simulations for the study site.

The climatic and soil inputs for each of the three SOC models are detailed in Tables 3.2 and 3.3.

Table 3.3 Climate and soil properties used as inputs for RothC, CENTURY and DNDC at the Wexford site.

Input	RothC	CENTURY	DNDC
Climate properties			
	Average monthly air temperature (°C) Total monthly precipitation (mm) Total monthly open-pan evaporation (mm)	Minimum monthly air temperature (°C) Maximum monthly air temperature (°C) Total monthly precipitation (mm)	Maximum daily air temperature (°C) Minimum daily air temperature (°C) Total daily precipitation (cm)
Soil			
Land-use type	–	–	[15]Moist grassland
Soil texture class	–	–	[16]Loam
Depth (cm)	[1]20	[3]20	[17]20
Sand fraction	–	[4]0.38	–
Silt fraction	–	[5]0.44	–
Clay fraction	[2]0.18	[6]0.18	[18]0.18
Bulk density	–	[7]1.23 g cm^{-3}	[19]1.23 g cm^{-3}
Wilting point	–	[8]0.11 (VSMC, 0–1)	[20]0.22 (WFPS, 0–1)
Field capacity	–	[9]0.25 (VSMC, 0–1)	[21]0.49 (WFPS, 0–1)
Saturated hydraulic conductivity	–	–	[22]0.025 m hr^{-1}
Porosity	–	–	[23]0.45 (0–1)
Depth of water retention layer (cm)	–	–	[24]100
pH	–	[10]5.8	[25]5.8
C in surface organic matter with fast turnover	–	[11]50 g C m^{-2}	–
C in SOM with fast turnover	–	[12]236 g C m^{-2},	–
C in SOM with intermediate turnover	–	[13]3464 g C m^{-2}	–
C in SOM with slow turnover	–	[14]4172 g C m^{-2}	–
Initial SOC content in surface soil (0–5 cm)	–	–	[26]0.039 kg C kg^{-1}
Initial NO_3^- concentration in surface soil	–	–	[27]11.7 mg N kg^{-1}
Initial NH_4^+ concentration in surface soil	–	–	[28]1.17 mg N kg^{-1}

[1, 3, 17] Soil depth set at 20 cm to allow comparison between model outputs.

[2, 4, 5, 6, 7, 10, 18, 19, 25] Hyde et al. (2006).

[8, 9] Saxton et al. (1986).

[11, 12, 13, 14, 24] Best estimate.

[15, 16, 20, 21, 22, 23, 26, 27, 28] Model default.

3.2.3 Running the models

3.2.3.1 RothC

When the annual returns to the soil are not know they can be calculated using the total SOC content of the soil to 20 cm depth. For the Cork site, the SOC content to 20 cm depth was 136.31 t C ha^{-1} and the IOM content of the soil was assumed to be 0.049 × (total organic carbon)$^{1.139}$ from Falloon et al. (1998a). For the Wexford site the TOC content of the soil to 20 cm depth was 78.72 t C ha^{-1} and the IOM content was calculated as for Cork. By running the model in reverse using the 'Calculate plant inputs knowing total carbon' mode the annual returns of C to the soil required to reach the measured SOC content for equilibrium content were calculated for both sites (Table 3.4). The model was then run to equilibrium for each site using the estimated soil inputs and constant climatic conditions. The constant climatic conditions were taken to be the average conditions during 1961–2000. The simulations were then continued from 2021 to 2060 using the same soil inputs and the climatic data for each of the three IPCC emission scenarios.

Table 3.4 Annual plant inputs to the soil at the Cork and Wexford sites calculated using the 'Calculate plant inputs knowing total carbon' mode of RothC.

	Plant residue (t C ha^{-1})	
Month	**Cork**	**Wexford**
January	0.14	0.11
February	0.14	0.11
March	0.14	0.11
April	0.56	0.23
May	0.56	0.23
June	0.56	0.23
July	0.14	0.23
August	0.14	0.23
September	1.96	1.26
October	1.96	1.26
November	1.96	1.26
December	0.14	0.11
Total	**8.40**	**5.37**

3.2.3.2 CENTURY

CENTURY was first run to equilibrium for each site using the climatic and soil data shown in Tables 3.2 and 3.3. For the Cork site model runs, management events and crop growth controls were scheduled as follows: 'Niwot Ridge' was chosen as the crop type for the plant submodel (see Metherell et al. (1993) for further information). The first month of crop growth was January and the last month was December. The grazing season was from March to October and the grazing system chosen was 'New Zealand pasture management' (see Metherell et al. (1993) for further information). Fertiliser was assumed to be applied once a month from March to August at a rate of 1g N m^{-2} (the N1 fertiliser application option). The model runs for the Wexford site were similar except that the grazing system chosen was 'Graze low intensity moderate effect on production' and no fertiliser was applied.

The model was run to equilibrium for 5000 years at each site using constant climatic conditions were taken to be the average conditions during 1961–2000. Following this, the simulations were continued from 2021 to 2060 for each of the three IPCC scenarios using the same soil, climatic and management inputs.

3.2.3.3 DNDC

Unlike RothC and CENTURY, DNDC is not run to equilibrium over several thousand years but is calibrated using the results of field experiments (e.g. Sleutel et al. 2006a; Zhang et al. 2006). For this study DNDC was initialised for each site using the climatic and soil data in Tables 3.2 and 3.3 as input. For the model initialisation the climatic conditions which were taken to be the average conditions during 1961–2000. Management events were scheduled as follows: at both sites the grazing season began on March 15 and end on October 15 with 20 hours grazing per day and two cattle per hectare. For the Cork site, fertiliser was applied at a rate of 18 kg N (NH_4NO_3) ha^{-1} of on the first day of March, May, July and September respectively. For the Wexford site, fertiliser was applied at a rate of 15 kg N (NH_4NO_3) ha^{-1} (1.5 g N m^{-2}) of on the first day of March, May, July and September respectively. The crop type was perennial grass and growth was simulated

Table 3.5 Parameters for perennial grass in the crop submodel of DNDC at the Cork site.

	Grain	Leaf + stem	Root
Maximum biomass (kg C ha^{-1})	280	7000	6720
Biomass fraction	0.02	0.5	0.48
Biomass C/N ratio	15	25	30
Total N demand (kg N ha^{-1})		552.67	
Accumulative thermal degree days		2500	
Water demand (g H_2O g DM^{-1})		550	
N-fixation index		1.01	
Maximum LAI		3	

Table 3.6 Parameters for perennial grass in the crop submodel of DNDC at the Wexford site.

	Grain	Leaf + stem	Root
Maximum biomass (kg C ha^{-1})	320	8000	7680
Biomass fraction	0.02	0.5	0.48
Biomass C/N ratio	15	25	30
Total N demand (kg N ha^{-1})		597.33	
Accumulative thermal degree days		2500	
Water demand (g H_2O g DM^{-1})		550	
N-fixation index		1.01	
Maximum LAI		3	

using the empirical growth module. The crop parameters used for each site are listed in Tables 3.5 and 3.6. During the model runs it was found that after 70 years the SOC stock in the top 20 cm varied by no more than 0.13% and 0.88% of the initial values at the Cork and Wexford sites respectively, and was considered to be stabilised. Following this 70 year initialisation period the simulations were continued from 2021 to 2060 for each of the three IPCC SRES scenarios using the same soil, climatic and management inputs.

3.3 Results

3.3.1 Output of the McGrath et al. (2005) RCM for the Cork and Wexford sites

All three future climate scenarios from the RCM of McGrath et al. (2005) predict changes in rainfall and temperature at the Cork site during 2021–2060 compared to 1961–2000 (Figures 3.1 and 3.2). Average annual precipitation during 1961–2000 is 1829 mm. The average annual precipitation predicted for 2021–2060 is 1819 mm, 1797 mm and 1799 mm for the A1B, A2 and B1 scenarios respectively (Figure 3.1a). The annual distribution of precipitation is changed under the climate scenarios compared to 1961–2000, with higher rainfall from January to March and after August, and lower rainfall in the spring and summer (Figure 3.1a). The mean monthly air temperature is increased by an average of 1.08ºC, 0.82ºC and 0.54ºC for the A1B, A2 and B1 scenarios respectively (Figure 3.2a). The minimum and maximum monthly air temperature is raised in each scenario by a similar amount (Figure 3.2b, c).

Output from the RCM of McGrath et al. (2005) shows that the Wexford site experiences lower rainfall and higher temperatures than the Cork site (Figures 3.1 and 3.2). Average annual precipitation during 1961–2000 is 1281 mm and is very similar at 1283 mm, 1298 mm and 1290 mm for the A1B, A2 and B1 scenarios respectively (Figure 3.1b). As in the Cork site, the annual distribution of

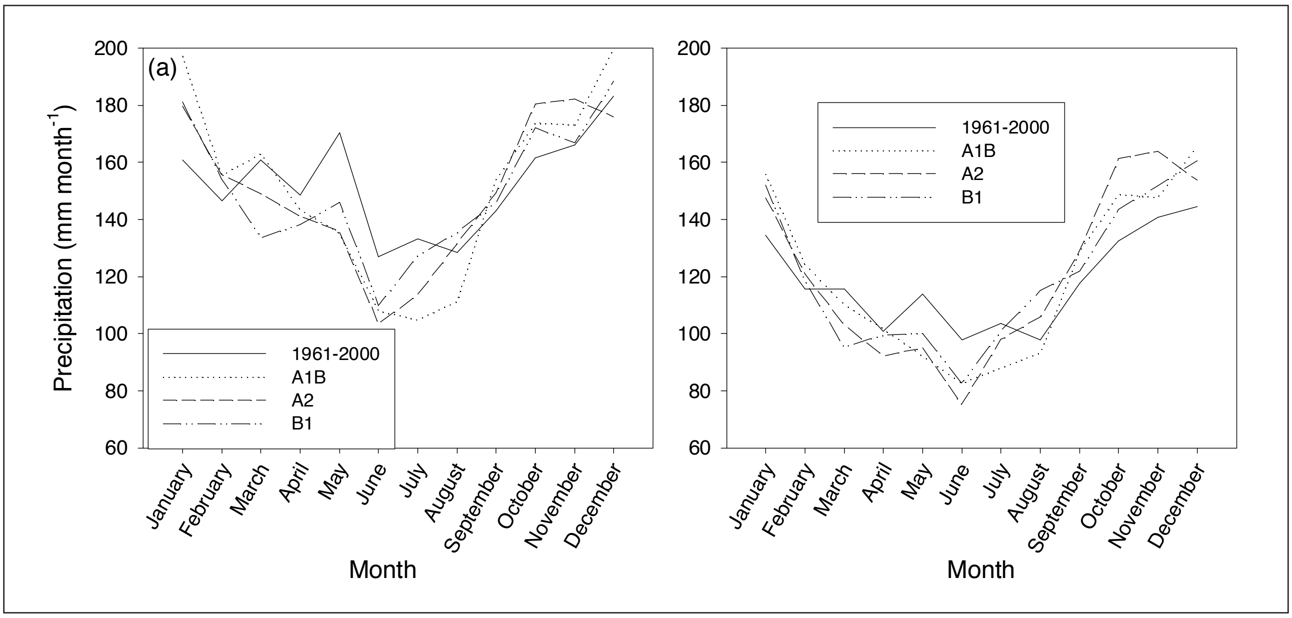

Figure 3.1 Total monthly precipitation at (a) the Cork site and (b) the Wexford site during 1961–2000 and during 2021–2060 for each of the three IPCC scenarios A1B, A2 and B1.

precipitation is changed under each scenario, with lower rainfall between March and July. The mean monthly air temperature is increased by an average of 1.10ºC, 0.86ºC and 0.55ºC for the A1B, A2 and B1 scenarios respectively (Figure 3.2d). The minimum and maximum monthly air temperatures are raised in each scenario by a similar amount (Figure 3.2e, f).

3.3.2 Projected changes in SOC stocks

All three models predicted a reduction in SOC stocks at the Cork site during 2021–2060 for each climate change scenario (Figure 3.3) with variation between models and scenarios. The range of reduction of SOC was 1.9 to 7.4 t C ha^{-1}, equivalent to a per cent loss range of 1.4 to 5.4%. Although the higher rainfall during the winter months may retard decomposition, this does not compensate for increased decomposition due to the higher temperatures and reduced summer rainfall. The lowest reductions in SOC were predicted by CENTURY, with an average reduction of 3.4 t C ha^{-1}, 2.5 t C ha^{-1} and 1.9 t C ha^{-1} during 2021–2060 for the A1B, A2 and B1 scenarios respectively. The changes predicted by RothC and DNDC were similar for the A1B and A2 scenarios. RothC predicted a reduction of 7.4 t C ha^{-1} and 5.7 t C ha^{-1} for the A1B and A2 scenarios, while DNDC predicted losses of 7.0 t C ha^{-1} and 6.2 t C ha^{-1}. For the B1 scenario, RothC and DNDC predicted reductions of 3.9 t C ha^{-1} and 2.0 t C ha^{-1} respectively. These reductions may be attributed to the increased temperatures and reduced summer precipitation associated with the climate change scenarios. If productivity is increased as a result of climate change, it may increase organic matter inputs sufficiently to compensate for the projected losses of SOC.

Although the McGrath et al. (2005) RCM predicts a shift towards drier summers and wetter winters as well as warmer temperatures at the Wexford site, the models predict a different response of SOC to the climate change scenarios compared to the Cork site (Figure 3.3). Both DNDC and CENTURY predict small changes in SOC stocks. The DNDC model predicts a SOC increase of 0.7 t C ha^{-1} (0.86%) during 2021–2060 for all scenarios (Figure 3.3d, e, f). This suggests that the DNDC model is insensitive to the differences in precipitation and temperature between the scenarios. The losses of SOC predicted by CENTURY vary between 0.05 and 0.7 t C ha^{-1} (0.07–0.94%) and are likely to not be detectable using conventional methods (Figure 3.3d, e, f). In contrast, RothC predicts losses of 4.4 t C ha^{-1}, 3.5 t C ha^{-1} and 2.3 t C ha^{-1} during 2021–2060 for the A1B, A2 and B1 scenarios respectively (Figure 3.3d, e, f).

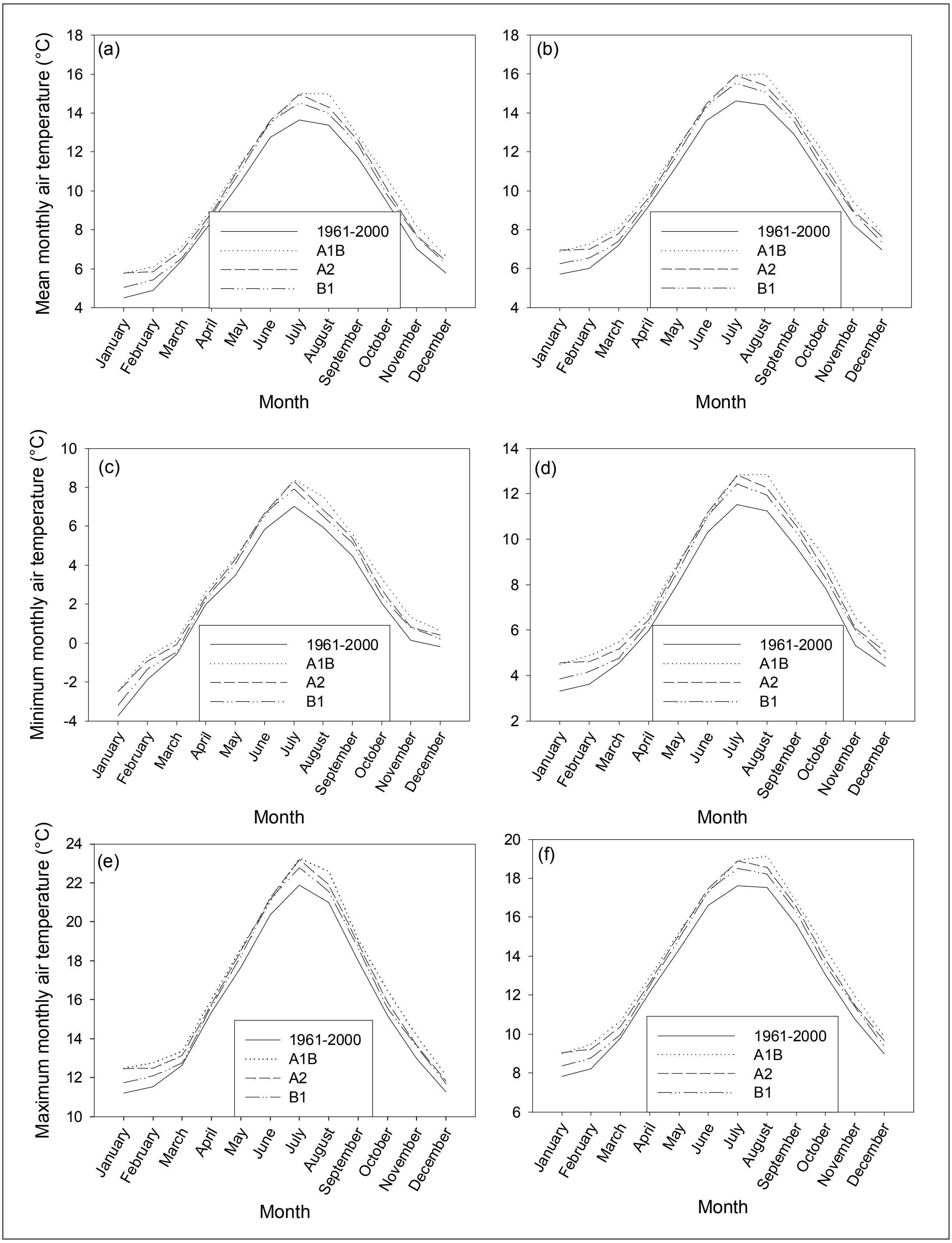

Figure 3.2 Mean monthly air temperature (°C) at (a) the Cork site and (b) the Wexford site; minimum monthly air temperature (°C) at (c) the Cork site and (d) the Wexford site; and maximum monthly air temperature (°C) at (e) the Cork site and (f) the Wexford site, during 1961–2000 and during 2021–2060 for each of the three IPCC scenarios A1B, A2 and B1.

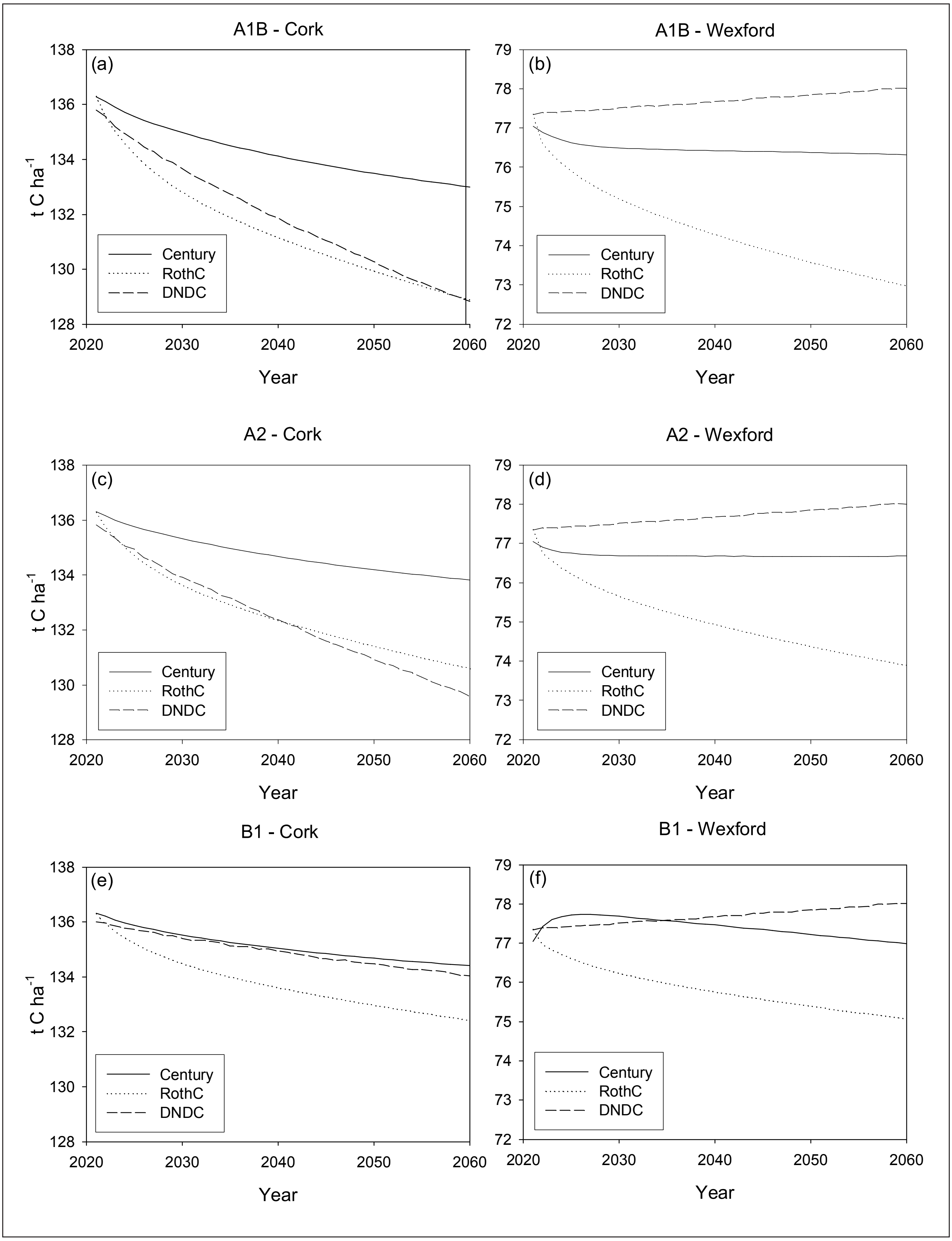

Figure 3.3 Change in SOC in the top 20 cm predicted by RothC, CENTURY and DNDC during 2021–2060 at the Cork site and the Wexford site for each of the three IPCC emission scenarios tested.

3.4 Discussion

This study illustrates the potential response of SOC stocks in Irish grasslands to projected changes in climate. Comparison of the results between sites and models indicates that there will be contrasting responses between soils with different SOC stocks and climate regimes. The Cork site, which has 43% more SOC than the Wexford site, seems more likely to lose SOC. However, the losses at the Cork site for all three models and at the Wexford site for RothC are small when compared to other studies. For example, using the CENTURY model, Ojima et al. (1993) and Parton et al. (1995) found that SOC in humid temperate grasslands was reduced by as much as 4.4% after 50 years in response to temperature increases of 2–5°C. In a study of European grassland soils, Smith et al. (2005) found that climate impacts would reduce the mean grassland soil carbon stock by 10 to 14% of the 1990 level by 2080. Bellamy et al. (2005) found that C was lost from the top 0–15 cm of soils in England and Wales at a rate of 0.6% yr^{-1} between 1978 and 2003 and suggested that this may be linked to climate change. The amount of precipitation in the humid temperature sites studied by Ojima et al. (1993) and Parton et al. (1995) (543–936 mm yr^{-1}) is considerably less than the average at the Cork and Wexford sites (1470 mm and 1281 mm yr^{-1} respectively) and may account for the small SOC losses reported in this study. Recent work at the Cork site by Jaksic et al. (2006a) site suggests that it is less likely to suffer moisture stress, and therefore increased decomposition, as a result of climate change. Jaksic et al. (2006a) compared net ecosystem exchange (NEE) between two years of contrasting precipitation (1785 mm and 1185 mm yr^{-1}) and found that NEE was not sensitive to variation in precipitation. This suggests that major changes in annual precipitation are unlikely to cause a major increase in decomposition and associated CO_2 losses. While there may be increased summertime losses of SOC, decomposition may remain relatively unchanged during the winter months as a result of the increased precipitation.

Comparison of the results from these two humid sites suggests that the potential reduction in SOC stocks is likely to increase with increasing rainfall and SOC stock. In such circumstances, soils at high elevation and in the west of the country would be most vulnerable to climate change.

When considered at a farm scale, the losses of SOC are quite small (%), however they may be quite significant at national scale. As mentioned previously, Eaton et al. (in press) estimated that grassland accounts for 53.3% (3.772 M ha) of the land area in the Republic of Ireland. A SOC loss of 0.1 t C ha^{-1} yr^{-1} would equate to a total loss of 0.377 million t C yr^{-1} if all grasslands responded in a similar fashion to the site studied here. This estimate illustrates the need to investigate the potential effect of climate change on SOC stocks in grassland with varying precipitation ranges, soil types, C content and management practices.

While SOC stocks may be reduced as a consequence of climate change, increased productivity as a result of changes in temperature, precipitation and CO_2 concentration may increase litter production and thereby increase SOC stocks. In a study of European grasslands, Smith et al. (2005) found that changes in net primary productivity compensated for losses of SOC in three out of four scenarios examined. Holden and Brereton (2002) studied the potential effect of climate change on grass yield in Ireland and found that summertime drought would lead to reduced grass yield over large parts of the south and east of the country. This would suggest that losses of SOC would not be compensated for by increased productivity and associated litter production.

All three SOC models gave largely similar results at the Cork site but gave divergent results when applied to the Wexford site. RothC and CENTURY were developed to model C dynamics in soil and have been widely used for that purpose. They require relatively few inputs (Table 3.2) which is advantageous when testing them across a range of soil and climatic conditions. However, there is some doubt about the suitability of CENTURY, given that it was not possible to incorporate fertiliser application (and therefore capture current management practices) in the model runs. In contrast to RothC and CENTURY, DNDC requires more input. Unlike RothC and CENTURY it has been more widely applied to simulate and predict soil N_2O emissions rather than changes in SOC. While these models should be tested at more sites, the results of this study suggest that RothC and CENTURY are the most preferable for simulating future changes in SOC stocks. A major shortcoming in assessing the applicability of these models to Irish conditions is the lack of soil, climatic and management data from long-term experiments similar to those employed for model applications elsewhere (Kelly et al. 1997; Li et al. 1997; Smith et al. 1997b). Paustian et al. (1997) consider this to be an essential prerequisite to upscaling to regional and national level. There is therefore an urgent need to establish experiments which will provide such data and provide a sound basis for further model comparisons and regional- and national-scale assessments.

4 Conclusions and Recommendations

When considering which models to use to assess changes in SOC stocks in grassland soils across a range of scales, RothC and CENTURY should be considered first. This is because they require fewer inputs than DNDC and PaSim and have been more widely used to simulate and predict changes in SOC stocks. All three SOC models predicted a reduction in SOC stocks at the Cork site during 2021–2060 for each climate change scenario, with variation between models and scenarios. The range of reduction of SOC was 1.9 to 7.4 t C ha^{-1}. In contrast, DNDC and CENTURY predicted a small change in SOC at the Wexford site and RothC predicted a loss of 2.3 to 4.4 t C ha^{-1}. Based on the results of Section 3, CENTURY and RothC are the most suitable models for further testing and calibration. There is an urgent need to establish long-term experiments across the range of soil, management and land-use conditions in Ireland. This would provide vital information which could be used to calibrate models at site scale and make future predictions. Suitable datasets relating to climate, soils and land management should be collated and harmonised so that a GIS-based platform for model upscaling can be developed and information gaps identified.

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Acronyms

BIO	microbial biomass
DNDC	denitrification–decomposition
DOC	dissolved organic carbon
DPM	decomposable plant material
EDCM	erosion–deposition–carbon model
FYM	farmyard manure
GHG	greenhouse gas
IOM	inert organic matter
LAI	leaf area index
NEE	net ecosystem exchange
RCM	regional climate model
RothC	Rothamsted Carbon Model
RPM	resistant plant material
SOC	soil organic carbon
SOM	soil organic matter
TSMD	topsoil moisture deficit
VSMC	volumetric soil moisture content
WFPS	water-filled porosity

An Ghníomhaireacht um Chaomhnú Comhshaoil

Is í an Gníomhaireacht um Chaomhnú Comhshaoil (EPA) comhlachta reachtúil a chosnaíonn an comhshaol do mhuintir na tíre go léir. Rialaímid agus déanaimid maoirsiú ar ghníomhaíochtaí a d'fhéadfadh truailliú a chruthú murach sin. Cinntímid go bhfuil eolas cruinn ann ar threochtaí comhshaoil ionas go nglactar aon chéim is gá. Is iad na príomh-nithe a bhfuilimid gníomhach leo ná comhshaol na hÉireann a chosaint agus cinntiú go bhfuil forbairt inbhuanaithe.

Is comhlacht poiblí neamhspleách í an Ghníomhaireacht um Chaomhnú Comhshaoil (EPA) a bunaíodh i mí Iúil 1993 faoin Acht fán nGníomhaireacht um Chaomhnú Comhshaoil 1992. Ó thaobh an Rialtais, is í an Roinn Comhshaoil agus Rialtais Áitiúil a dhéanann urraíocht uirthi.

ÁR bhFREAGRACHTAÍ

CEADÚNÚ

Bíonn ceadúnais á n-eisiúint againn i gcomhair na nithe seo a leanas chun a chinntiú nach mbíonn astuithe uathu ag cur sláinte an phobail ná an comhshaol i mbaol:

- áiseanna dramhaíola (m.sh., líonadh talún, loisceoirí, stáisiúin aistrithe dramhaíola);
- gníomhaíochtaí tionsclaíocha ar scála mór (m.sh., déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta);
- diantalmhaíocht;
- úsáid faoi shrian agus scaoileadh smachtaithe Orgánach Géinathraithe (GMO);
- mór-áiseanna stórais peitreail.

FEIDHMIÚ COMHSHAOIL NÁISIÚNTA

- Stiúradh os cionn 2,000 iniúchadh agus cigireacht de áiseanna a fuair ceadúnas ón nGníomhaireacht gach bliain.
- Maoirsiú freagrachtaí cosanta comhshaoil údarás áitiúla thar sé earnáil - aer, fuaim, dramhaíl, dramhuisce agus caighdeán uisce.
- Obair le húdaráis áitiúla agus leis na Gardaí chun stop a chur le gníomhaíocht mhídhleathach dramhaíola trí comhordú a dhéanamh ar líonra forfheidhmithe náisiúnta, díriú isteach ar chiontóirí, stiúradh fiosrúcháin agus maoirsiú leigheas na bhfadhbanna.
- An dlí a chur orthu siúd a bhriseann dlí comhshaoil agus a dhéanann dochar don chomhshaol mar thoradh ar a ngníomhaíochtaí.

MONATÓIREACHT, ANAILÍS AGUS TUAIRISCIÚ AR AN GCOMHSHAOL

- Monatóireacht ar chaighdeán aeir agus caighdeáin aibhneacha, locha, uiscí taoide agus uiscí talaimh; leibhéil agus sruth aibhneacha a thomhas.
- Tuairisciú neamhspleách chun cabhrú le rialtais náisiúnta agus áitiúla cinntí a dhéanamh.

RIALÚ ASTUITHE GÁIS CEAPTHA TEASA NA HÉIREANN

- Cainníochtú astuithe gáis ceaptha teasa na hÉireann i gcomhthéacs ár dtiomantas Kyoto.
- Cur i bhfeidhm na Treorach um Thrádáil Astuithe, a bhfuil baint aige le hos cionn 100 cuideachta atá ina mór-ghineadóirí dé-ocsaíd charbóin in Éirinn.

TAIGHDE AGUS FORBAIRT COMHSHAOIL

- Taighde ar shaincheisteanna comhshaoil a chomhordú (cosúil le caighdéan aeir agus uisce, athrú aeráide, bithéagsúlacht, teicneolaíochtaí comhshaoil).

MEASÚNÚ STRAITÉISEACH COMHSHAOIL

- Ag déanamh measúnú ar thionchar phleananna agus chláracha ar chomhshaol na hÉireann (cosúil le pleananna bainistíochta dramhaíola agus forbartha).

PLEANÁIL, OIDEACHAS AGUS TREOIR CHOMHSHAOIL

- Treoir a thabhairt don phobal agus do thionscal ar cheisteanna comhshaoil éagsúla (m.sh., iarratais ar cheadúnais, seachaint dramhaíola agus rialacháin chomhshaoil).
- Eolas níos fearr ar an gcomhshaol a scaipeadh (trí cláracha teilifíse comhshaoil agus pacáistí acmhainne do bhunscoileanna agus do mheánscoileanna).

BAINISTÍOCHT DRAMHAÍOLA FHORGHNÍOMHACH

- Cur chun cinn seachaint agus laghdú dramhaíola trí chomhordú An Chláir Náisiúnta um Chosc Dramhaíola, lena n-áirítear cur i bhfeidhm na dTionscnamh Freagrachta Táirgeoirí.
- Cur i bhfeidhm Rialachán ar nós na treoracha maidir le Trealamh Leictreach agus Leictreonach Caite agus le Srianadh Substaintí Guaiseacha agus substaintí a dhéanann ídiú ar an gcrios ózóin.
- Plean Náisiúnta Bainistíochta um Dramhaíl Ghuaiseach a fhorbairt chun dramhaíl ghuaiseach a sheachaint agus a bhainistiú.

STRUCHTÚR NA GNÍOMHAIREACHTA

Bunaíodh an Ghníomhaireacht i 1993 chun comhshaol na hÉireann a chosaint. Tá an eagraíocht á bhainistiú ag Bord lánaimseartha, ar a bhfuil Príomhstiúrthóir agus ceithre Stiúrthóir.

Tá obair na Gníomhaireachta ar siúl trí ceithre Oifig:

- An Oifig Aeráide, Ceadúnaithe agus Úsáide Acmhainní
- An Oifig um Fhorfheidhmiúchán Comhshaoil
- An Oifig um Measúnacht Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáide

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag ball air agus tagann siad le chéile cúpla uair in aghaidh na bliana le plé a dhéanamh ar cheisteanna ar ábhar imní iad agus le comhairle a thabhairt don Bhord.

National Development Plan 2007 - 2013

Science, Technology, Research and Innovation for the Environment (STRIVE) 2007-2013

The Science, Technology, Research and Innovation for the Environment (STRIVE) programme covers the period 2007 to 2013.

The programme comprises three key measures: Sustainable Development, Cleaner Production and Environmental Technologies, and A Healthy Environment; together with two supporting measures: EPA Environmental Research Centre (ERC) and Capacity & Capability Building. The seven principal thematic areas for the programme are Climate Change; Waste, Resource Management and Chemicals; Water Quality and the Aquatic Environment; Air Quality, Atmospheric Deposition and Noise; Impacts on Biodiversity; Soils and Land-use; and Socio-economic Considerations. In addition, other emerging issues will be addressed as the need arises.

The funding for the programme (approximately €100 million) comes from the Environmental Research Sub-Programme of the National Development Plan (NDP), the Inter-Departmental Committee for the Strategy for Science, Technology and Innovation (IDC-SSTI); and EPA core funding and co-funding by economic sectors.

The EPA has a statutory role to co-ordinate environmental research in Ireland and is organising and administering the STRIVE programme on behalf of the Department of the Environment, Heritage and Local Government.

Environmental Protection Agency
An Ghníomhaireacht um Chaomhnú Comhshaoil

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SSTI Strategy for Science, Technology and Innovation

Comhshaol, Oidhreacht agus Rialtas Áitiúil
Environment, Heritage and Local Government