Nutrient Cycling in Agroecosystems **70:** 231–239, 2004.

ICBM regional model for estimations of dynamics of agricultural soil carbon pools

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Key words: Agriculture, Budget, Carbon, Modelling, Sequestration, Soil

Abstract

Swedish arable land covers 3 Mha and its topsoil contains about 300 Mton C. The mineral soils seem to be close to steady-state, but the organic soils (about 10% of total arable land) have been estimated to lose ca. 1 Mton/year. We have devised a conceptual model (ICBMregion), using national agricultural crop yield/manuring statistics and allometric functions to calculate annual C input to the soil together with a five-parameter soil carbon model (ICBMr), calibrated using long-term field data. In Sweden, annual yield statistics are reported for different crops, for each of eight agricultural regions. Present topsoil carbon content and regional distribution of soil types have recently been measured. We use daily weather station data for each region together with crop type (bulked from individual crop data) and soil type to calculate an annual soil climate parameter for each crop/soil type permutation in each region. We use 14 soil types and 9 crop types, which gives 126 parameter sets for each year and region, each representing a fraction of the region's area. For each year, region, crop and soil type, ICBM-region calculates the change in young and old soil carbon per hectare, and sums up the changes to, e.g., national changes. With eight regions, we will have 1008 parameter sets per year, which easily can be handled, and what-if scenarios as well as comparisons between benchmark years are readily made. We will use the model to compare the soil C pools between the IPCC benchmark year 1990 and the present. In principle, we use inverse modelling from the sampled, recent soil C pools to estimate those in 1990. In the calculations, soil climate and yield for each year from 1990 onwards are taken into account. Then we can project soil C balances into the future under different scenarios, e.g., business as usual, land use change or changes in agricultural crops or cultivation practices. Projections of regional climate change are also available, so we can quite easily make projections of soil C dynamics under, e.g., different climate scenarios. We can follow the dynamic effects of carbon sequestration efforts – and estimate their efficiency. The approach is conceptually simple, fairly complete, and can easily be adapted to different needs and availability of data. However, perhaps the greatest advantage is that the results from this comprehensive approach used for, e.g., a 10-year period, can be condensed into a very simple spreadsheet model for calculating effects of management/land use changes on C stocks in agricultural soils.

Introduction

Swedish arable land covers about 3 Mha and its topsoil contains about 300 Mton C. The mineral soils seem to be close to steady-state, but the organic soils (about 10% of total arable land) have been estimated to lose ca. 1 Mton/year (Andrén and Kätterer 2001).

Calculations of national soil carbon budgets run into a number of problems: Lack of data, low or unclear precision of data, biased data as well as lack of detailed knowledge about how controlling factors affect, e.g., annual input of C to the soil. However, the basic principles behind soil C balances are fairly well known, and for a given m^2 it is quite easy to calculate soil C balances in a 30–50 year perspective (Hénin et al. 1945; Andrén and Kätterer 1997, 2001).

The Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 1997) recommend calculations of soil C mass changes from the baseline year (1990). In principle, the recommendation is to calculate or measure later soil C pools and assume a linear change. However, the recommendations are open-ended, and improved methodology is encouraged.

A systems analysis approach, i.e., keeping track of the carbon mass fluxes through the topsoil, is absolutely necessary for drawing the correct conclusions. In the following, we give a few examples.

The rate of change of soil carbon is dependent on the distance from the steady-state soil C mass. Thus, if we increase annual carbon input to a soil that is in balance, the rate of change in soil C, or the slope, will gradually decrease to zero as the system approaches the new steady-state C mass. This system behaviour sometimes leads to interpretation of the new steady-state mass as 'saturation' or 'storage capacity' etc. In other words, a behaviour that is general for a system with inputs and outputs is interpreted as a property of a particular soil (Andrén and Kätterer 2001).

In soil science, carbon concentration (by weight) is often used as an indicator of treatment effects, but it can be misleading. For example, a long-term field experiment may result in lower C concentration in the topsoil, when the topsoil carbon mass (kg ha^{-1}) has actually increased. This can happen when the ploughing depth has increased during the experiment (soil compaction, human error, new equipment), and thus the wrong conclusions can be drawn (see, e.g, Kätterer and Andrén 1999).

Even the well-known 'stabilizing effect' of clay soils can partly be explained by flawed, concentration-based thinking. Let us assume we have an annual C input that results in a steady-state C mass of 80000 kg ha^{-1} in a 30-cm deep topsoil. Assume one clay soil with bulk density 1.2 kg dm^{-3} and one sandy with 1.5. With 80000 kg ha^{-1} in 30 cm topsoil, the C concentration becomes 2.2% and 1.8% in the clay and sand, respectively – where the C mass, annual input and annual output are identical.

For national soil C monitoring and reporting, a natural approach would be to base the budgeting and projections on detailed GIS maps, and in the ideal case we would have 5 $\times$ 5 m resolution of soil type, C stock, C input, daily soil moisture and temperature etc. With this information, it is reasonably easy to run a simple model with a unique parameter set for each 'pixel' and produce an illustrative and accurate map of what is happening or will happen to the soil C pools. In the case of Swedish arable land, however, this will require 1.2×10^9 'pixels', which may demand too much computing (and perhaps even more man-) power. In any case, we are not aware of any country where a high-resolution, high-precision and complete database exists for the whole country, so compromises have to be made. At what stage of compromise the whole exercise becomes meaningless (colourful maps of wild guesses) is an open question, far beyond the scope of this paper.

Lower-resolution GIS-based approaches have been used in a number of countries, and these have certainly yielded valuable results (e.g., Falloon et al. 2002; Heidmann et al. 2002). However, the lack of full information for each grid point, even in a low-resolution grid, still makes clear interpretations difficult. A more cost-effective approach may be to begin with surveying available data, and decide from the amount, resolution and quality of these how we can apply the theoretical knowledge mentioned above. We use Sweden as an example, but the principle should be applicable everywhere.

Daily weather station data are available from a network covering the whole country, and annual yield statistics are reported for each of eight agricultural regions (Anonymous 1990–2002). Present topsoil carbon content and regional distribution and properties of soil types have recently been measured (Eriksson et al. 1997, 1998).

These data sets can by used to calculate parameter values for a model, and the measured carbon content in 1995 gives us an anchoring point, from which we can project carbon pools forwards in time or even backwards. Thus we can use the available information to calculate the carbon pools in the IPCC baseline year (1990) to present time and all years in between, individually for each production region. A five-parameter soil carbon model (ICBMr), calibrated using long-term field data, is used for the soil C calculations.

We use the national agricultural yield and manuring statistics together with allometric functions to calculate annual C input to the soil (i). C inputs from manure vs. crops are weighted to a common input quality factor, h, which is short for humification quotient. The two parameters k_Y and k_O, which denote decomposability of young and old C in the soil, respectively, are kept constant (For practical reasons; but see Kätterer and Andrén 2004).

The annual crop yield statistics are reported for different crops, for each of the eight production regions (Anonymous 1990–2002). We use weather station data for each region together with crop type (bulked from individual crop data) and soil type to calculate annual soil climate for each crop/soil type permutation in each region. For each year, region, crop and soil type, ICBMr calculates the annual change in young and old soil carbon per hectare, and sums up the changes to, e.g., national changes. What-if scenarios as well as comparisons between benchmark years are readily made.

Projections of regional climate change are also available (Rummikainen 2002) so we can quite easily make projections of soil C dynamics under different climate (or land use/management) scenarios. We can follow the dynamic effects of carbon sequestration efforts – and estimate their efficiency.

Methods

Overall conceptual model (ICBMregion)

Parameters for ICBM are generated in the following way (Figure1). For each region, crop and soil type carbon input i, soil climate r_e and humification coefficient h are calculated. The input data and thus the resulting parameters are different for each year, excepting the 'Constants', k_Y and k_O. Crop, weather, and soil data for each region are used in the W2r_e module, calculating soil climate, r_e, for each region, crop and soil (*top left*). Crop yield data are recalculated using allometric functions and weighted according to regional distribution of crops and soil types to produce soil carbon input, i, per region and soil type (*bottom right*). Manure also generates carbon input, and the proportion crop residues/manure determines the humification coefficient, h (bottom left).

Weather to soil climate module (W2r_e)

The soil water balance calculations were based on FAO concepts (Allen et al. 1998). Inputs are daily weather station data (daily mean air temperature, precipitation and potential evapotranspiration).

The water store, Ω (mm), in the topsoil at day t is given by:

$$\Omega_t = \Omega_{t-1} + PPT - ET_{soilact} - ET_{cropact} - P_{\text{interception}} - \Omega_{Sink} \quad (1)$$

where PPT is precipitation, ET is evapotranspiration and the indices $_{soilact}$ and $_{cropact}$ are short for soil actual and crop actual, respectively. $P_{interception}$ and Ω_{Sink} are crop interception of precipitation and runoff/percolation, respectively. Water loss by interception occurs at days when precipitation occurs and does never exceed potential evapotranspiration (ET_{pot}) or 2 mm day^{-1}. The remaining potential evaporative demand (ET_{pot} – $P_{interception}$) is distributed between soil evaporation ($ET_{soilpot}$) and transpiration ($ET_{croppot}$) according to FAO guidelines (Allen et al. 1998). Further, $ET_{soilpot}$ and $ET_{croppot}$ were multiplied by response functions to yield $ET_{soilact}$ and $ET_{cropact}$ representing a decrease in soil water supply with decreasing soil water content.

Ω is delimited by the field capacity and a minimum water store, which corresponds to a certain fraction (α) of that at wilting point.

To convert from mm water to volumetric water content (θ) we divided Ω by the topsoil thickness in mm (L), in our case 250:

$$\theta = \frac{\Omega}{L} \quad (2)$$

Differences between soil types are accounted for by using the volumetric water content at wilting point (θ_{wilt}) and at field capacity (θ_{fc}) as input parameters. For simplicity, differences between crops are accounted for simply by using two dates – start and cessation of growth, which are used in a simple time-dependent, bell-shaped function representing the crop water demand.

The relative water content (θ_r) between the minimum water content ($\alpha\theta_{wilt}$) and θ_{fc}

$$\theta_r = \frac{\theta - \alpha\theta_{wilt}}{\theta_{fc} - \alpha\theta_{wilt}} \quad (3)$$

was used for describing the dependence of decomposition on soil water content

$$r_w = \theta_r^{\gamma} \quad (4)$$

and γ (= 1.3) was chosen to approximate the water response function presented by Lomander et al. (1998). This implies that water response factor r_w is zero at $\alpha\theta_{wilt}$ and about 10 times higher at field capacity than at wilting point.

Table 1. The parameters of the ICBM model, their typical units and the effect on total soil carbon mass of an increase in value.

Parameter	Symbol	Typical unit	Effect on soil C mass of increase
Input	i	kg year^{-1}	Positive
Decomposition rate constant for Y	k_Y	year^{-1}	Negative
'Humification coeff.'	h	Dimensionless	Positive
Decomposition rate constant for O	k_O	year^{-1}	Negative
External influence on k_Y and k_O	r_e	Dimensionless	Negative

Table 2. Parameter values used in the allometric function $C = a + sH$ to calculate soil C input (C) from crop yield data (H).

	Straw		Residues		Roots	
	a	s	a	s	a	s
Fallow	0	0	0	0.3	0	0.6
Green_fallow	0	0	0	0.3	0	0.6
Ley	0	0	330	0.2	0	0.4
Root_crops	0	0	0	0.42	0	0.2
Seed_ley	2700	0	905	0	540	0
Spring_cereals	140	0.83	500	0.15	570	0.2
Spring_oilseed	0	1.6	0	1.6	0	0.7
Winter_cereals	320	0.62	540	0.4	670	0.06
Winter_oilseed	0	0.85	0	0.85	740	0.7

Soil temperature (T_{soil}) was calculated from daily mean air temperature (T_{air}) according to the empirical equation

$$T_{soil} = \max(-2; 0.92T_{air}) \quad (5)$$

The effect of T_{soil} on decomposition rates was modelled according to the quadratic relationship

$$r_T = \frac{(T_{soil} - T_{\min})^2}{(30 - T_{\min})^2} \quad (6)$$

where T_{min} is the lower temperature limit for decomposer activity (here set to − 3.8 °C according to Kätterer et al. 1998).

To account for the differences in decomposer activity between crops due to differences in soil cultivation intensity and frequency, we use r_c, the cultivation factor. This factor differs between crops, and is set lowest in leys and highest in root crops. Note that this factor also can be used to project the effects that will occur if, e.g., no-till is introduced for a certain crop.

To calculate annual r_e-values for each region, crop and soil, we first multiplied $r_w \times r_T \times r_c$ for each day and then calculated annual means.

Allometric function set (C2hi)

The allometric functions and their parameter values used to calculate annual carbon input from crop yield data are based on detailed investigations of carbon allocation in various crops as described in Kuzyakov and Domanski (2000). The allometric functions were combined into:

$$C = a + sH \quad (7)$$

C denotes the carbon mass of straw, stubble or roots, and H is the observed crop yield (as carbon). Parameters a and s are empirically based, and differ between straw, stubble and roots and are also different for different crop types (Table 2).

ICBM

ICBM, Introductory Carbon Balance Model, was developed as a minimum approach for calculating soil carbon balances in a 30-year perspective (Andrén and Kätterer 1997). The model is based on well-known concepts (see, e.g., Hénin and Dupuis 1945), and it has two state variables or pools, 'Young' (Y) and 'Old' (O) soil carbon. Two pools were necessary, since the model has to follow the fate of fairly large

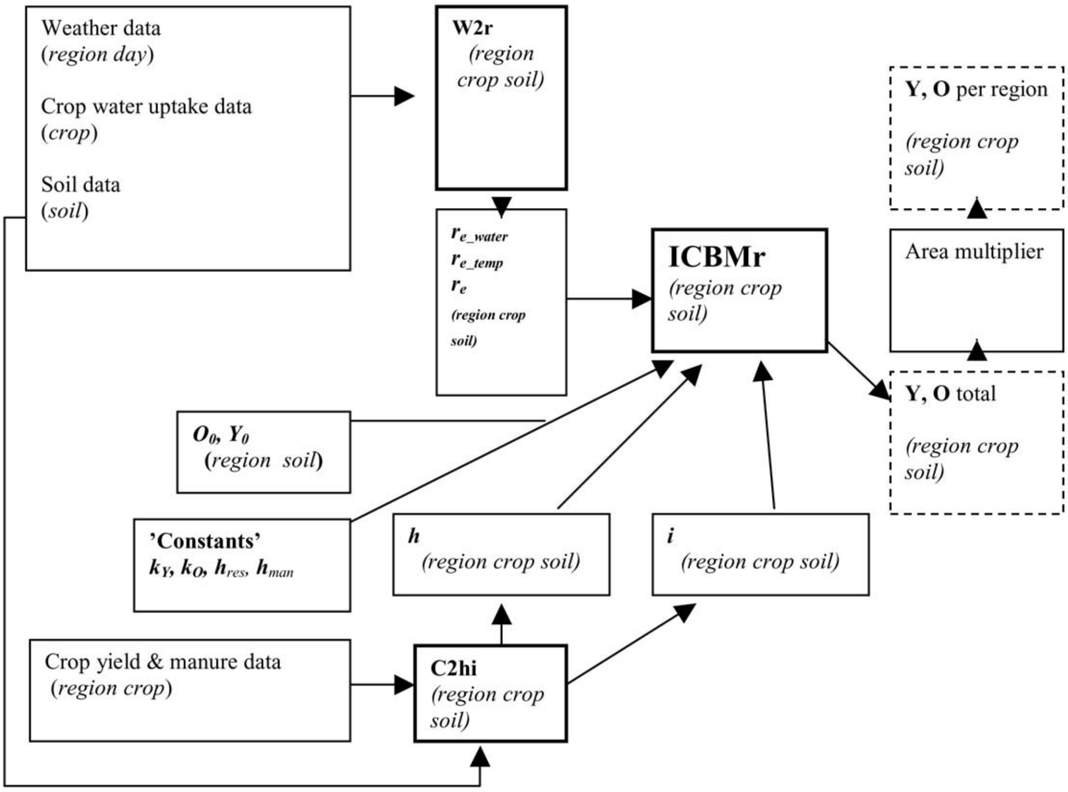

Figure 1. The ICBMregion concept. Crop, weather, and soil data for each region are used in the weather-to-r_e module ($W2r_e$), calculating soil climate, r_e, for each region, crop and soil (*top left*). The initial carbon mass values (O_0, Y_0) are taken from the literature. Parameters k_Y, k_O, h_{res}, h_{man} are regarded as constants (Table 1), and the indices *res* and *man* indicate crop residues and manure, respectively. Crop yield and manure input data are used to calculate C input to soil (*i*), as well as a weighted *h*, by the allometric functions in the *C2hi* module. The two initial values (O_0, Y_0) and the five parameters (r_e, k_Y, k_O, *h, i*) are then used for calculating *Y* and *O* (kg ha^{-1}). These are then multiplied by the actual area to obtain totals for, e.g., region.

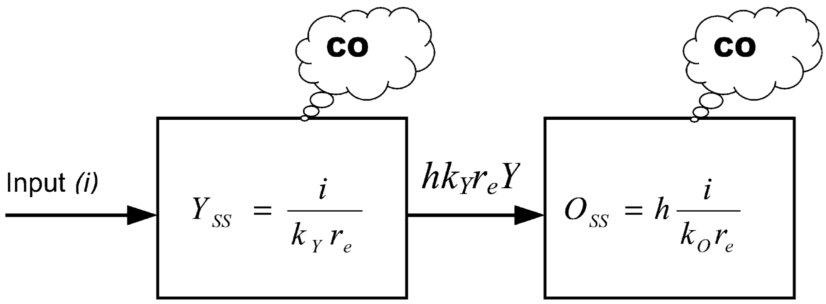

Figure 2. The ICBM model describing soil carbon balances. i = (annual) input, C = pool of soil carbon, Y = young soil carbon, O = old soil carbon, k_Y = fraction of Y that decomposes (per year), k_O = fraction of O that decomposes (per year), h = humification coefficient, r_e = external influence coefficient. The index 'SS' denotes the equation for calculating the steady-state value for that pool. From: Andrén and Kätterer (2001).

instantaneous inputs of litter, e.g., ploughing of grassland, and thus we cannot consider all organic soil carbon as 'humus'. ICBM has five parameters: *i*, k_Y, *h*, k_O, and r_e (Table 1, Figure 2).

The 'humification coefficient' (*h*) controls the fraction of *Y* that enters *O* and ($1-h$) then represents the fraction of the outflow from *Y* that directly becomes

CO_2-C. The parameter r_e summarizes all external influence on the decomposition rates of Y and O.

The model is analytically solved, i.e., simulation techniques are not necessary, model properties can be mathematically analysed and the model can be run and optimised in an ordinary spreadsheet program (Excel etc.). There are also equations for steady-state conditions, i.e., when the pools are constant and the inputs and outputs balance out.

However, it is also possible to run the model as a simulation, with i, h and r_e as driving variables, i.e., with different values for each time step (Kätterer et al. 2004).

ICBMr

Note that *ICBMregion* is the whole concept (Figure 1) and *ICBMr* is the actual soil C model. ICBMr is a version of ICBM that is adapted to using annual data classified according to production region, soil type and crop type. In the following, all sets of annual inputs are classified according to these. For example, if we run the model for 10 years, we will have 10 (years) × 8 (regions) × 14 (soil types) × 9 (crop types) = 10080 input lines.

The input to ICBMr is an initial carbon mass (Y_0, O_0) and the five parameters needed for ICBM. Initial carbon mass is calculated from the national survey by Eriksson et al. (1997). Parameters k_Y and k_O are regarded as constants, with the values 0.8 and 0.006, respectively (Andrén and Kätterer 1997; but see also Kätterer et al. 2004). Parameter r_e is calculated from weather, soil and crop data by *W2r*$_e$ (see above) and parameters h and i are delivered by *C2hi* (see above). The state equations are modified from the original ICBM:

$$Y_t = (Y_{t-1} + i_{t-1})e^{-k_Y r_e} \quad (8)$$

$$O_t = \left(O_{t-1} - h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}\right)e^{-k_O r_e} + h\frac{k_Y(Y_{t-1} + i_{t-1})}{k_O - k_Y}e^{-k_Y r_e} \quad (9)$$

Each time step is regarded to start immediately after the previous crop has been ploughed under, and during each year the soil carbon decomposes according to an exponential function (Kätterer et al. 2004). ICBMr also has functions for summing up and reporting the results as ton/ha, and finally, for reporting according to actual areas in tons per region, etc.

Organic soils with subsidence (lowering of the soil surface which results in gradual incorporation of subsoil into the topsoil) are treated as a special case. Besides the C inputs from crop residues, an annual import of C from the subsoil is estimated from subsidence data. See Andrén and Kätterer (2001) for more details.

Final notes

The project is currently in the testing phase, so it is probable that details will change before a final version is available. However, as an example of how the yield, climate and land use data affect the calculated topsoil C pool we present an output from ICBMregion (Figure 3). Note that the differences between years are slightly less than 2 Mt, in the order of 3% of the total pool, and that this region and period have seen no dramatic changes in the topsoil C pool. For comparison, we included a scenario where we each year multiplied r_e by 1.2 (corresponding to, e.g., an increase in soil temperature with 2.5 °C) and calculated the effects. If the original parameter setup was close to steady-state at 60 Mton, this would give a steady-state mass of 60/1.2 = 50 Mton. As can be seen from Figure 3 this is far from realised during the period of time presented.

The approach presented here is conceptually simple, fairly complete, and can easily be adapted to different needs and availability of data. As may be inferred from the 'Methods' section, the actual application is not that simple, with numerous input data sets, parameterisation decisions and calculations. However, the results from this comprehensive approach used for, e.g., a 10-year period, can be condensed (using table functions for generating parameter values) into a simple spreadsheet model for improving, e.g., 'accountability' – the ability to determine if a proposed measure actually sequesters the amount of C promised.

The current version of ICBMregion is available at http://www.mv.slu.se/vaxtnaring/olle/icbm.html, where also other ICBM information can be found. Presently, the ICBMregion modules and models are available as SAS programs, which are readable by, e.g., MS Word.

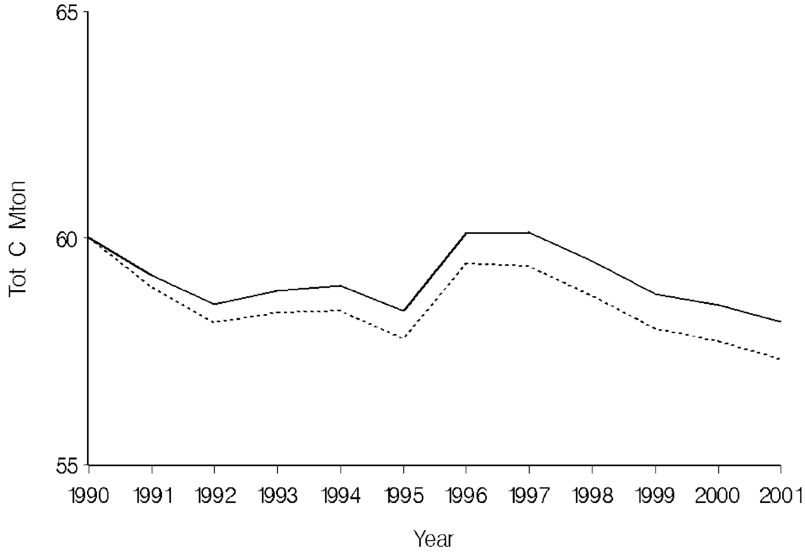

Figure 3. Example of output from ICBMregion. The solid line shows the calculated dynamics of topsoil C mass between 1990–2000 for the central plain region of Sweden. The dotted line shows topsoil C mass dynamics if we assume that r_e, soil climate affecting decomposition, is 20% increased and all other factors are unchanged. Note that the Y axis does not start at origo.

Acknowledgements

This work contributes to the GCTE Core Research Programme, Category 1, which is a part of the IGBP. Financial support was received from the Swedish Environmental Protection Agency. Roland Sigvald helped us to access weather station data. We are grateful to Per-Erik Jansson for providing access to the Swedish soil data base.

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