

Simulating trends in soil organic carbon in long-term experiments using the CANDY model

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Abstract

CANDY (CARbon and Nitrogen DYnamics) is a simulation system based on long-term experiments of organic matter turnover and nitrogen dynamics at Bad Lauchstädt, Germany. Key driving variables are soil physical properties, meteorological data and management information. The main application of the CANDY model is the calculation of short-term dynamics of nitrogen transformation and long-term dynamics of organic matter turnover in arable soils. This paper concentrates on the evaluation of the model in simulating carbon dynamics in long-term experiments representing different land uses and very different geographical sites. The experimental data came from data sets that were made available to modellers at a workshop held at Rothamsted in 1995. In this paper we describe how the different data sets were modelled and provide a qualitative assessment of model performance. The performance of several models, including CANDY, are compared quantitatively in Smith et al. (1997).

Our results show that the mathematical basis of the model, its consideration of a biological time base and its calculation of the 'reproducing carbon' are applicable over a wide range of sites and land-use scenarios. Most of the standard parameters can be used for other sites and land-use systems. © 1997 Elsevier Science B.V.

Keywords: soil organic matter; soil organic matter model; model evaluation; long-term experiment

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1. Introduction

The simulation system CANDY (CARbon and Nitrogen DYNAMics) describes all important soil processes concerning the dynamics of C and N in rural landscapes. Key driving variables are soil physical properties, meteorological data and management information. The CANDY system is based on long-term experiments of organic matter turnover and nitrogen dynamics at Bad Lauchstädt. CANDY is mainly used for calculating short-term dynamics of nitrogen transformation and long-term dynamics of carbon accumulation in the soil of arable fields. The performance of the model with respect to temperature, water and nitrogen dynamics is reported elsewhere (Franko et al., 1995a). This paper concentrates on carbon dynamics in long-term field experiments.

2. Materials and methods

The mathematical formulation of the model is described in detail by Franko (1995). Because carbon accumulation is a very slow process it is not always necessary to use a daily time step. Based on the mathematical description of carbon turnover in the CANDY model, simplifications were made in order to create an annual time-step algorithm that can be used in a database (FOXPRO) application or in an EXCEL spreadsheet.

The day-step model simulates dynamics of soil water and temperature and calculates a daily value of the turnover activity in terms of the biological active time (BAT). The BAT of a given time interval (e.g. month or year) is the time needed at optimal environmental conditions to obtain the same microbial performance as for real conditions during the considered time interval. It is calculated by means of reduction functions expressing the effects of temperature, moisture and aeration in soil (Franko, 1995). The turnover of organic material, and nitrogen dynamics, are simulated simultaneously using numerical solutions to the basic differential equations. Lack of nitrogen may slow down the turnover of organic material of high carbon content. Inputs of organic material are calculated from the data provided on organic matter inputs using special properties for different classes (e.g. manure, slurry, straw and composts). A second source of organic matter, the amount of plant and root residues after harvest, is calculated from the yield using a linear relationship. Depending on the carbon source, only a part of the daily decomposed carbon is used to generate new soil organic matter (SOM). This part is given by the synthesis coefficient η . The amount of matter that goes from the fresh organic matter pool into SOM is called reproducing carbon (C_{REP}) or reproducing organic matter.

The annual time-step model uses an analytical solution to the differential equations assuming a mean biologically active time and a constant annual flux of reproducing organic matter. The amount of this annual flux is calculated from

the annual input of each source multiplied by its synthesis coefficient. This model can be used where daily meteorological data is incomplete, or where input parameters can be improved using measurements of soil organic matter.

Depending on the quantity and type of experimental data available, the daily or annual model was selected. The application of the daily model is limited to arable fields and requires a detailed soil description, daily meteorological data (rainfall, air temperature and global radiation) and land-use data (especially the yield of the cultivated crops) for the whole period. Both models need an initial value for the decomposable carbon.

3. Results

3.1. Rothamsted Park Grass

Three treatments from the Rothamsted Park Grass experiment (Poulton, 1996a) were chosen for this evaluation. These treatments are: nil input (NIL), organic manure (OMA) and sodium nitrate (SNI). The simulations of SOM dynamics were carried out with the simplified annual model using the analytical solutions within an EXCEL spreadsheet. A preliminary simulation of the temperature and water dynamics with the daily model provided values of the biologically active time (t_{BAT}). Carbon sources were assumed to derive from roots, plant residues and organic manure. The carbon input of fishmeal to SOM was neglected. Carbon input from plants was distributed throughout the topsoil while organic manure was applied only to the uppermost soil layer; t_{BAT} was calculated for both cases (Fig. 1). The average of t_{BAT} in the topsoil was found to be 23.8 d. The average biological activity was 45% higher at the soil surface because of lower aeration stress and higher temperatures than deeper in the soil. For this reason, the manure application gave an unusually low contribution to SOM accumulation.

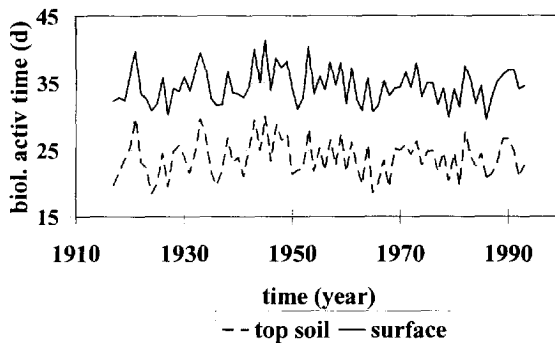


Fig. 1. Simulation results of turnover activity in Rothamsted Park Grass experiment.

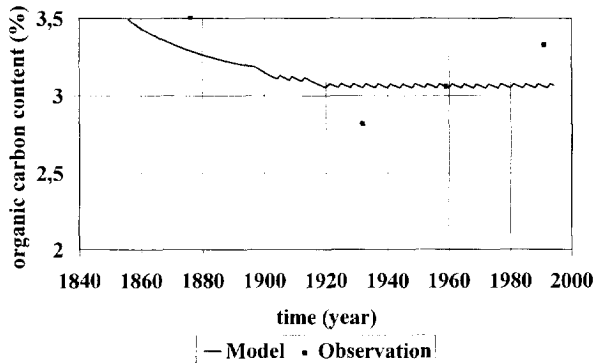


Fig. 2. Carbon dynamics in Rothamsted Park Grass experiment (OMA treatment).

The carbon input of the grass crop to SOM was assumed to be independent of yield ($C_{rep} = 1.54$ t/ha). As for inert carbon, it was estimated by fitting the model to the experimental values. Usually, the inert carbon pool is calculated from the amount of the particle size fraction $\leq 6 \mu\text{m}$ by multiplying it with a constant factor (CIF). Based on clay content, particles $\leq 6 \mu\text{m}$ was estimated to be 30.5%. All other soil physical properties were obtained from standard expressions for clay soil (Franko et al., 1995b).

The model outputs and the experimental results show in all cases a decline in the initial SOM content (Figs. 2–4). For the OMA treatment, the model indicates that the SOM content had reached a steady state in 1920. The experimental values of SOM increase after this time. This increase, however, seems to be too high compared to the calculated organic matter input.

3.2. Long term fertilizer experiment Bad Lauchstädt

The Bad Lauchstädt data set (Körschens and Müller, 1996) contains all information required to run the daily time-step model. Soil data were obtained

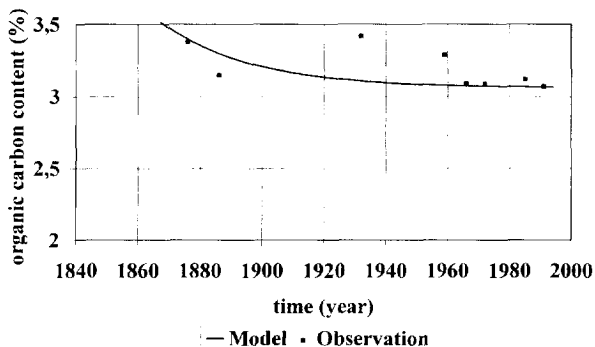


Fig. 3. Carbon dynamics in Rothamsted Park Grass experiment (NIL treatment).

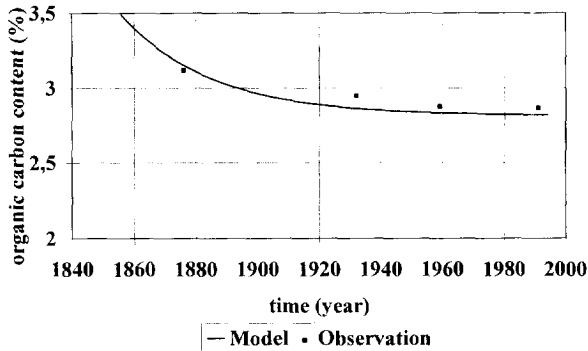


Fig. 4. Carbon dynamics in Rothamsted Park Grass experiment (SNI treatment).

from standard expressions (Franko et al., 1995b). The experimental data set, and thus the simulation, started more than 50 years after the beginning of the experiment. For this reason it was assumed that the carbon content had reached its steady state and the initial values for the decomposable carbon were calculated according to the simplified steady-state model. From 1956 to 1993, the average biological active time was 29.4 d (Fig. 5). The carbon inputs from plant residues were calculated from the given nitrogen uptake using a linear relationship between yield and organic matter of roots and plant debris.

The results of the selected four treatments agree with the assumption of steady state (Fig. 6). The difference between the treatments is very clear and variations in the experimental results appear to be systematic. This leads to the hypothesis that systematic experimental errors occurred during the experiment due to changes in analytical procedure. These errors can be reduced by calculating differences relative to the NIL treatment (Fig. 7).

3.3. Calhoun Forest

This experiment provides data concerning a land use change from cultivated land to forestry (Richter and Markewitz, 1996). Simulations were performed

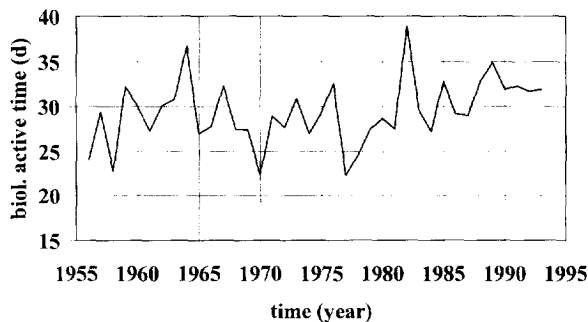


Fig. 5. Simulation results of turnover activity in the long-term experiment, Bad Lauchstädt.

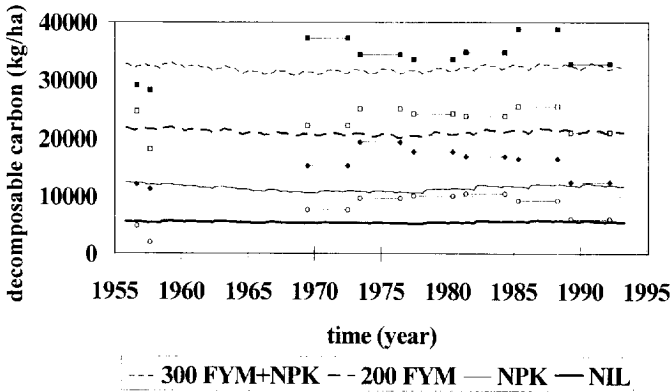


Fig. 6. Carbon dynamics of selected treatments in the long-term experiment, Bad Lauchstädt (lines between symbols indicate averages in time).

with the annual time-step model. The input of reproducing carbon ($C_{REP} = 703$ kg/ha) to the soil was estimated from the nitrogen input assuming that the C/N ratio and the turnover parameters of the litter are similar to those of straw. Parameters from standard records describing physical soil properties were used according to the given range of clay content. The simulations were performed for two different sets of soil parameters because of the wide range of clay contents.

The inert carbon was estimated by means of a fitting procedure and amounted to 12.5 t/ha. The turnover conditions of the Calhoun site were determined using the assumption that evapotranspiration of the trees is 40% higher than of a grass crop. The average biological active time was 29.1 d, ranging from 26.6 d to 31.6 depending on the clay content in the different soil profiles (Fig. 8).

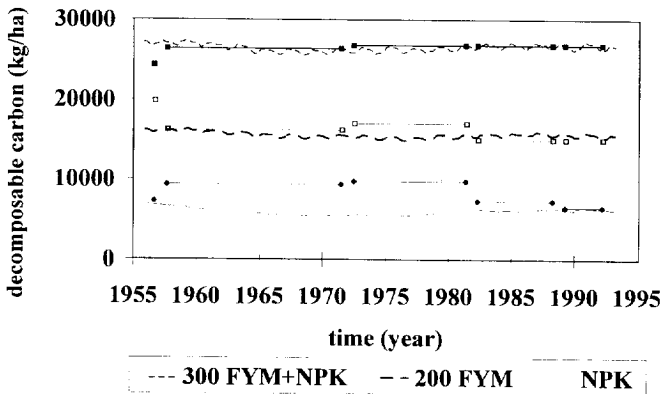


Fig. 7. Carbon dynamics as differences to the NIL plot of selected treatments in the long-term experiment Bad Lauchstädt (lines between symbols indicate averages in time).

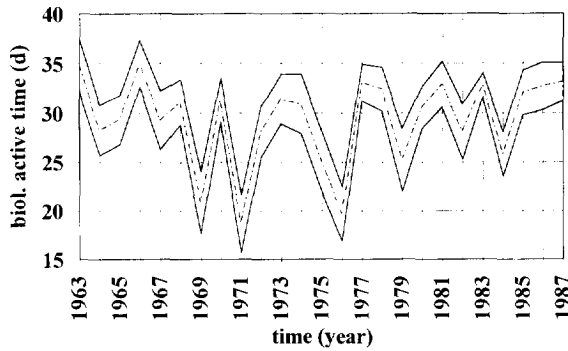


Fig. 8. Simulation results of turnover activity in the Calhoun Forest experiment.

The simulation indicates an initial increase in SOM leading to steady state after 100 years (Fig. 9). Because both observed values were used in initialising model parameters, further information is required to judge model performance.

3.4. Rothamsted Geescroft Wilderness

Details of the experiment are given in Poulton (1996b). The biological active time of 23.8 d, as estimated for the Park Grass Experiment, was used. The effective carbon input to SOM was estimated by a curve-fitting procedure using the annual time-step model in an EXCEL spreadsheet. The amount of reproducing carbon of $C_{REP} = 1800 \text{ kg}/(\text{ha} \cdot \text{a})$ relates to an annual carbon input of fresh organic matter of about 3 t/ha. In contrast to the experimental data, the model suggests that the steady state was almost reached by 1980 (Fig. 10).

3.5. Tamworth black soil

The Tamworth data set provides a wealth of experimental data (Crocker and Holford, 1996). In this first step of model evaluation we concentrated on

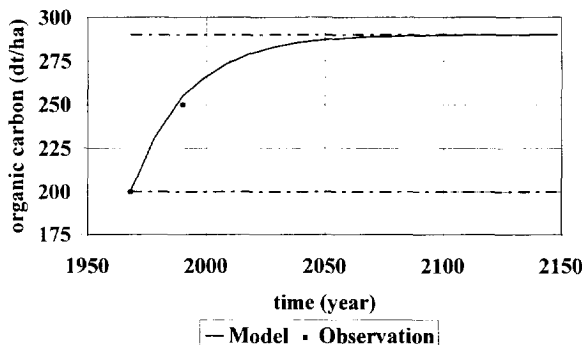


Fig. 9. Carbon accumulation in the forest experiment at Calhoun.

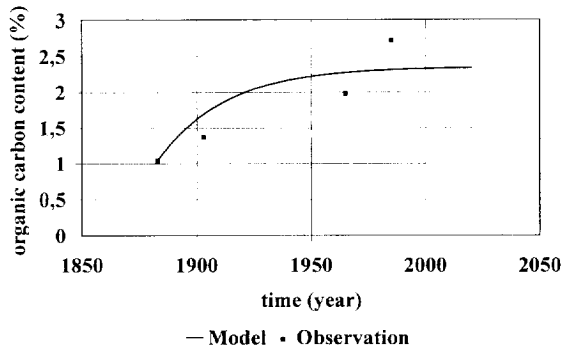


Fig. 10. Carbon accumulation in the Geescroft Wilderness experiment.

treatment 1, a site-specific crop rotation, and treatment 5, with a lower carbon input due to occasional fallow years. All parameters (soil, crop and SOM turnover) used were from the set of standard expressions with respect to the given soil properties (Franko et al., 1995b).

In this case the daily simulation model was used. Despite the high clay content of the soil, the biological activity was found to be very high ($t_{\text{BAT}} = 39.8$ d). The inert carbon pool was estimated at 1% C_{org} .

The model outputs show, in agreement with the experimental results, an increase in SOM for treatment 1 (Fig. 11). Systematic fallowing reduces the input of fresh organic matter. The model output for treatment 5 (Fig. 12) shows no overall change in SOM content. However, the observed data from 1979 to 1991 show a decrease in the initial SOM as a result of only one crop every 2 years. Only the last measurement suggests that the carbon content remains constant. However, the apparent large increase in SOC in 1991–1993, which occurs in both treatments, may be aberrant because there is no agronomic reason for this behaviour.

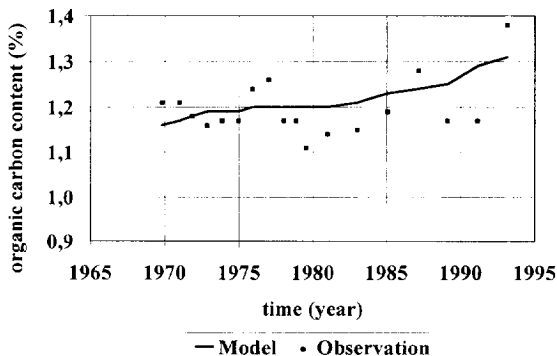


Fig. 11. Carbon dynamics in the Tamworth black soil experiment (treatment 1).

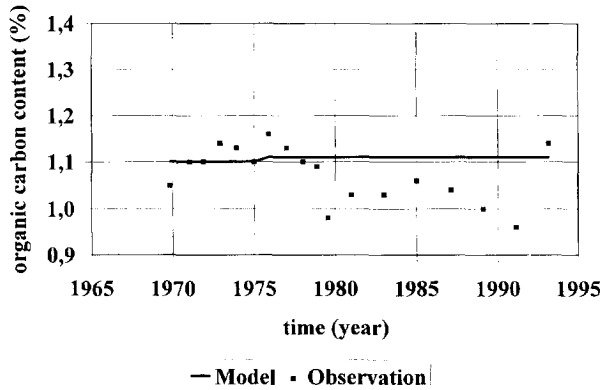


Fig. 12. Carbon dynamics in the Tamworth black soil experiment (treatment 5).

3.6. Long-term fertilizer experiment, Praha–Ruzyne

This experiment provides all the data necessary for a daily simulation with the CANDY model (Klír, 1996). All inputs (soil, crop and SOM turnover) were used from the set of standard expressions (Franko et al., 1995b) with respect to the given soil properties. With $t_{\text{BAT}} = 21$ d the average biological activity lies within the expected range for this site. The inert carbon pool was estimated at 1.02%. The comparison of the NIL treatment (no inputs) with the high input treatment (FYM and mineral fertilizer) shows a marked increase in SOM in the high input treatment (Figs. 13 and 14). This increase may be slightly overestimated by the model, but the very last analytical results, carried out with a more refined technique (Klír, pers. commun.) indicate comparable results to the CANDY output. Despite the variation in experimental results, the NIL treatment shows almost no long-term change in SOM content (Fig. 13). This leads us to the hypothesis that this treatment is very close to its steady state.

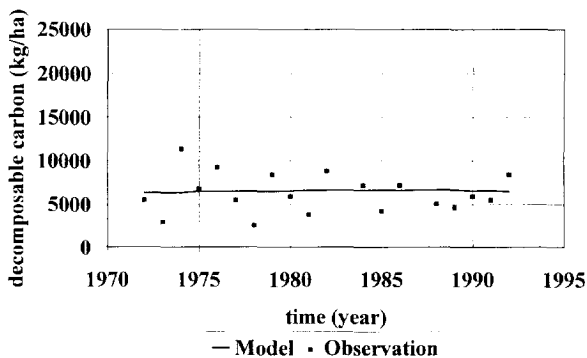


Fig. 13. Dynamics of decomposable carbon on NIL treatment at Praha–Ruzyne.

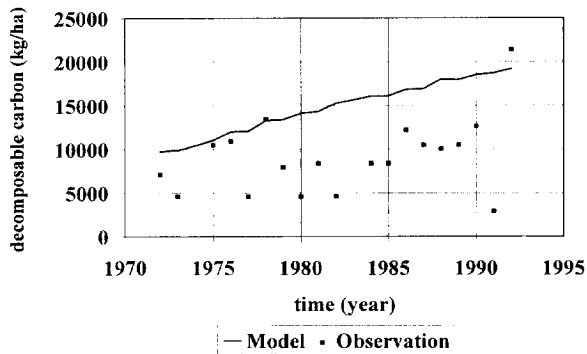


Fig. 14. Accumulation of decomposable carbon due to FYM and fertilizer input at Praha–Ruzyne.

3.7. Waite permanent rotation trial

The Waite experiment (Grace, 1996) provides information about the carbon changes after different cultivation practices on previously native grassland. This examination deals with treatment 2 (wheat–fallow) and treatment 5 (wheat–oats–non legume pasture–fallow). Data from treatment 2 were used for site-specific model calibration. The given yields were used to calculate the averaged annual inputs of reproducing organic carbon. This carbon input was found to be 106 kg/ha for treatment 2 and 546 kg/ha for treatment 5. The observed values of soil organic carbon in treatment 2 were used to estimate the biological active time of the Waite site at 24.8 d. This figure was also applied to treatment 5, thus neglecting the influence of the different crop rotation. Treatment 5 produces a higher input of reproducing carbon (546 kg/ha), leading to a slower decomposition of the initial carbon pool (Fig. 15). This blind test is discussed in Smith et al. (1997).

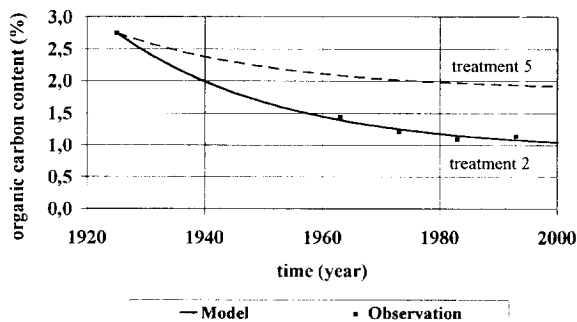


Fig. 15. Carbon dynamics in the Waite experiment.

4. Discussion

Long-term experiments provide an excellent database for the development and validation of SOM models. In particular, the validation of a model with data sets from very different sites gives some measure of how well the model simulates reality. These validation results show that the CANDY model is able to simulate the dynamics of organic matter over a wide range of sites and land-use practices. An advantage of using this model is that the user has the ability to select different model specifications, depending on the available data and the problem to be solved. Consequently, it is very simple and needs little data to calculate steady-state soil organic matter, which can be used as an initial value for the annual time-step model or the daily time-step model. The application of the annual time-step model provides an opportunity for parameter estimation. If all data are available, it is better to use the daily time-step model because this model simulates not only carbon dynamics, but also the fate of nitrogen.

Modelled results do not always give results comparable to the observed data. In some cases (Tamworth and Praha) we have to consider the very large variability in the soil carbon data. This is a problem with many long-term experiments if the soil samples have not been stored and thus cannot be reanalysed. Results reflect not only the changes in organic matter content but also changes in analytical procedures over long periods of time. The aggregation of SOM analyses over a time interval of a few years (as in the Bad Lauchstädt experiment) may provide a better understanding of real SOM changes. In most cases CANDY shows the same trend in SOM dynamics as do the experimental results. In two cases, however (Tamworth, treatment 5 and Praha–Ruzine, FYM treatment), CANDY tends to overestimate the observed carbon storage. It should be noted that, in all cases, calibration of model inputs and parameters have been kept to a minimum. Better results could have been obtained if more information about the quality of the added organic matter or the plant and root residues was available. It is also likely that the relations between crop yield and carbon input from roots are dependent on the particular soil and climatic conditions.

The evaluation shows that the mathematical basis of the model, which was originally developed only for arable fields in the German Black Earth Region, is applicable over a wide range of sites and land-use scenarios. Most of the parameters seem to be useful for other sites and land use systems. By considering a biological time base and by using the concept of “reproducing carbon” (Franko, 1995), there are opportunities to apply the model to very different scenarios.

One problem encountered in this exercise is the estimation of the inert carbon, which is neglected in the turnover processes. The relationship between soil texture and the amount of inert carbon was not constant for the different experiments. Consequently, it was necessary to use at least one observation of the carbon content of each site for the determination of this parameter.

Acknowledgements

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