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**Translocation of soils to simulate climate change: CO<sub>2</sub> emissions and modifications to soil organic matter**

M. REY<sup>a</sup>, E. GUNTIÑAS<sup>a</sup>, F. GIL-SOTRES<sup>a\*</sup>, M.C. LEIRÓS<sup>a</sup> & C. TRASAR-CEPEDA<sup>b</sup>

<sup>a</sup> *Departamento de Edafología y Química Agrícola, Facultad de Farmacia, Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, and* <sup>b</sup> *Departamento de Bioquímica del Suelo, Instituto de Investigaciones Agrobiológicas de Galicia, CSIC, Apartado 122, E-15780 Santiago de Compostela, Spain*

Correspondence: F. Gil-Sotres. E-mail: [edgils@usc.es](mailto:edgils@usc.es)

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## Summary

The effect of climate change on CO<sub>2</sub> emissions was studied on undisturbed soil monoliths (40-cm diameter, 25-cm high), which were translocated to warmer zones than their place of origin. Thirty-two months after the translocation, a climatic factor deduced from the moisture content of the soil and from the effective mean temperature (temperatures in excess of 5 °C) revealed that translocation increased the potential of the climate to enhance the biological processes by between 73% and 26% compared with what the soil would support in its place of origin. At the end of the study, the transported soils had lost a large proportion of both total carbon and nitrogen (between 20 and 45%). During the experiment, the CO<sub>2</sub> emissions from the soils, measured under field conditions, were quite variable, but were usually greater than from soils *in situ*. The variation in labile C in the soil throughout the experiment was calculated from a first-order kinetic equation for organic matter decay. The relative CO<sub>2</sub> emissions, expressed in terms of the labile carbon fraction in the soils, were clearly greater in those translocated soils that underwent the most intensive climate change, which indicates that the variations in emissions over time are basically a function of the size of the labile organic matter pool.

## Introduction

Today, it is widely accepted that the concentration of CO<sub>2</sub> and other greenhouse gases in the atmosphere are rising continuously (Thorning *et al.*, 1989). Although it seems apparent that these increases are affecting the climate, and result in an increase in the surface temperature of the Earth, the effects of an increase in atmospheric CO<sub>2</sub> on the biogeochemical carbon cycle are still being debated (Powlson, 2005). A number of authors consider that the increase in temperature may lead to a positive feedback effect, since it will provoke an increase in atmospheric CO<sub>2</sub> by stimulating the mineralization of organic matter in the soil (Thornley *et al.*, 1991; Kirschbaum, 1995). Other authors consider a negative feedback effect more likely, since greater concentrations of atmospheric CO<sub>2</sub> would lead to increased photosynthetic activity, which, in turn, would result in even greater amounts of fixed CO<sub>2</sub> in the plant biomass (Wigley & Raper, 1992; Grifford, 1994).

The effects of climate change on the processes that affect the decomposition of soil organic matter (SOM) are difficult to predict, mainly because of the complexity of the interactions among soil respiration, temperature and moisture (Kirschbaum, 1995; Davidson *et al.*, 2000). Kirschbaum (2000) has summarized the different approaches that have been used to verify the modifications exerted by the climate on the processes affecting SOM: 1) collection of paleoecological and historical data (Prentice & Sykes, 1995; Bellamy *et al.*, 2005); 2) calculation of the relationships between SOM contents and climatic characteristics (Post *et al.*, 1982); 3) calculation of the SOM turnover periods on the basis of the distribution of carbon isotopes in different fractions of the organic matter in soils under different climatic conditions (Trumbore *et al.*, 1996); 4) *in situ* measurements of soil respiration (Keith *et al.*, 1997; Leirós *et al.*, 1999); 5) experiments with artificial soil warming (Lükewille & Wright, 1997), and 6) measurements of soil respiration under

conditions of controlled moisture and temperature in climatic chambers (Kirschbaum, 1995). The aim of most of these studies was to evaluate the effect of climate change on future emissions of CO<sub>2</sub>. In some cases the experimental data have been used as input data in mathematical models of different levels of complexity, with the aim of clarifying the extent to which the CO<sub>2</sub> losses brought about by warming are caused by the different sensitivities of the fractions of soil organic matter to the temperature (Bol *et al.*, 2003; Knorr *et al.*, 2005) or to a gradual decrease in the most labile pool of soil organic matter as a result of increased microbial activity (Kirschbaum, 2004). These two approaches have generated opposing lines of argument based on the reliability of the models rather than on new experimental evidence that would confirm one of the hypotheses.

Galicia (NW Spain) is located north of 40 degrees N, within the zone where the effects of climate change (both temperature and rainfall changes) are considered to be most significant (Lloyd & Taylor, 1994). There are several, different climatic zones in Galicia, because of the physiography of the region; these range from the mountainous interior zone with a cold-humid climate (average annual temperature, 6.3 °C; average annual potential evapotranspiration (PET), 520 mm) to the southern coastal zone with an almost Mediterranean-type climate (average annual temperature, 15.0 °C; average annual PET, 950 mm). The pronounced climatic gradient that occurs within a relatively short distance (less than 200 km), enables the effects of climate change to be studied by means of a scarcely-reported type of experiment: the transfer of undisturbed soil monoliths from one climatic zone to another, and the comparison of certain soil properties, after a given period of time, with control soils maintained *in situ* (Botter *et al.*, 2000; Kirschbaum, 2000).

The goal of the present study was to investigate the extent to which climate change affects CO<sub>2</sub> emissions and the organic matter content of soils, by transferring soil monoliths to different climatic zones. The experimental data obtained will help to resolve the current questions regarding the effect of climate change on soils: if climate change modifies the activity of edaphic microorganisms or if the changes are due to the different sensitivities of soil organic matter at different temperatures.

## Materials and methods

### *Study sites*

The study was carried out in three different climatic zones in Galicia (NW Spain): an interior mountainous region (Navia, *N*), a central zone (Sobrado, *S*), and a southern coastal zone (Pontareas, *P*). Sites with similar topography (gentle slope near the valley floor) and soil type (Umbrisols with a 20-cm deep Ap horizon; ISSS Working Group RB, 1998) were selected at the three locations. At all sites, the vegetation was planted meadow, with ryegrass and white clover predominating; management included periodic harvesting and light fertilization with cattle slurry. The general characteristics of the three locations, and the general data for the Ap horizon of the soils used in the experiment (*N*, *S* and *P* soils) are shown in Table 1.

*Experimental design*

In June 1997, after the grass was cut, 20 monoliths from the *N* soil and 10 monoliths from the *S* soil were extracted, with the least disturbance possible, with open PVC cylinders (40-cm diameter and 25-cm height, bored with several holes to allow lateral water flow). Immediately after extraction, the monoliths were transported and buried (still in the cylinder) in the selected areas in the climatic zones that differed from the area of origin. Monoliths from soil *N* were gently introduced into bores of the same size (made by the same procedure as used for monolith extraction) in the Sobrado area (*Ns* soil) and in the Pontareas area (*Np* soil); similarly, monoliths from the *S* soil were buried in the Pontareas area (*Sp* soil). Ten control monoliths that were also enclosed within similar PVC cylinders were kept in each area under study (*in situ* soils: *N*, *S* and *P*, respectively). Considering the different climatic characteristics of the three areas (Table 1), this experiment allowed study of the effects on the soil of a moderate climatic change [interior mountain (*N*) → central zone (*Ns*); central zone (*S*) → coastal zone (*Sp*)] and a more drastic change [interior mountain (*N*) → coastal zone (*Np*)].

As indicated above, 10 replicates for each soil and location were installed at each site: 8 for soil sampling and 2 for gas analysis. Soil sampling was always carried out on two previously unsampled monoliths (4 determinations throughout the entire experiment), whereas the gas emissions were determined monthly throughout the experiment on the same pair of monoliths for each soil, which were only used for these measurements.

*Characterization of soil climate*

The climatic data (maximum and minimum daily temperatures, daily rainfall, and PET values) were obtained from the *Navia*, *Sobrado* and *Pontareas* climatic stations (close to the *N*, *S* and *P* soils, respectively). Using these data, the different soil climate components during the period under study were estimated as follows:

**1 Temperature factor:** For each climatic station and for each day of the year, the product of the average daily temperature above 5 °C [the value taken as biological zero (Margaleff, 1974)] multiplied by the hours in the day in which the temperature was in excess of 5 °C was calculated. The sum of these daily values was used to obtain the thermal integral for each month and for the overall period of study. The temperature factor (*FT*), which represents the “*effective mean temperature*”, was obtained for each month by dividing the value of the monthly integral by the number of days in the month and by 24 (hours).

**2 Moisture factor:** The moisture regime of the soils was modelled by means of Thornthwaite diagrams (Thornthwaite, 1931), by means of the monthly rainfall and PET data obtained from the climatic stations and by assuming a similar water storage capacity in all three soils (50 mm). Days in which the control section of the soil (i.e. the volume of soil that retained 50 mm of water) remained totally moist, partially dry or totally dry were counted. As in the soil moisture model provided by MAFF (1967), each day was assigned a different value, according to the state of the control section moisture: 1.00 when the soil was saturated (water content of the control section between 90 and 100% of the water

holding capacity), 0.75 when the soil was slightly affected by drought (water content of the control section between 60 and 90% of water holding capacity), 0.50 when the soil was moderately affected by drought (containing between 40 and 60% of water holding capacity), 0.25 when the soil was seriously affected by drought (10-40%) and 0.00 under conditions of extreme drought (<10%). For each month, the sum of the daily values divided by the number of days of the month provided a semi-quantitative estimate of the moisture status throughout the month (*FM*).

**3 Combined factor:** Given that both soil temperature and soil moisture affect microbial activity, some expression is required to integrate the two factors to illustrate the climatic differences between the locations under study. Among the different models cited (Davidson *et al.*, 2000), the model proposed by Wildung *et al.* (1975) was chosen because it condenses the characteristics of the edaphic climate in a single parameter, and because the model was used by these authors in a similar way to that intended in the present study. In the present study, the climatic parameter of the model was the monthly product of the aforementioned temperature and moisture factors:  $FT \times FM$ . The units of the combined factors will therefore be arbitrary and will hereafter be referred to as climatic units. The sum of the monthly values of the resulting product allows the integral for the combined factor for the entire period to be obtained. The values of this integral can be considered as an estimate of the potential of the climate to allow biological processes to take place in each area.

#### *Gas and soil sampling*

Soil CO<sub>2</sub> emissions were measured once a month between August 1997 and December 1999 (except for the period July 1998 - November 1998, because of problems with the gas measuring equipment), with static chambers (21-litre capacity) that allowed the atmosphere in the chamber to be sampled at different times (Clayton *et al.*, 1994). To avoid possible effects of daily fluctuations, all gas samples were collected at the same time of day (between 10.00 a.m. and 12.00 a.m.). Vegetation growing in the cylinders used for the study of the gas emissions was cut carefully before gas sampling, then the chamber was placed on each of the two cylinders and the connection between the cylinder and the chamber was sealed with water. Prior experiments carried out in the laboratory showed that losses of gas from the chamber were nil when this type of sealing was used. After 15 and 135 minutes, air samples (100 ml) from inside the chamber were collected (in duplicate) with a syringe. The long interval (120 min) was necessary for reliable measurement of other greenhouse gases (methane, nitrogen oxides), the changes in which will be the subject of a future study.

The gases were transported from the field to the laboratory for analysis, in 20-ml vials previously filled with distilled water and sealed hermetically with a Teflon plug and a metal capsule (Denmead & Raupach, 1993). In brief, the gas samples were collected in syringes and then transferred to the vials through one of two needles inserted into the plug. As the gas was introduced into the vial, the water was pushed out of the escape needle, and the vial became filled with the gas without the need for excess pressure. This method

avoids the solubilization of CO<sub>2</sub> in the water contained in the vial, because of the greater volume of air (100 ml) that is pushed into the vial in relation to the volume of water it contains (20 ml). Eight such vials were analyzed for each soil and sampling time, four corresponding to the initial atmosphere (15 minutes) and another four corresponding to 135 minutes in the chamber.

In November 1997, 1998 and 1999 and in March 2000, soil samples were removed carefully from the top 10 cm from two of each soil monolith. The samples taken from each monolith were sieved (< 4 mm) and the total carbon and total nitrogen contents (10 replicates each) were determined on air-dried subsamples.

#### *Analytical methods*

The CO<sub>2</sub> contained in the vial was analyzed in a GC Top 800 series control unit (CE Instruments, Manchester, UK) fitted with a digital pressure monitor, digital pressure and flow control regulator and a headspace module with an automatic HS 850 injector. The detection system comprised a MD-800 mass spectrometry detector with an electronic impact source. The CO<sub>2</sub> emission flux (mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>) was calculated as the difference between the values obtained for the aforementioned vials sampled 15 minutes and 135 minutes after the chamber was placed over the cylinders.

The general soil properties (pH, total carbon and nitrogen, texture) were determined following the methodology described by Guitián & Carballas (1976).

#### *Organic matter decay equation*

The variation over time in the carbon and nitrogen contents of soils as a result of climate change was modelled by a bi-compartmental model of soil organic matter in which the mineralization would only affect the labile fraction of the soil. This model was selected for its simplicity, and also because of the relatively short duration of the experiment (32 months), which allowed the assumption that the most recalcitrant fraction of the humus (to which a turnover time between 40 and 1000 years is attributed, McMurtrie *et al.*, 2000) would not be affected. Moving averages for two consecutive observations were included in the model (to offset the fluctuations caused by the heterogeneity of the soil and seasonal effects), as were the initial concentrations of carbon and/or nitrogen in the soils. The data were fitted to a first-order decay equation of the type:

$$\log (X_t - X_r) = a + b\Delta_t, \quad (1)$$

where  $X_t$  is the total carbon (C<sub>t</sub>) or the total nitrogen (N<sub>t</sub>) content of the soil (expressed as g 100 g<sup>-1</sup>) at each moment;  $X_r$  is the recalcitrant carbon (C<sub>r</sub>) or nitrogen (N<sub>r</sub>) also expressed as g 100 g<sup>-1</sup> (the difference  $X_t - X_r$  represents the labile or mineralizable carbon or nitrogen at each moment);  $\Delta_t$  is a measure of the climatic difference between two places for the period  $t$  and is obtained as the difference between the integral of the combined climatic factor at the location under consideration (Sobrado or Pontearreas) and the integral of the combined climatic factor at the location of origin (in this case Navia);  $a$ , is a constant,

which when  $\Delta_t = 0$  (i.e. at the start of the experiment) represents the log of the mineralizable carbon or nitrogen initially present, and  $b$  is the mineralization rate (loss ~ negative value), which units will be the inverse of the arbitrary climatic units of the combined climate factor.

#### *Monitoring of the translocated soils*

Textural analysis of the soil monoliths was carried out periodically to verify that they had not been contaminated with material from the new location during the experiment, since the three soils are derived from different original material and therefore the texture of each is different (Table 1). This analysis revealed that in some of the *S* soil monoliths transferred to Pontareas (*Sp* soil), from 1998 onwards, mixing between the monolith soil and soil from the surrounding area had taken place. Consequently, the samples of soil *Sp* collected in November 1998 and November 1999 were discarded. No contamination had occurred in the monoliths used for gas sampling, and therefore once the gas sampling phase was over, these monoliths were used for the March 2000 soil sampling. No contamination of the other translocated soils occurred.

#### *Statistical analysis*

For each property studied, the values in the Tables represent the averages and standard deviations (SD) for all the measurements made for each soil. Statistical differences between average values were determined by a Student's  $t$  test and parameters of the regression curves were calculated by Statistica 6.0 (StatSoft<sup>®</sup> Inc., Tulsa, OK, USA) for Windows.

## **Results**

#### *Climatic variation during the experiment*

Thermal integrals for the three sites indicate that the Pontareas site was warmest, followed by Sobrado, and then Navia (Figure 1a). In all cases the warmest months of the year were July and August, and the coldest months were January and February, although in Navia and Sobrado the cold period extended into mid-Spring. The mean effective temperature for the entire period of the study was 10 °C for Navia, 11.3 °C for Sobrado, and 14 °C for Pontareas. As regards the moisture conditions (Figure 1b), in all cases the periods of total drought occurred in mid-Summer, and the maximum moisture factor value was usually recorded between November and May. The periods during which biological activity might have been limited because of a shortage of water were similar for the three different sites, although it was slightly longer for Navia than for the other two. The values of the combined factor ( $F_T \times F_M$ ) were similar: the largest values corresponded to Pontareas, and the smallest to Navia (Figure 1c). Maximum values of this factor were reached in autumn and spring, and the minima in summer.

*Total carbon and nitrogen: changes over time, and parameters of decay equation*

Although there was a short-lived increase in carbon and nitrogen between November 1997 and November 1998 in both translocated soils and those left *in situ* (Table 2), within the total period of study, the total carbon and total nitrogen contents of the three soils in their places of origin (soils *in situ*: *N*, *S* and *P*) remained almost constant (Table 2). The small fluctuations are attributed to the heterogeneity and to the seasonal changes in soils (Leirós *et al.*, 1999). In other words, the soils *in situ* were in a steady-state, i.e. they showed equilibrium between the carbon losses and gains. Independently of the increase in total carbon between November 1997 and November 1998, the translocated soils, *Ns* and *Np* showed a progressive decrease in total carbon and nitrogen (Table 2), which was already noticeable four months after transfer of the soils. It was not possible to monitor soil *Sp* in the same way, because of the contamination mentioned above. At the end of the study the total carbon and nitrogen concentrations in the *Ns* soil were 84 and 82% respectively of those in soil *N*; in the *Np* soil the corresponding percentages were 57 and 56%; in the *Sp* soil, the total carbon and nitrogen concentrations were 78% and 68%, respectively, of the values corresponding to the *S* soil. These results indicate clear decreases in the total carbon and nitrogen contents of the translocated soils (although not always statistically significant, see Table 2), which tended to be greater the greater the climate change.

For soil *Sp*, only the initial and final total C values can be considered valid, because of the contamination suffered, and the variations in carbon and nitrogen could only be modelled for soil *N*. Fitting of the experimental data for this soil to the decay equation (the data for *Ns* and *Np* were combined into a single set, because they refer to the same soil) provided values of 0.357 for *a*, and for *b*, -0.00477 for each unit of difference for the climatic factor  $\Delta_t$  between the point of origin and the point where the soil was transferred (Table 3). The  $R^2$  value (0.97) ( $n = 7$ ) indicated a highly significant fit to the equation ( $P \leq 0.001$ ). Less statistical significance ( $R^2 = 0.85$ ,  $P \leq 0.05$ ) was obtained for the nitrogen data, although this indicated that this element also followed the decay model considered.

The value of the constant *a* indicated that for soil *N*, 33% of the total carbon can be considered mineralizable in the short term [for  $a = 0.357$ ,  $(C_t - C_r) = 2.275$ , then  $100 (C_t - C_r)/C_t = 33\%$ ], and the remaining 67% would be recalcitrant, at least for the duration of the experiment. Similar calculations for the total nitrogen revealed that 64% of the total nitrogen in the soil can be considered recalcitrant, and the remaining 36% as mineralizable in the short term. The nitrogen mineralization rate was slightly greater than that obtained for carbon (Table 3).

*CO<sub>2</sub> emissions*

The measures of monthly CO<sub>2</sub> emissions were very variable throughout the experiment and depended on both the soil type and the time of the year (Fig. 2). The greatest emission was from soil *Sp* in June 1998 (1200 mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>), and the least from soil *Np* in March 1999 (92 mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>). Considering the mean emission values obtained for the entire period, it can be seen that the greatest mean emission values for the *in situ* soils were from



soil **P** ( $512 \pm 274$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>), (compared with values for soils **N** and **S** of  $427 \pm 204$  and  $428 \pm 158$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>, respectively). The mean emission from soil **S** increased slightly when the soil was transferred to Pontareas (from  $428 \pm 159$  for soil **S** to  $447 \pm 252$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup> for soil **Sp**), whereas the mean emission from soil **N** ( $427 \pm 204$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>) only increased in the soil transferred to Sobrado, the **Ns** soil ( $485 \pm 198$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>), and decreased sharply in the soil transferred to Pontareas, the **Np** soil ( $394 \pm 201$  mg CO<sub>2</sub> m<sup>-2</sup> hour<sup>-1</sup>). However, none of the differences were significantly different, because of the large standard deviations associated with the values.

## Discussion

The soils transferred from their original positions to the Sobrado and Pontareas sites underwent a true climate change, mainly in terms of temperature as there was scarcely any difference in the moisture factor. Considering “*effective temperatures*”, the average daily increase involved in the transfer from Navia → Sobrado was 1.3 °C, in the transfer from Sobrado → Pontareas, 2.7 °C, and in the transfer from Navia → Pontareas, more than 4 °C. Moreover, the plots of the accumulated data of  $FT \times FM$ , i.e., the integral of the combined factor, revealed that: a) in the three zones, the climatic potential that allows the biological processes to take place differed, as the combined factor was 73% greater for Pontareas than for Navia, 26% greater for Pontareas than for Sobrado and 37% greater for Sobrado than for Navia; b) there was a clear climatic gradient, with the climatic potential that allows the biological processes to take place increasing in the direction Navia → Sobrado → Pontareas; and c) the period with the least favourable conditions for biological activity occurred in mid-Summer, because of drought, which greatly reduced the beneficial effect of high temperatures on biological activity, whereas moderate or favourable conditions for biological activity were maintained during the rest of the year (except at the Navia site in 1999). The modifications in the soil properties must be considered as being fundamentally caused by the experimental climate change, which allows conjecture about possible effects of climate change in Galician soils.

The CO<sub>2</sub> emissions were extremely variable throughout the experiment, and despite the relatively long time that the chamber was above the soils, are within the range cited in previous studies (Davidson *et al.*, 2000; Dilly *et al.*, 1997; Grogan & Chapin, 1999). Throughout the entire period, the CO<sub>2</sub> emissions followed a seasonal pattern, with the least emissions in winter (November to January), a progressive increase during the Spring and the maximum emissions at the beginning of Summer (June-July), although the maximum varied from year-to-year (Figure 2). Similar patterns were observed for soils **S** and **Sp**, with the only difference being the greater emissions from the latter during the Spring of the first year post-transfer. The fluctuations were greater in the **N** soil and, during the first year post-transfer, **Ns** and, above all, **Np** emitted more CO<sub>2</sub> than soil **N**; nevertheless, this pattern was reversed during the second year, when the emissions from **N** tended to be greater than those from **Ns** and **Np**. Thus, the patterns of emissions from the translocated soils **Ns**, **Np** and **Sp** were similar: they emitted more CO<sub>2</sub> during the first year post-transfer

than the corresponding soils *in situ*, and the reverse occurred in the second year. Although this may suggest that the climate change did not result in a clear trend in CO<sub>2</sub> efflux, patterns of this type have been attributed to the fact that different pools of soil organic matter show different degrees of sensitivity to increases in temperature (Dalias *et al.*, 2001; Knorr *et al.*, 2005). However, some authors attribute such patterns to a pronounced reduction in the pool of easily mineralizable organic matter in soils under more favourable climatic conditions, which leads to a slower respiration rate compared with that of control soils (Kirschbaum, 2004). The patterns can also be explained by physiological changes in the micro-organisms, which after an initial mineralizing boom - a result of the greater temperatures - would have adapted to the new climatic conditions (Luo *et al.*, 2001). Furthermore, given that a large part of the CO<sub>2</sub> emissions may result from mineralization of non-humified organic matter, the observed reduction in respiration can be related to a decrease in the amount of recently-fixed carbohydrates.

The most noteworthy effect on soil properties caused by the climate change was the loss of a large part of the carbon and nitrogen that was initially present, so that in the 32-month period in the soil that underwent the most intense climate change (*Np*) there was a decrease of almost 40% in both initial carbon and nitrogen. Although these percentages may seem large, it should be borne in mind that the mineralizable fraction is usually associated with the most labile fraction within the soil carbon of density < 2 g cm<sup>-3</sup>. In Galician soils this labile fraction is between 40 and 80% of the total soil carbon for surface horizons (Carballas *et al.*, 1979). Moreover, for soils in areas with mean annual temperature between 10-15 °C (like those of the present study), the fast-cycling pools are considered to represent around 35-40% of the soil organic matter in the upper 20-cm soil layer (Trumbore *et al.*, 1996). Both observations are consistent with the value obtained in the present study.

In all cases, the loss of soil organic matter occurred very rapidly, since it was already evident four months after transfer of the soils. Given that during these four months the differences among the three locations in terms of climate conditions were minimal (Figure 1c), it seems unlikely that the initial decrease was only due to a large increase in mineralization. We assume that, in the translocated soils, there was a reduction in organic material inputs due to the initial stress that the vegetation underwent as a consequence of the transfer, which was intensified by the Summer drought. In any case, monitoring of the vegetation throughout the experiment showed that the stress disappeared after the first rainfall (approximately six months after the start of the experiment), so that by the end of the study the plant cover on the different monoliths placed in the same location was of similar composition and density. Taking into account this recovery, and the consequent re-establishment of organic inputs to the soil, it may be assumed that the subsequent decrease in carbon and nitrogen contents, after the initial equilibration period of four months, is a consequence of the increase in the rate of mineralization brought about by the different climatic conditions caused by the change of location of the soils. Similar reasoning was made by Bellamy *et al.* (2005) to explain the carbon losses from soils across England and

Wales between 1978-2003, a period in which there was a mean temperature increase of 0.5 °C and changes in the rainfall distribution.

Knowledge of the parameters of the decay equations and of the variation over time in factor  $\Delta t$  for two locations makes it possible to deduce the monthly values of  $C_t$  throughout the study, i.e. the total carbon content of the soils every month throughout the experiment (obviously, the modifications that would arise from the plants and the root exudates cannot be taken into account). Given the absence of experimental values for soil *S*,  $C_t$  in the *Sp* soil was estimated from the same decay parameters as for the *N* soil (i.e. 67% recalcitrant fraction and  $-0.00477$  climatic units<sup>-1</sup> for the mineralization rate). Furthermore, if it is accepted that  $C_r$  may not vary throughout the experiment (since this fraction represents the pool of humified C, the most recalcitrant C fraction), it is possible to calculate how the pool of mineralizable carbon varies from month to month. Clearly this is only tentative, since it is assumed that all C losses result from CO<sub>2</sub> emissions, without taking into consideration any possible losses of soluble carbon or any modifications that the growth of plants may have generated.

The monthly values calculated for mineralizable carbon in the soils were used to estimate the CO<sub>2</sub> emissions per unit of mineralizable carbon, given that the emission of CO<sub>2</sub> from the soils should arise fundamentally from the mineralization of the most labile carbon fractions. The estimated values for the *Np*, *Sp* and *P* soils (in this case the mineralizable carbon value was considered to be constant throughout the period of study, as there was no variation in the total carbon content in soil *P*) are shown in Figure 3. For the first year of the experiment, the emissions per unit of mineralizable carbon obtained for all three soils were very similar (Figure 3), which revealed that the emissions (as calculated by us) are a function of the climatic characteristics only (minimum values in the Winter, maximum values for Spring and the beginning of the Summer) and that our modelling approach can be considered as suitable. In the second year, there were small random differences among the soils, but generally similar patterns were still evident in all three soils.

The CO<sub>2</sub> emissions per unit of mineralizable carbon for the three soils from Navia: *N*, *Ns* and *Np*, are shown in Figure 4, once again assuming a constant value for mineralizable carbon throughout the entire experiment for the soil *in situ*. It can be seen how, for almost the entire duration of the experiment, the emissions from *Np* were clearly greater than from the other two soils, and that they were greater from *Ns* than from the soil *in situ* (*N* soil). The maximum emissions of CO<sub>2</sub> per unit of mineralizable carbon generally coincided with the end of Spring and the onset of Summer, and the minimum values were recorded during the Winter. Soils from Sobrado showed similar patterns (Figure 4): the emissions per unit of mineralizable carbon were clearly greater for soil *Sp* than in the soil *in situ* (*S* soil) in the first year, although in the second year, the difference between the relative emissions tended to be less.

In both the *S* and *N* soils, the relative emissions per unit of carbon depended mostly on climate, and there was a clear decrease in the absolute emissions with time, as with the labile carbon content. Both of these findings suggest that such variations in emissions are a

function of the size of the pool of labile organic matter of the soil, as demonstrated by the results of soil warming experiments (Kirschbaum, 2004), and are not the result of physiological adaptation of microorganisms, as has been suggested by other authors (Luo *et al.*, 2001; Strömngren, 2001).

## Conclusions

The experimental transfer of soils clearly led to rapid loss of soil organic matter, since the stimulation of microbial activity as a consequence of the more favourable climatic conditions was combined with a longer period in which biological activity was possible. The CO<sub>2</sub> emissions were greater in the translocated soils than in the control soils during the first year of the study, and decreased notably thereafter. These results indicate that the effects of climate change on soil organic matter, although intense, are short-lived. However, expression of the values of the CO<sub>2</sub> emissions per unit of mineralizable carbon revealed that the more drastic the climate change, the greater the relative emission and the longer these large emissions were maintained. This demonstrates progressive impoverishment of the most labile C fraction in the affected soils. In other words, modification of the edaphic climate leads to progressive loss of the most labile components which, according to the decay equation used, may reach up to 40% of the total soil C. Although the impact of climate change on enrichment of atmospheric CO<sub>2</sub> from organic matter only appears to be of concern during the moment of change, the stimulation of microbial activity favoured by the change will be associated with progressive soil degradation as the soil lacks the fraction of organic matter with the fastest turnover, which cannot be restored by the vegetation growing on the soil, at least within the time scale of the present study.

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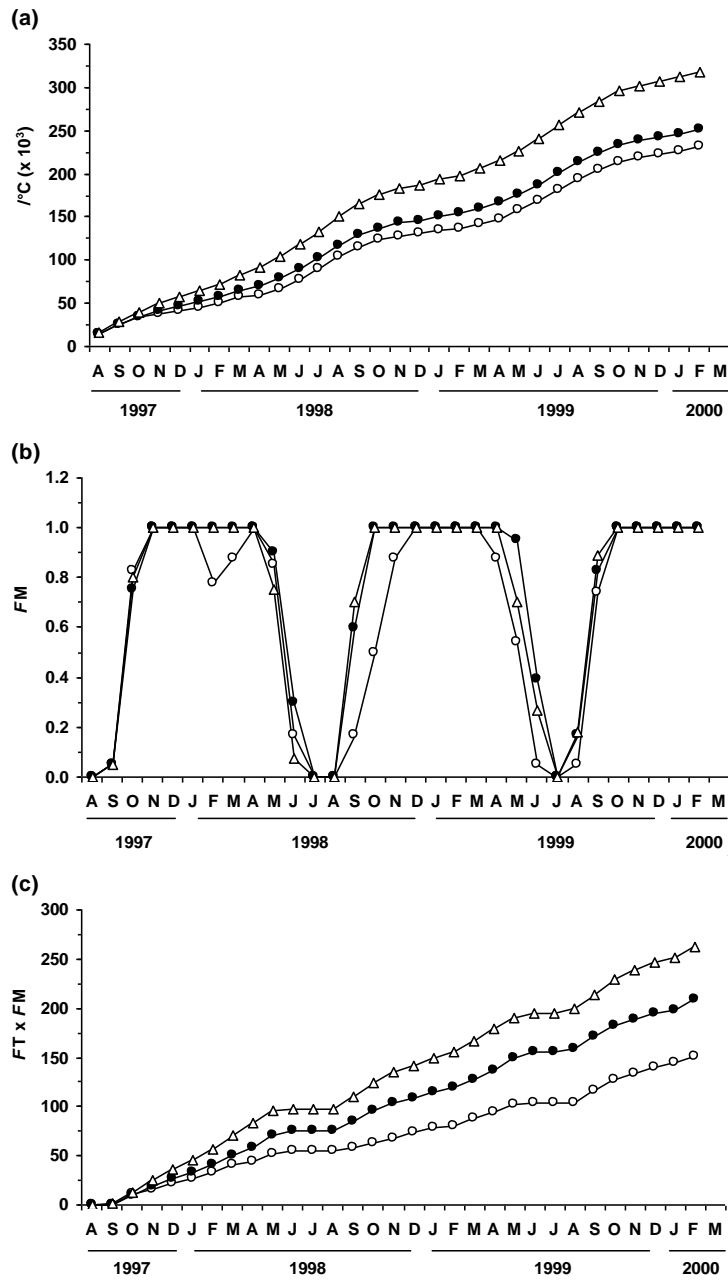
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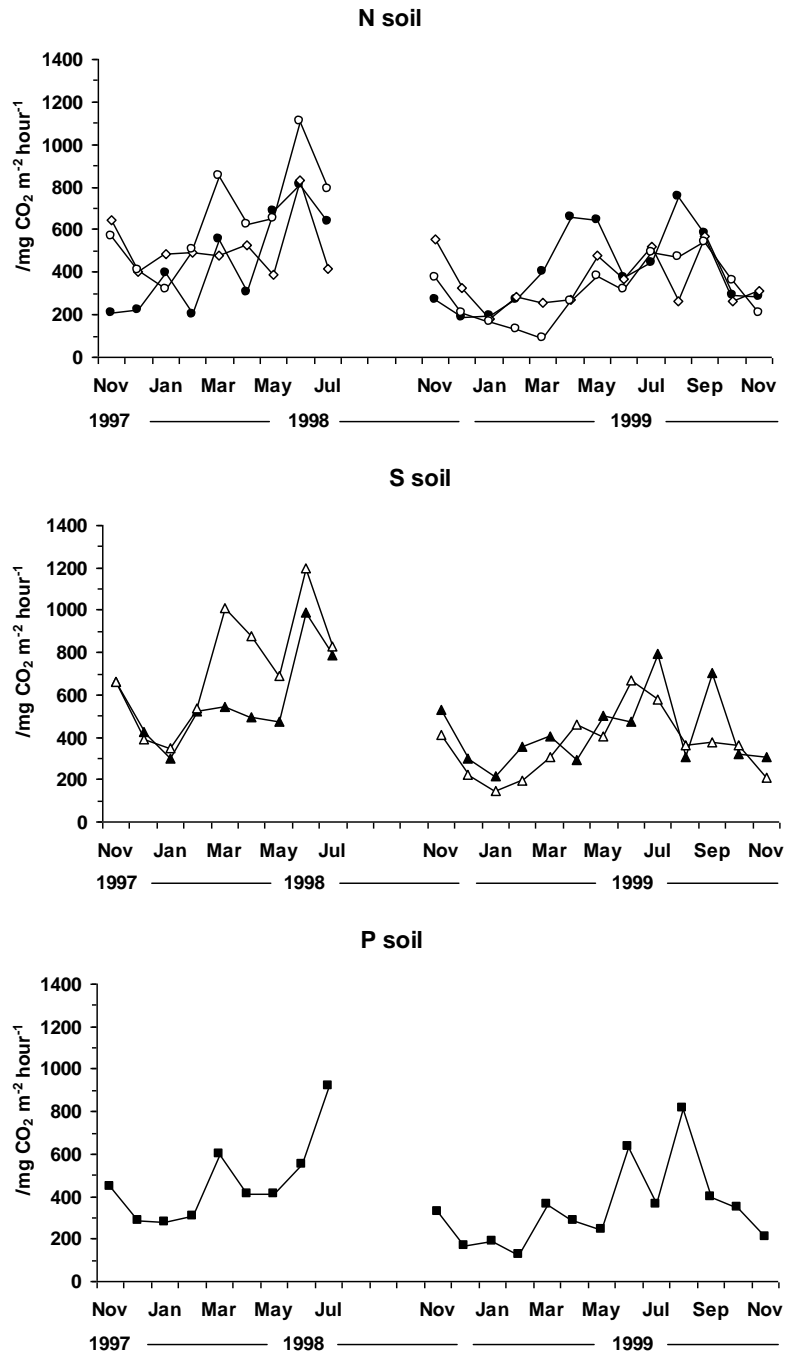
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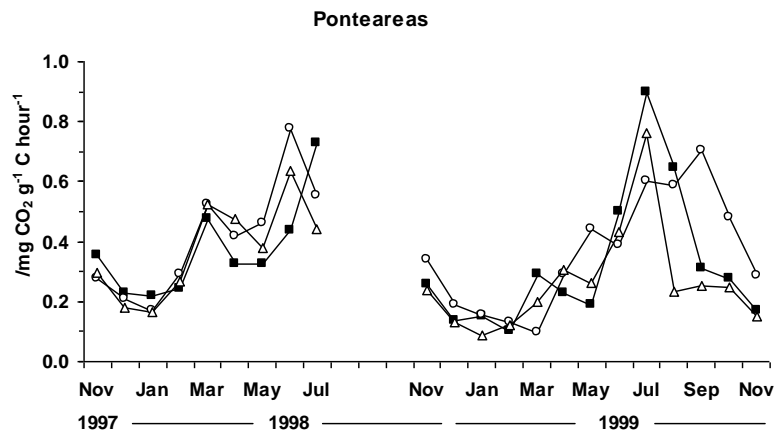


**Figure 1** Changes in the climatic factors throughout the experiment for the soils in the Navia (*N*), Sobrado (*S*) and Pontearas (*P*) sites: a) thermic integral ( $^{\circ}\text{C} \times 10^3$ ), b) moisture factor (*FM*), and c) combined factor (*FM* x *FT*). Navia (*N*):  $\circ$ , Sobrado (*S*):  $\bullet$ , Pontearas (*P*):  $\triangle$ .

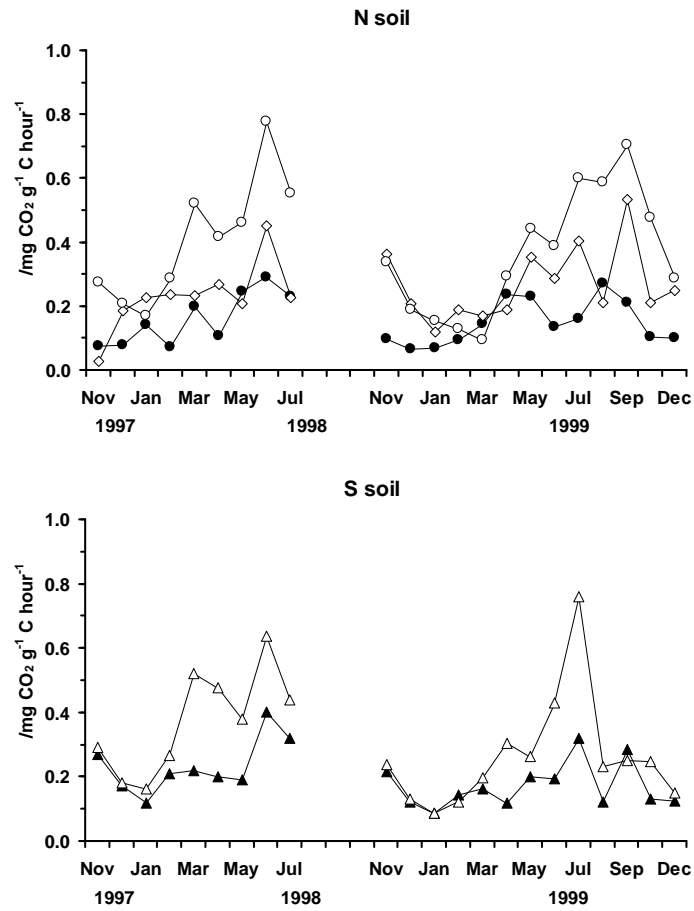




**Figure 2** Field CO<sub>2</sub> emissions from *in situ* and translocated soils throughout the experiment. N soil: *in situ* ●, Ns ◇, Np ○; S soil: *in situ* ▲, Sp △; P soil: *in situ* ■.



**Figure 3** Relative emissions of CO<sub>2</sub> (CO<sub>2</sub> emitted per unit of mineralizable carbon) for soils at the Pontearreas site: *in situ* ■, *Np* ○, and *Sp* △ soils.



**Figure 4** Relative emissions of CO<sub>2</sub> (CO<sub>2</sub> emitted per unit of mineralizable carbon) for both *in situ* and translocated Navia (*N*) and Sobrado (*S*) soils: a) *N* soils (*in situ* ●, Ns ◇, Np ○), and b) *S* soils (*in situ* ▲, Sp △).

**Table 1** Location of the three sites, climatic characteristics and some properties of the Ah horizon (0-20 cm) of the soils used in the study.

Soil	Location	Latitude	Longitude	Altitude /m	Range monthly in temperatures /°C <sup>a</sup>	Annual rainfall /mm <sup>a</sup>	Soil parent material	pH		Texture	Total carbon <sup>c</sup> /%
		N	W					H <sub>2</sub> O	KCl		
<i>N</i> <sup>b</sup>	Navia	42°57'10"	6°52'02"	910	15.5 - 3.6	1453	Slates	4.92	3.99	Loam	6.87±0.35
<i>S</i>	Sobrado	43°02'45"	8°01'00"	500	16.5 - 6.7	1428	Basic schists	5.62	4.68	Sandy loam	6.02±0.26
<i>P</i>	Pontareas	42°10'55"	8°31'10"	50	21.7 - 8.5	1543	Granites	5.21	4.30	Sandy clay loam	3.19±0.14

<sup>a</sup> Refers to 1960-90.

<sup>b</sup> Data from Folgueira de Aigas climatic station, close to the sampling area.

<sup>c</sup> Mean±SD (n = 10 determinations for each soil)

**Table 2** Changes in total carbon and total nitrogen contents of the soils (mean±SD, ten replicates) throughout the experiment (ND: not determined).

Soil	Nov 1997	Nov 1998	Nov 1999	Mar 2000	Mean 1997-2000
Total carbon (%)					
<i>Navia soils</i>					
<i>N</i>	A6.78±0.29a	A7.41±0.76b	A6.66±0.83a	A6.93±0.73ab	<b>6.95±0.33</b>
<i>Ns</i>	B6.20±0.45a	B5.96±0.58a	B5.32±0.22b	A5.67±1.04ab	
<i>Np</i>	C5.47±0.40a	B5.91±0.42a	C4.84±0.52b	B3.59±0.54c	
<i>Sobrado soils</i>					
<i>S</i>	A5.72±0.17a	6.54±0.77ab	6.13±0.52b	A6.20±0.90ab	<b>6.15±0.34</b>
<i>Sp</i>	A6.18±0.45a	ND	ND	B4.80±0.50b	
<i>Ponteareas soil</i>					
<i>P</i>	2.90±0.15a	3.51±0.17b	3.52±0.54b	3.31±0.31b	<b>3.31±0.29</b>
-----					
Total nitrogen (%)					
<i>Navia soils</i>					
<i>N</i>	A0.553±0.119a	A0.666±0.015b	A0.608±0.019a	A0.610±0.020a	<b>0.609±0.046</b>
<i>Ns</i>	A0.513±0.059ab	B0.540±0.017b	B0.445±0.015c	B0.493±0.056a	
<i>Np</i>	B0.412±0.037a	C0.513±0.020b	C0.412±0.012a	C0.328±0.045c	
<i>Sobrado soils</i>					
<i>S</i>	A0.371±0.063a	0.488±0.016b	0.422±0.020bc	A0.414±0.024c	<b>0.424±0.048</b>
<i>Sp</i>	A0.386±0.073a	ND	ND	B0.257±0.010b	
<i>Ponteareas soil</i>					
<i>P</i>	0.200±0.015a	0.263±0.018b	0.182±0.027a	0.197±0.012a	<b>0.211±0.036</b>

For each sampling time and for soils from each location (Navia, Sobrado, Ponteareas), values preceded by the same capital letter were not significantly different at  $P \leq 0.01$ . For each soil, values at different sampling times followed by the same small letter were not significantly different at  $P \leq 0.01$ .

**Table 3** Kinetic parameters obtained by fitting the values of the changes in total carbon and nitrogen to the bi-compartmental model (\*\*\*,  $P \leq 0.001$ ; \*\*  $P \leq 0.05$ ).

	$R^2$	Recalcitrant fraction	$a$	$b$ /climatic units <sup>-1</sup>
Total carbon	0.95***	67 %	0.357	-0.00477
Total nitrogen	0.85**	64 %	-0.660	-0.00518