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Predicting changes in soil organic carbon in mediterranean and alpine forests during the Kyoto Protocol commitment periods using the CENTURY model

T. Chiti[1], D. Papale[1], P. Smith[2], D. Dalmonech[1], G. Matteucci[3], J. Yeluripati[2], M. Rodeghiero[4] & R. Valentini[1]

[1]*Dipartimento di Scienze dell'Ambiente Forestale e delle sue Risorse (DISAFRI), Università della Tuscia, via San Camillo De Lellis s.n.c., 01100 Viterbo, Italy,* [2]*Institute of Biological & Environmental Sciences, School of Biological Sciences, University of Aberdeen, Cruickshank Building, St. Machar Drive, Aberdeen AB24 3UU, UK,* [3]*Istituto per i Sistemi Agricoli e Forestali del Mediterraneo – National Research Council (ISAFOM-CNR), via Cavour 4/6, I-87036 Roges di Rende, CS – Italy, and* [4]*IASMA, Research and Innovation Centre Fondazione Edmund Mach, Environment and Natural Resources Area, Viote del Monte Bondone, 38040 Trento, Italy*

Abstract

Six Italian research sites, representative of Mediterranean and mountain forests and equipped with eddy covariance towers, were used in this study to test the performance of the CENTURY 4.5 model in predicting the dynamics of soil organic carbon (SOC) changes during the commitment periods (CP) of the Kyoto Protocol (2008–2012; 2013–2017). We show that changes in SOC stocks over short periods of time are difficult to detect, and explore the potential for models to be used for reporting SOC changes for forests that will remain forests, under Article 3.4 of the Kyoto Protocol. As the eddy covariance flux sites have been active for 10 yr on average, being initiated over the period between 1996 and 1998, the model was evaluated by comparing the modelled SOC stocks with those directly measured at each site in different years. Since long term series of observed values for soil carbon were not available, the validation of other model outputs such as net primary production (NPP) and soil nitrogen stocks, gives some confidence in long term simulations. Once the model performance was evaluated, two climate change scenarios, A1F1 (world markets-fossil fuel intensive) and B2 (local sustainability), were considered for prediction of C stock changes during the commitment periods of the Kyoto Protocol. In general, despite the need to consider the uncertainties in the direct measurements, at each site model fit with measured SOC stocks was good, with the simulated values within the standard deviation of the measurements. In this regard, the similarity between the SOC measured in 2008 and that predicted for the two forthcoming commitment periods points out the difficulty of detecting carbon stock changes by direct measurements, given the closeness in time to the present of the commitment periods. In any case, all sites show positive variations that are possibly related to the fertilization effects of increasing CO_2 and to longer growing seasons, since no change in management occurred. Compared with the SOC measured in 2008, at the end of the second commitment period, the modelled SOC variations were smaller than 2% in the Mediterranean forests and comprised between 2% and 7% in the mountain forests. These variations, although small, indicate it might be possible to statistically detect differences after 10 yr in mountain forests with a reasonable number of samples. In conclusion, this work shows that since SOC stock changes are minimal within both CP, models can be effective tools for estimating future changes in SOC amounts, as an alternative to, or in support of, direct measurements when a short period of time is considered.

Keywords: Mediterranean forests, model evaluation, mountain forests, Kyoto Protocol, soil organic carbon

Correspondence: T. Chiti. E-mail: tommaso.chiti@unitus.it
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Introduction

Soil organic carbon (SOC) turnover models are often used to assess the regional or global dynamics of SOC in response to shifts in land use, management or climate (Falloon & Smith, 2002). In the latter case, such changes in SOC are associated with an altered CO_2 exchange between terrestrial ecosystems and the atmosphere, and they impact significantly on regional carbon budgets (Janssens *et al.*, 2003). A net carbon loss from soils adds to the increase in the atmospheric CO_2 concentration, probably leading to higher global temperatures [Intergovernmental Panel on Climate Change (IPCC), 2001], which, in turn, could accelerate decomposition of SOC (Cox *et al.*, 2000; Jones *et al.*, 2005), whereas net soil CO_2 sequestration could help to mitigate the greenhouse effect and to improve soil quality. Hence, soil carbon sequestration has a great global mitigation potential, both in terms of enhancement of C sink and reduced C emissions (Smith *et al.*, 2007, 2008). At the international level, the various Conventions arising from the 1992 United Nations Conference on Environment and Development in Rio (e.g. Climate Change, Biodiversity and to Combat Desertification) have the issue of SOC levels at their core. Further, under the Kyoto Protocol of the United Nation Framework to Combat Climate Change (UNFCCC, 1998), which came in to force on February 16th 2005, for the activities listed in Article 3.3 (afforestation, reforestation and deforestation since 1990) and Article 3.4 (forest management, cropland management, grazing land management, re-vegetation), collectively named 'Land Use, Land-Use Change and Forestry' (LULUCF) and later referred to as 'Agriculture, Forestry and Other Land Use' (AFOLU), the soil is among the carbon pools to be reported for the upcoming commitment periods (2008–2012; 2013–2017). Hence, the countries that elected the forest management among the activities to be reported under Article 3.4, have to supply an estimate of the change in the SOC and the other four C pools (above ground biomass, below ground biomass, litter and dead wood) at the end of each commitment period. The ability to predict the effects of environment (e.g. climate and atmospheric composition) and land use change on SOC dynamics is therefore, of utmost importance in formulating environmental and agricultural policies (Smith *et al.*, 1997). Thus, determining precise SOC stock changes is of crucial importance. The procedures for estimating and reporting changes in SOC under the Kyoto Protocol are described by the International Panel on Climate Change reports Good Practice Guidance for LULUCF (IPCC, 2003) and the Revised Guidelines for National Greenhouse Gas Inventories Volume 3 (IPCC, 2006). Nevertheless, estimating changes in the SOC pool at national scale represents a challenge for most European countries. In fact, it is difficult to detect a change in SOC within a 5-yr time frame without a prohibitively large sample size (Conen *et al.*, 2003, 2004; Smith, 2004a). In this respect, models might be able to help if integrated with repeated soil measurements, and with the choice of appropriate measurable parameters for their evaluation. Modelling is a powerful means to simulate a range of complex processes, including the prediction of SOC changes (Romanyà *et al.*, 2000; Carvalho Leite *et al.*, 2007), and has been applied from site to regional or country scale with excellent results (Kelly *et al.*, 1997; Falloon & Smith, 2002). To increase the robustness of future SOC projections, validation of model outputs over a fixed period is of utmost importance. Apart from measuring total SOC and comparing it with modelled results, validation of other parameters is necessary to build confidence in model projections (Smith *et al.*, 1997). Here, the performance of a SOC model is evaluated in four Mediterranean and two mountain forest sites in Italy. All the sites are characterized by the presence of eddy covariance systems equipped with instruments to measure CO_2, water and energy fluxes together with meteorological variables (Aubinet *et al.*, 2000), and since their activation (7–13 yr ago) information about the site management history and soil features (e.g. particle size distribution, bulk density) have been collected. More importantly, direct measurements of SOC and soil organic nitrogen (SON) in different years and measures of soil CO_2 fluxes by the use of chambers, were available for all sites, and in some cases estimates of net primary production (NPP) obtained by biometric measurements.

The aim of this study is to evaluate the performance of a soil carbon model, CENTURY, at sites where the C dynamics are well described, to test if it can confidently predict SOC changes during the first, and the second commitment period of the Kyoto Protocol for forests whose activity is comprised under article 3.4 of the Kyoto Protocol (forest management). An ancillary aim was to assess whether or not the magnitude of such changes could have been measured directly.

Materials and methods

Site selection

In this study four Mediterranean and two mountain forest sites in Italy, equipped with eddy covariance systems, were considered, covering different plant functional type and age classes. The basic characteristics of these sites are reported in Table 1. Two of the Mediterranean forests are located along the Tyrrhenian coast: San Rossore and Castelporziano. San Rossore site is a 37-yr-old plantation of *Pinus pinaster* Ait., representing a succession of the natural *Quercus ilex* L. and mixed oaks vegetation that was originally dominant along the Tyrrhenian coast. The Castelporziano forest site is a 46-yr-old stand of *Quercus ilex* L. managed as high forests until 1945 when it was converted to coppice and then, in 1982 reconverted to high forest. The third and fourth Mediterranean forests are included in the Roccarespampani public estate. This *Quercus cerris* L. forest is divided into several plots managed as coppice with standard for about 300 yr. In particular, two plots were considered: one 8 yr after coppicing (Rocca 1) and another 17 yr after coppicing

Table 1 Study sites sorted by Longitude and their characteristics

Site	Active from	Vegetation type	Species	Stand age (yr)	Latitude (°)	Longitude (°)	Elevation (m.a.s.l.)	MAT (°C)	MAP (mm)	Soil type[a]	Site description
Lavarone	2002	ENF	Silver fir, swiss pine	100	45.96	11.28	1353	7.8	1150	Humic Umbrisol	Rodeghiero & Cescatti (2006)
San Rossore	1998	ENF	Maritime pine	35	43.73	10.29	5	14.2	920	Albic Arenosol	Zenone *et al.* (2008)
Rocca 1	1998	DBF	Turkey oak	8	42.41	11.93	224	15.2	876	Chromic Luvisol	Rey *et al.* (2002)
Rocca 2	2000	DBF	Turkey oak	17	42.41	11.93	224	15.2	876	Chromic Luvisol	Tedeschi *et al.* (2006)
Collelongo	1996	DBF	Beech	100+	41.85	13.59	1560	7.4	1140	Humic Alisol	Valentini *et al.* (1996)
Castelporziano	1996	EBF	Holm oak	36	41.71	12.38	3	15.6	767	Haplic Arenosol	Tirone *et al.* (2003)

EBF, evergreen broad-leaf forest; ENF, evergreen needleleaf forest; DBF, deciduous broad-leaf forest. [a]According to IUSS Working Group WRB, 2006.

(Rocca 2). In the recent past, at Roccarespampani, the rotation period is 18–20 yr. The mountain forests of Lavarone and Collelongo are located on the Alps and on the central Apennine, respectively. The Lavarone forest site is a mixed unevenaged conifer stand of *Abies alba* Mill and *Pinus cembra* L. with ages up to 100 yr managed under selection cuttings, while Collelongo site is a *Fagus sylvatica* L. forest with trees more than 100 yr old, where tree shelterwood management is applied. All of the investigated forests undergo activities that are regarded as 'forest management' under article 3.4 of the Kyoto Protocol.

The CENTURY C and N model

The simulation of SOC was performed with version 4.5 of the CENTURY model, one of the most widely used SOC models. CENTURY is a model of terrestrial C, N, phosphorus (P), sulphur (S) dynamics and plant growth that uses a four-pool soil organic matter (SOM) sub-model (Parton *et al.*, 1987). The pool divisions are based on SOM decomposition characteristics, or turnover rates. The model was developed for grasslands, but it has been successfully extended to arable crops, forests and savannas (Parton & Rasmussen, 1994; Kirschbaum & Paul, 2002). CENTURY uses a monthly time step with monthly average maximum and minimum air temperature, and monthly average precipitation data, which modify decomposition of each organic matter compartment. At each site, the CENTURY model was run to simulate changes in soil C contents in the upper 20 cm of mineral soil. In view of an extensive applicability of the model, CENTURY was applied using only the minimum amount of site-specific parameters necessary to run the model: latitude, longitude, climatic data, soil texture, bulk density and site management history. At each site, long-term climatic averages (1961-yr of first SOC estimate), available from the nearest meteorological stations, were used to bring the model to the year one of the simulation, which is represented by the year of the first available SOC estimate. Usually this estimate coincides with the year the eddy covariance tower was activated. For the simulation (year of first SOC estimate-2008) climatic data recorded directly at each site by the instruments installed on the eddy covariance towers were used. Soil specific parameters, particle size distribution and bulk density, were taken from previous studies carried out at each site under the EU projects Forcast, Canif, CarboEurope and Euroflux (Table 2). Since site management history is very important, information stretching from a minimum of 150 yr at Lavarone, to a maximum of 300 yr at Rocca, were used. To initialize the ecosystem status and distribute the total SOC in the different pools considered by the CENTURY model (Table 2), a spin-up run for a fix period, 5000 yr, has been used. The length of the spin-up was chosen after it was noticed that was the time necessary for all sites to equilibrate

Table 2 Model inputs for simulations of the six forest sites using version 4.5 of the CENTURY model

Site	Texture (% of sa, si, cl)	Bulk density (g/m^3)	Initial SOM ($g\ C/m^2$)			
			Active surface	Active soil	Slow soil	Passive soil
Lavarone	25, 47, 28	0.936	93	212	4630	3599
San Rossore	94, 2, 2	1.267	11	110	3924	1056
Rocca 1	36, 31, 33	1.292	61	86	2578	2847
Rocca 2	40, 25, 35	1.249	50	70	3400	2100
Collelongo	30, 40, 30	0.990	126	238	5459	3526
Castelporziano	89, 5, 6	0.601	33	57	2121	731

SOM, soil organic matter.

with the conditions of year one of the simulation. To make projections of SOC stock changes during the two upcoming commitment periods, two climate change scenarios based on the IPCC emission scenarios for the region of interest were applied: A1F1 'world markets-fossil fuel intensive' and B2 'global sustainability' (Nakićenović *et al*., 2000). These two scenarios were chosen as they represent extremes of climate forcing (A1F1 is highest, B2 among the lowest). The monthly climate data were available at 10′ by 10′ spatial resolution, and are described in detail in Mitchell *et al.* (2004) whilst the underlying emissions scenarios were described in detail in Nakićenović *et al*., 2000).

Model testing and statistics

The model was evaluated during the simulation (year of first SOC estimate-2008) by comparing the simulated and observed SOC estimates from the first data point to each successive data point using a regression. Mean SOC stocks in g/m^2 for different years, calculated from percentage carbon content and bulk density, were derived at each site from previous projects. In order to make direct comparisons between observed and simulated values, the observations were adjusted to match the 20 cm simulation depth required by CENTURY model. To assess whether the model could accurately simulate SOC while maintaining realistic levels of production, the modelled NPP was compared with that estimated indirectly, or in some cases directly, at each of the sites. The net primary production is an important parameter for CENTURY 4.5, the validation of which is required to build confidence in all the other model outputs (Parton *et al*., 1993). Since direct measurements or continuous NPP data series were not available at all sites, indirect estimates of NPP were derived considering the NPP of forests as a constant fraction of gross primary production (GPP). The general value of 0.47 proposed by Waring *et al.* (1998) was used for Mediterranean broadleaves forests, while more specific ecosystem type values were derived from Luyssaert *et al.* (2007) for Mediterranean warm evergreen forests (0.54), temperate humid evergreen forests (0.44) and deciduous forests (0.54). The GPP has been estimated for each site-year partitioning the Net Ecosystem Exchange (NEE) direct measurements (processed following the standard CarboEurope-IP methodology described in Papale *et al*., 2006 and Moffat *et al*., 2007) in the two components GPP and Ecosystem Respiration (Re) according with Reichstein *et al.* (2005). Direct estimates of NPP obtained by biometric methods, were instead collected for most of the investigated sites from previous research studies. In addition, at each site, the modelled annual heterotrophic soil respiration value was contrasted with the total annual soil respiration (measurements taken with soil chambers) to verify that the ratio between the two fell within the range of those proposed for Mediterranean and temperate mountain forests in the literature by the review of Subke *et al.* (2006). The performance of the model was assessed by calculating the mean difference between the simulations and the measurements (RMSE – equation 1), model efficiency (EF – equation 2), coefficient of determination (CD – equation 3) and relative error (E – equation 4), while the consistent over- or under-prediction errors of the model (bias error) was evaluated by calculating the mean difference (MD – equation 5) between measurements and simulations (Smith *et al*., 1997; Moffat *et al*., 2007; Smith & Smith, 2007).

$$\text{Relative} - \text{RMSE} = \sqrt{\sum_{i=1}^{n} (Pi - Oi)^2 \Big/ n} \tag{1}$$

$$\text{EF} = \frac{\sum_{i=1}^{n} (Oi - \bar{O})^2 - \sum_{i=1}^{n} (Pi - Oi)^2}{\sum_{i=1}^{n} (Oi - \bar{O})^2} \tag{2}$$

$$\text{CD} = \frac{\sum_{i=1}^{n} (Oi - \bar{O})^2}{\sum_{i=1}^{n} (Pi - \bar{O})^2} \tag{3}$$

$$\text{E} = \frac{100}{n} \sum_{i=1}^{n} (Oi - Pi) \Big/ Oi \tag{4}$$

$$\text{MD} = \frac{1}{n} \sum_{i=1}^{n} (Pi - Oi) \tag{5}$$

where Oi are the observed (measured) values, Pi are the predicted values, $\bar{O}$ is the mean of the observed (measured) data and *n* is the number of paired values.

The RMSE and CD range from 0 to ∞, EF from −∞ to 1 and E from −∞ to ∞. For an ideal fit, RMSE and E equal zero and CD and EF equal 1. Note that CD as defined here is not the same as the more familiar coefficient of determination R^2, of regression analysis.

Results

In general, the model fit to measured SOC data was very good, with modelled results falling within the uncertainties of the measured C stocks (Figure 1). The agreement between the modelled and measured data is shown in Figure 2. Also, the comparison of the other outputs chosen for model evaluation show good agreement with measurements. The modelled NPP fits quite well with that derived from the GPP (Figure 3) and even better with the NPP data from direct measurements (Figure 4). The modelled N stocks also show good agreement with the measured stocks at all sites (Figure 5), and the ratio

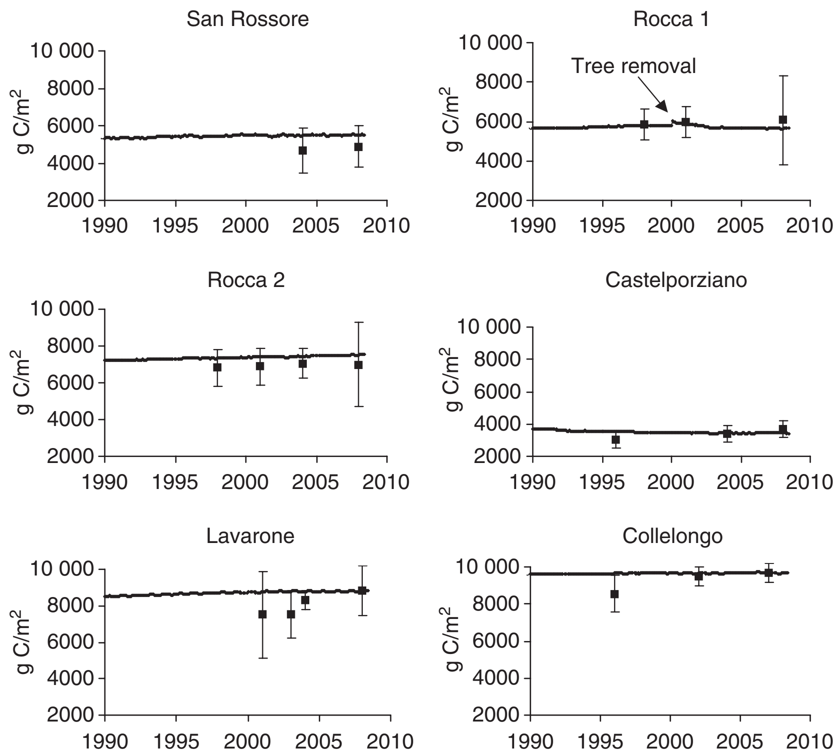

Figure 1 Best fit between modelled (solid line) and measured (dots) soil organic carbon (SOC) stocks in the top 20 cm of mineral soil of the six investigated stands. Bars represent the standard deviation.

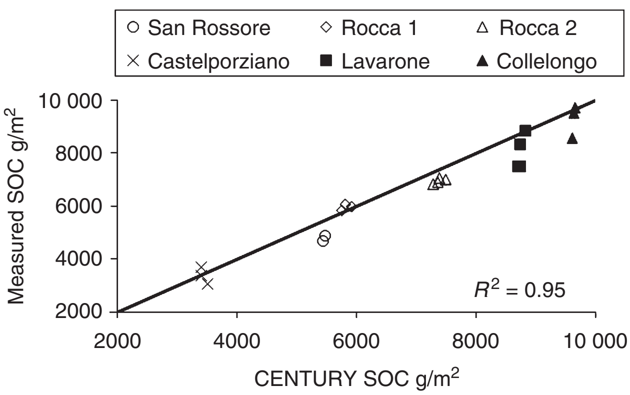

Figure 2 Measured against modelled soil organic carbon stocks. The line indicates the 1:1 relation.

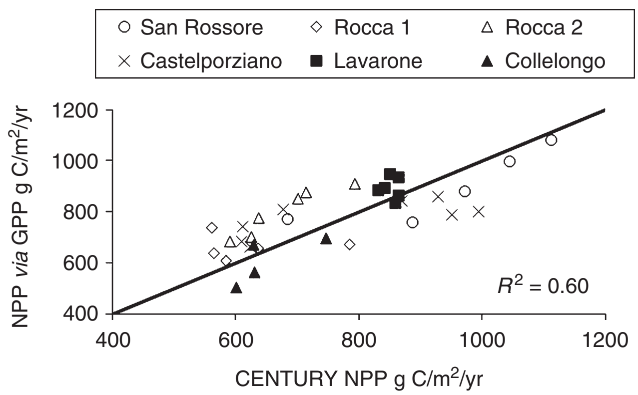

Figure 3 Net primary production (NPP) derived from gross primary production against modelled NPP. The line indicates the 1:1 relation.

between modelled heterotrophic respiration and total respiration fall in the range of the literature values (Table 3). Table 4 shows a statistical comparison of modelled and measured SOC, NPP (derived from GPP and from biometric measurements) and SON over the same time period for each forest, indicating an optimal correspondence between the two types of data. The SOC simulation resulted in a RMSE of 586.8 g C m^2, with a model efficiency (EF) of 0.9, an overestimate of the real value of 372.8 g C/m^2 and a R^2 of 0.9. CD is 0.8 while its error (E) is 5.7. Contrasting the modelled NPP with that derived from GPP, the modelled values show a RMSE of 81.5 g C m^2 with an EF of −0.7, a R^2 of 0.6, a CD of 0.7 and an E of 2.3. The model slightly underestimates the NPP derived by GPP by about 19.4 g C m^2, but when the modelled NPP is compared with that estimated by biometric measurements, the RMSE is 55.3 g C/m^2 with an EF of 0.5, a R^2 of 0.8, a CD of 1.6, an E of −0.4 and an overestimate of 8.1 g C/m^2. The N stocks were also statistically well simulated with a RMSE of 88.2 g N m^2, an EF of 0.8, a R^2 of 0.8, a CD of 0.9, an E of −0.2 and a MD of −9.4 g N m^2.

According to both selected scenarios, at the four Mediterranean sites, there was an increase in SOC stock at the end of the first commitment period compared with the

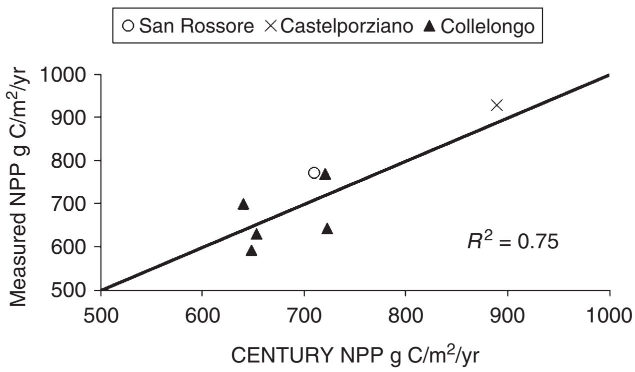

Figure 4 Measured net primary production (NPP) against modelled NPP. The line indicates the 1:1 relation. The measured NPP was taken from Chirici *et al.* (2007) for San Rossore, Tirone *et al.* (2003) for Castelporziano and Mollicone *et al.* (2003) for Collelongo.

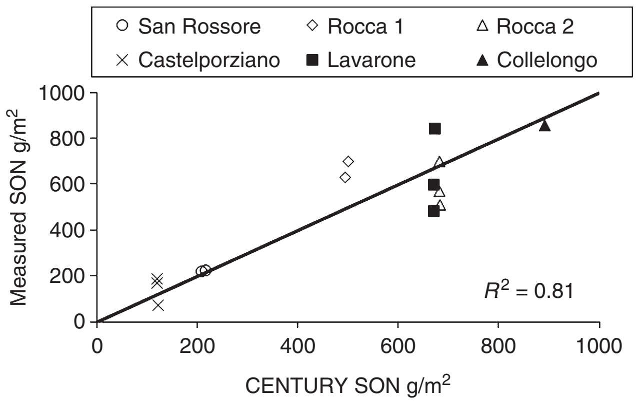

Figure 5 Measured against modelled soil nitrogen stocks. The line indicates the 1:1 relation.

SOC stock in 2008, which ranged between 0.2% and 1.3% for the A1F1 scenario, and between 0.2% and 1.0% for the B2 scenario, at Rocca 1 and San Rossore, respectively. At the end of the second commitment period, the change varies between 0.2% and 3.4% for the A1F1 scenario, and between 1.1% and 3.4% for B2. In both cases, the lower value occurs at San Rossore and the higher at Castelporziano. Large changes are observable only after longer simulation periods (e.g. 2050) with the A1F1 scenario indicating a variation from the reference SOC stock in 2008 ranging from −8.0% at San Rossore to 8.3% at Rocca 1. The same sites also show the extreme values for the B2 scenario, −3.2% and 9.1%, respectively. At the mountain forest sites, a positive variation in SOC stock from 0.4% to 2.3% at the end of 2012 is obtained under the A1F1 scenario and from 0.4% to 2.1% under the B2 scenario. The lower and higher values are observed at Collelongo and Lavarone, respectively. At the end of 2017, the positive SOC stock variations range from 2.0% to 7.1% for the A1F1 scenario and from 2.0% to 6.7% for B2. For longer simulation periods (2050) the mountain forests do not show substantial variations in SOC stock compared with the end of the second commitment period. In fact, with respect to the value measured in 2008, the positive variations observed in 2050 range between 9.4% and 4.0% for the A1F1, and from 4.3% to 4.8% for the B2 scenario at Lavarone and Collelongo, respectively (Figure 6).

Table 3 Modelled heterotrophic respiration (Rh) to measured total soil respiration (SR) ratio, compared with literature values for each specific forest type

Site	Year	Modelled Rh/Total SR	Range[a]	Source total SR
San Rossore	2000	0.58	0.53[b]	Tirone, 2002
	2001	0.60	0.53[b]	Tirone, 2002
	2001	0.56	0.53[b]	Tirone, 2002
Rocca 1	1999	0.47	0.48–0.77	Dore, 1999
	2000	0.54	0.48–0.77	Rey *et al.*, 2002
Rocca 2	1999	0.46	0.48–0.77	Dore, 1999
	2000		0.48–0.77	Rey *et al.*, 2002
Castelporziano	1996	0.60	0.48–0.77	Muratore, 1998
	1998	0.64	0.48–0.77	Dore, 1999
	2000	0.56	0.48–0.77	Tirone, 2002
	2001	0.67	0.48–0.77	Tirone, 2002
	2002	0.59	0.48–0.77	Tirone, 2002
Lavarone	2001	0.91	0.26–0.80	Rodeghiero & Cescatti, 2006
Collelongo	1997	0.58	0.29–0.94	Matteucci *et al.*, 2000
	2007	0.63	0.29–0.94	Guidolotti, 2008

[a]From Subke *et al.* (2006). [b]No range was available for this type of ecosystem.

Table 4 Statistics describing the performance of CENTURY version 4.5 in simulating organic C stocks, net primary production, and soil nitrogen stocks

	SOC	NPP *via* GPP	Measured NPP	SON
RMSE (g C/m²)	586.8	181.5	55.3	88.2
EF	0.9	−0.7	0.5	0.8
R^2	0.9*	0.6*	0.8*	0.8*
CD	0.8	0.7	1.6	0.9
E	−5.7	2.3	−0.4	−0.2
MD (g C/m²)	372.8	−19.4	8.1	−9.4

CD, coefficient of determination; E, relative error; EF, model efficiency; GPP, gross primary production; MD, mean difference; NPP, net primary production; SOC, soil organic carbon; SON, soil organic nitrogen. *$P < 0.001$.

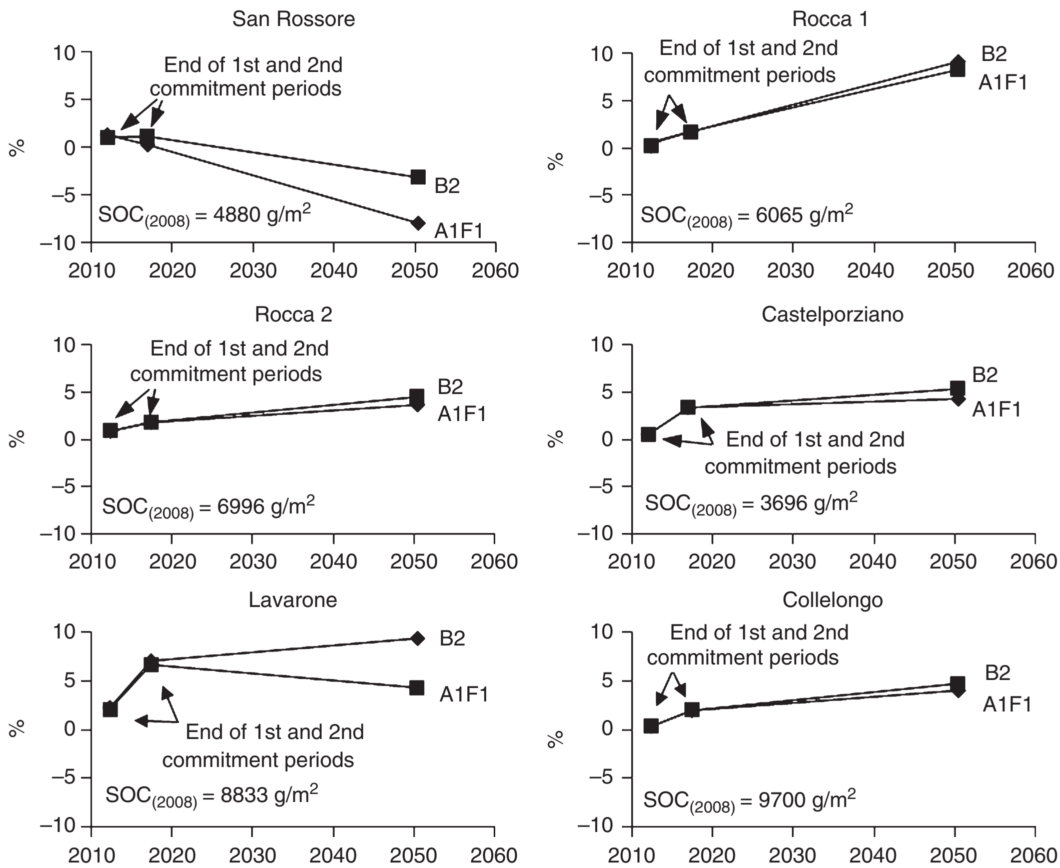

Figure 6 Percentage variation in soil organic carbon (SOC) amount compared with the reference year (2008) according to the selected climate change scenarios A1F1 and B2.

Discussion

Across climates, sites, forest types and treatments, the CENTURY model successfully simulates changes in SOC. A regression between observed and simulated changes in SOC over the life of the experiments yielded a significant relationship with an R^2 of 0.9 ($P < 0.001$; Table 4). Concerning the indirect estimates, the small RMSE (81.5 g C/m^2) and a MD of 19.4 g C/m^2, indicate a good performance of the model in predicting NPP. In general the NPP is better modelled in the mountain forests ($R^2 = 0.9$) than in the Mediterranean forests ($R^2 = 0.6$). More importantly, the modelled NPP shows good agreement with the available estimate of NPP obtained by biometric measurements (Table 4). Based on the results of this modelling exercise, there can be some confidence in using CENTURY 4.5 for predicting future SOC stock changes. Taking into account both climate change scenarios, at the end of 2012 the predicted positive changes in SOC will be smaller than 100 g C/m^2 in the Mediterranean forest sites, while for mountain forests these changes will range between 38 g C/m^2 and about 200 g C/m^2. This small increment will be very difficult to detect unless a large sampling scheme is applied (Conen *et al.*, 2003; Smith, 2004a). Given these minimal differences, for countries electing forest management activities under article 3.4, it seems more likely that any differences in SOC stock would be more reliably measured at the end of the second commitment period (2017) than at the end of the first one. In fact, at the end of 2017 the increase in SOC stocks, compared with the 2008 values, are predicted to be slightly higher than 100 g C/m^2 for Mediterranean forests and ca. 200–600 g C/m^2 for mountain forests. These variations point out the difficulty for detecting changes in SOC in Mediterranean forests even after 10 yr, while for mountain forests, it will be easier to statistically detect such changes with a reasonable number of samples. The use of benchmark sites is essential for verifying such changes (Smith, 2004b), but it seems that Mediterranean forests will respond differently to mountain forests with respect to climate change, with the latter showing higher rates of SOC sequestration during both commitment periods. The positive variations in SOC observed at all sites indicate the soil, currently considered a biospheric sink of C (Valentini *et al.*, 2000; Smith, 2005), will continue to store C during the

Kyoto Protocol commitment periods under both scenarios (Figure 6). The effects of global warming, such as increases in temperature and atmospheric CO_2 and a longer growing season have documented positive influences on tree physiology, metabolism, and growth (Pataki *et al.*, 2006; Luo, 2007; Penuelas *et al.*, 2009). If there are no other limitations (e.g. water, nutrient resources), these effects provide positive feedback on SOC accumulation (McMahon *et al.*, 2010) although, in the long term, these effects are expected to decline (Cao & Woodward, 1998; Schimel *et al.*, 2007). The sites investigated do not suffer from relevant water or nutrient limitation, and the SOC tends to gradually increase despite the fact that management has not changed over many decades. Collelongo, the only site where NPP was directly measured for 4 yr support the SOC increment, through increased tree growth and, consequently, increased C inputs to soil. In fact, NPP increased from 6.5 t/ha/yr in 1996 to 7.2 t/ha/yr in 1999. Further, the only site that is relatively more water and nutrient limited, San Rossore, accumulates SOC at a lower rate than the others during both commitment periods and it become a source of SOC at the end of the second commitment period (Figure 6). It is worth noting that the larger increments are observable under the less impacting of the scenarios, the B2. This fact is possibly related to the soil acclimation allowing the soil to equilibrate with the changing condition especially if the change is gradual as in the case of the B2 scenario (Wan *et al.*, 2007).

As demonstrated by measured (Figure 1) and modelled (Figure 6) results, soil C accumulation is a slow processes that can be affected by several environmental and disturbance factors. As the forest sites used in this paper are all under active management, at a higher (e.g. Rocca 1 and Rocca 2) or lower intensity, future management options should properly consider the conservation or possibly the increase of soil C, both at Mediterranean and Mountain sites. The maintenance of a continuous forest cover may avoid sudden exposure of soil to direct radiation and warmer temperatures that may favour soil C decomposition, while a fraction of slash (small branches, foliage, deadwood) should be left on-site to favour nutrient and carbon cycle at soil level. As far as possible, fire prevention should be a priority, particularly for Mediterranean sites.

Taking into account the mean soil C stock of the upper 20 cm, measured at each site in 2008 using 36 samples (Carboitaly; Inglima & Cotrufo, 2006), and the given standard error of the mean stock, the minimum variation in soil organic carbon detectable with statistical significance can be estimated in a one-tailed, one-sample *t*-test as a product of the standard error and the sum of the critical *t* values for type I and II error probabilities (Zar, 1999). For a type I error probability (α) of 0.05 and a type II error probability (β) of 0.10 (i.e. statistical power = 0.90), this sum is 2.976. Thus, the minimum detectable positive variation would be between 361 g/m^2 and 595 g/m^2 in the Mediterranean forests and between 682 g/m^2 and 1300 g/m^2 for mountain forests. Compared with the changes predicted by CENTURY at the end of each commitment period, these values support the model results, pointing out the possibility to detect variation in SOC after 10 yr, but only for mountain forest. Theoretically, if sample size is increased to 72 at each site, the minimum positive variation can be greatly reduced to allow the detection at the end of 2017 also for Mediterranean forests. In any case, the variation will not be detectable in 2012 with a reasonable number of samples. Attempting to detect significant changes over even shorter periods would be unreasonable, given the fact that forest processes and climate change occur on a time scale of decades, rather than years (Conen *et al.*, 2003).

The results of this work point out the difficulty of detecting changes in SOC by direct measurements during the 1st and 2nd commitment periods of the Kyoto Protocol, since the amount of C emitted/removed by soil will fall within the uncertainties of the stock measured in the reference year (2008), unless a very large sampling is applied. Hence, they support the findings of Smith (2004a) and Conen *et al.* (2004), namely that measuring C stock changes in the field (e.g. for Kyoto verification) by direct measurements is a difficult task *per se*. Moreover, the 5 yr required for the Kyoto verification is too short a timeframe for detecting significant changes in a relatively low dynamic compartment such as soil. This fact will result in serious difficulties at National level for reporting the changes in the SOC pool under Article 3.4 of the Kyoto Protocol.

Using only the minimum input parameters needed to run the model, CENTURY successfully simulated SOC dynamics at both Mediterranean and mountain forest sites. This set of simulations reinforces the utility of using models as a tool for monitoring and predicting SOC changes across climates, and treatments within sites. When the need to report a change in SOC stock after short periods of time is necessary, models can be useful if supported by a good evaluation of their performance, since detecting changes by direct measurements is both time consuming and costly.

In conclusion, modelling can be a promising approach for reporting purposes under the Kyoto Protocol commitment periods. In particular, based on the values already measured in 2008, and inferring the SOC stock at the end of 2012 by a SOC model such as CENTURY proved to be a cost-effective and sufficiently reliable alternative option to the direct repeat measurement. However, its application and reliability at larger scale would need to be assessed against SOC data at similar scale (e.g. from large scale soil inventories). In any case, the methodological choice between model and direct measurements will depend upon the criteria considered acceptable under international reporting and verification frameworks (Smith, 2004b).

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