Carbon and water balance of European croplands throughout the 20th century

Sebastien Gervois, Philippe Ciais, Nathalie de Noblet-Ducoudre, Nadine Brisson, Nicolas Vuichard, Nicolas Viovy

Carbon and water balance of European croplands throughout the 20th century

Sébastien Gervois,[1,2] Philippe Ciais,[1] Nathalie de Noblet-Ducoudré,[1] Nadine Brisson,[3] Nicolas Vuichard,[1,4,5] and Nicolas Viovy[1]

Received 24 May 2007; revised 5 November 2007; accepted 24 January 2008; published 13 June 2008.

[1] We assessed the effects of rising atmospheric CO_2, changing climate, and farmers' practice on the carbon and water balance of European croplands during the past century (1901–2000). The coupled vegetation-crop model ORCHIDEE-STICS is applied over western Europe for C3 crops (winter wheat) and for maize, with prescribed historical agricultural practice changes. Not surprisingly, the enormous crop yield increase observed in all European regions, 300–400% between 1950 and 2000, is found to be dominantly explained by improved practice and varieties selection, rather than by rising CO_2 (explaining a ~11% uniform increase in yield) and changing climate (no further change in yield on average, but causing a decrease of ~19% in the southern Iberian Peninsula). Agricultural soil carbon stocks in Europe are modeled to have decreased between 1950 and 1970, and since then to have increased again. Thus, the current stocks only differ by 1 ± 6 tC ha^{-1} from their 1900 value. Compensating effects of increasing yields on the one hand (increasing stocks) and of higher harvest index values and ploughing on the other hand (decreasing stocks) occur. Each of these processes taken individually has the potential to strongly alter the croplands soil carbon balance in the model. Consequently, large uncertainties are associated to the estimated change in carbon stocks between 1901 and 2001, roughly ±6 tC ha^{-1} a^{-1}. In our most realistic simulation, the current cropland carbon balance is a net sink of 0.16 ± 0.15 tC ha^{-1} a^{-1}. The annual water balance of cropland soils is influenced by increasing crop water use efficiency, one third of which is caused by rising CO_2. However, increasing water use efficiency occurred mainly in spring and winter, when water is not limiting for plant growth, whereas no strong savings of soil water are achieved in summer through elevated CO_2. Overall, trends in cultivation practices have caused a 3 times larger increase of water use efficiency than rising CO_2.

Citation: Gervois, S., P. Ciais, N. de Noblet-Ducoudré, N. Brisson, N. Vuichard, and N. Viovy (2008), Carbon and water balance of European croplands throughout the 20th century, *Global Biogeochem. Cycles*, *22*, GB2022, doi:10.1029/2007GB003018.

1. Introduction

[2] In the 21st century, atmospheric CO_2 will continue to increase and temperature to rise, reaching up to 2.1 to 4.4°C higher than today, according to different climate scenarios [*IPCC*, 2001]. These changes are anticipated to impact on the functioning of crops [*Ghaffari et al.*, 2002]. The fertilizing effect of CO_2 on C3 plants is expected to increase productivity [*Long et al.*, 2004]. Controlled FACE experiments reviewed by *Long et al.* [2006] suggest a slight increase in wheat yield on the magnitude of 10 to 16% for high (550 ppm) compared to ambient CO_2 [*Ewert et al.*, 2002; *Pinter et al.*, 1997], while no significant increase has been observed for maize yield in the absence of drought [*Leakey et al.*, 2006]. However, CO_2 fertilization by decreasing stomatal conductance increases the water use efficiency and may reinforce the resistance of plants in situation of drought [*Long et al.*, 2004; *Van de Geijn and Goudriaan*, 1996]. The effect of warming on the other hand is less straightforward to assess, as it depends on the range and variability of temperatures encountered and on the species considered [*Rosenzweig et al.*, 2000; *Wheeler et al.*, 2000]. *Juin et al.* [2004] demonstrated that future warming could allow farmers to grow maize and fodder plants at higher altitudes, thereby expanding the areas suitable for cultivation. *Abrol and Ingram* [1996] predicted that optimum photosynthesis temperatures could be approached during the 21st century for many cereals, but that the seasonal development of crops will be shortened,

[1]Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay, Gif-sur-Yvette, France.
[2]Now at Laboratoire d'Océanographie et de Climat, Expérimentation et Approche Numérique, Université Pierre et Marie Curie, Paris, France.
[3]INRA, Unité Climat, Sol et Environnement, Site Agroparc-Domaine St Paul, Avignon, France.
[4]Department of Forest Resources and Environment, University of Tuscia, Viterbo, Italy.
[5]Also at Centre International de Recherche sur l'Environnement et le Développement, EHESS, CNRS, Nogent sur Marne, France.

0886-6236/08/2007GB003018

thereby decreasing the length of the grain filling stage and the yield.

[3] It is important to understand how recent changes in climate, CO_2, and management practices have affected European agriculture in order to better predict the future. During the 20th century, the intensification of farming practices (selection and use of new species, increasing use of mineral fertilizers instead of manure, irrigation) has produced a threefold to fourfold increase in European crop yields [*Mazoyer*, 2002]. During the same time period, climate has warmed up by 0.8°C, and atmospheric CO_2 has increased by 30% (90 ppm). The large and widespread increase in yield observed everywhere in Europe does not seem to have entrained a similar increase in soil carbon stocks [*Arrouays et al.*, 2002], and soil carbon may have even decreased in many regions of intensive agriculture [*Walter et al.*, 1995; *Fardeau et al.*, 1988]. Finally, the effects of past and present agricultural changes on the European water balance remain quite uncertain.

[4] This study aims at elucidating the relative impacts of climate change, increased CO_2, and intensified farmers' practices during the 20th century on the yields of maize and winter wheat, as well as on soil carbon and water storage. To do so, we constructed a coupled model between the global vegetation model ORCHIDEE [*Krinner et al.*, 2005] and the crop model STICS [*Brisson et al.*, 1998a, 2002, 2003]. The coupled model is described in section 2. Simulated changes in crop productivity, cropland soil carbon, and soil water contents during the 20th century are analyzed in sections 3–5. The relative contribution of each factor is finally discussed at the regional and continental level.

2. Methods

2.1. ORCHIDEE-STICS Model

[5] This study is based on a coupled model [*Gervois et al.*, 2004; *de Noblet-Ducoudré et al.*, 2004] between a dynamic global vegetation model called ORCHIDEE [*Krinner et al.*, 2005] and a process-oriented crop model called STICS [*Brisson et al.*, 1998a, 2002, 2003]. The ORCHIDEE model calculates the distribution of carbon and water stocks and their hourly fluxes on a European grid under prescribed climatic, atmospheric, and edaphic conditions for diverse vegetation types (plant functional types). However, ORCHIDEE does not represent accurately cultivated plants, neither their phenology, nor the farming practices impacting their growth. Further, ORCHIDEE has no explicit nitrogen cycle. In contrast, the STICS crop model is designed to predict yields at given sites, and thus includes the attributes by which crops differ from natural grasses. STICS has yet sufficiently generic parameterizations to allow simulating various crop species: wheat and maize which are the focus of this study, but also tomato, banana, soybean, vineyards... can be modeled [*Brisson et al.*, 1998b; *Flenet et al.*, 2004; *Sierra et al.*, 2003]. Wheat and maize parameterizations in our study describe generically winter C3 and C4 crops over Europe. Wheat is the most common C3 crop in Europe, and many C3 winter crops have a similar phenology than winter wheat.

[6] Management information required to drive STICS are the sowing date and crop species parameters. Information on the amount of fertilizers and irrigation are also needed to calculate crop yields, but they can be alternatively computed from the modeled plant stress within the model itself. However, STICS is not designed for spatially explicit simulations and has no soil carbon decomposition module.

[7] When coupling the two models, we let STICS calculate daily foliar index, root density profiles, nitrogen stress, vegetation height, and irrigation requirements (Figure 1). These variables are then sequentially assimilated into ORCHIDEE each day. ORCHIDEE calculates CO_2, water, and energy fluxes in relation with climate. In ORCHIDEE, a mosaic of different vegetation types can coexist within the same grid point; crops then compete with other types of vegetation for access to soil water. In the soil water submodel of ORCHIDEE, there are two soil layers [*Choisnel*, 1977, *Ducoudré et al.*, 1993]. Different vegetation types can only compete for water in the subsurface layer. In the surface layer, water is not shared. The irrigation demand as calculated by STICS is added to the surface layer for maize (C4 crop PFT) only, so that does not interfere with other vegetation types.

[8] At the site level, the ORCHIDEE-STICS model results were evaluated against eddy covariance measurements of carbon and water fluxes over wheat and maize canopies at Bonville and Ponca (United States) [*Gervois et al.*, 2004; *de Noblet-Ducoudré et al.*, 2004]. A very good fit to the observed seasonal and diurnal variations of NEE, latent, and sensible heat was found at these two sites. At the continental level, the coupled model was tested over western Europe, and the modeled yields were shown to compare well with FAO data in each country (FAO, 2002, FAOSTAT: Food and Agricultural Organization statistical databases, available at http://faostat.fao.org/) by *Gervois* [2004] and P. C. Smith et al. (Accounting for crops in a terrestrial ecosystem model over Europe: Evaluation of ORCHIDEE-STICS across a range of temporal and spatial scales, manuscript in preparation, 2008). Nevertheless, the simulated yields are overestimated in Spain, Portugal, and Italy (Figure S1).[1] In the STICS model, the soil depth is constant with a high value of 2 m, which may cause water stress to be underestimated.

2.2. Simulations Over the 20th Century

2.2.1. Land Cover

[9] The coupled ORCHIDEE-STICS model was run over a western European domain bounded by 35.5°N and 54.5°N in latitude and 9.5°W and 19.5°E in longitude. In 2000, the area covered by croplands in the domain is 56 Mha, about 35% of the total land area. The distribution of natural and cultivated vegetation is derived from the CORINE data set [*Buttner et al.*, 2000]. In ORCHIDEE, natural vegetation classes are being grouped into nine plant functional types over Europe. Country-level information on the C3 and C4 percent cover area (FAO, 2002) was added to the agricultural land cover map (Figure S2). A 14% fraction of croplands is covered by C4 crops (maize).

[1]Auxiliary materials are available in the HTML. doi:10.1029/2007GB003018.

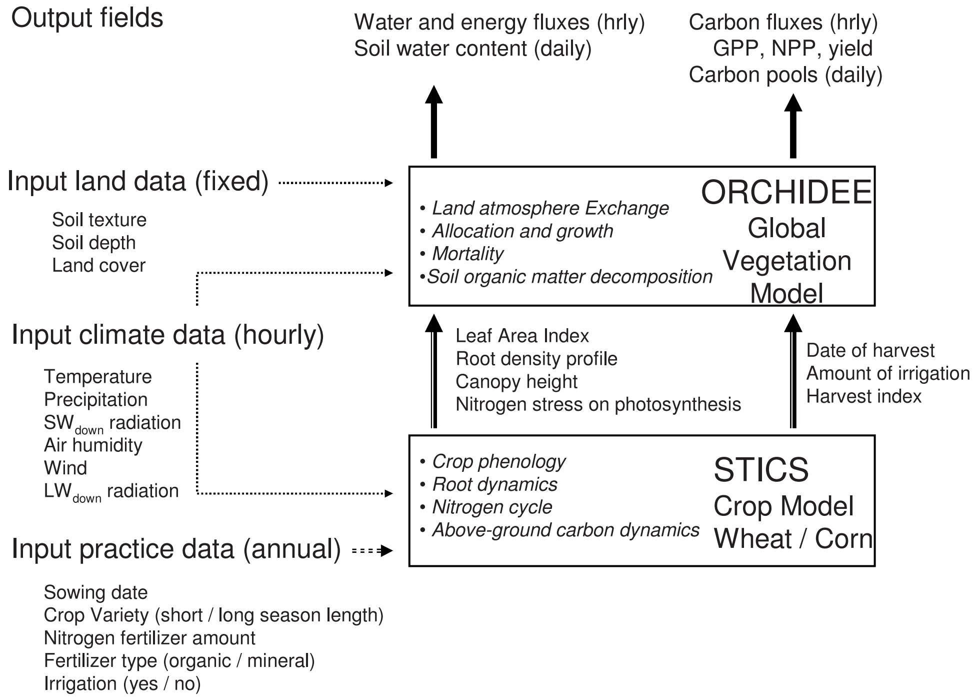

Figure 1. Coupling of the ORCHIDEE dynamic global vegetation model with the STICS crop model. Dotted line indicates the gridded input fields which are common to both models. Double dotted arrows indicate input practice data (uniform over Europe). Double solid arrows indicate the variables which are sequentially assimilated from STICS into ORCHIDEE each day. Thick solid arrows indicate the output fields.

[10] The area of cropland has been set constant in our simulations during the whole period 1901–2000. This is a reasonable approximation. Between 1901 and 2000, only 7% of croplands abandonment has taken place [*Ramankutty and Foley*, 1999], mostly to the benefit of forests and urban areas [*IIA*, 1947; FAO, 2002]. Strictly speaking, neither the replenishing of forest carbon stocks after cultivation, nor the impacts of urbanization, are part of the cropland carbon balance calculated by ORCHIDEE-STICS. Yet, on the basis of historical cropland area changes (FAO, 2002) [*Mather et al.*, 1998; *Agreste*, 2006], we made a preliminary calculation of soils carbon gains in the forests and grasslands established over abandoned cultivation (S. Gervois et al., The carbon balance of European croplands controlled by farmers practice and land-use changes: Insights from a process based model, manuscript in preparation, 2008). This gain of 7.8 tC ha^{-1} between 1901 and 2000 amounts to 30 MtC over the abandoned croplands (3.9 Mha). This small change in stock is well within the uncertainties in the soil C changes over the remaining 93% of croplands, which justifies neglecting land cover changes in this analysis.

2.2.2. Climate and Atmospheric CO_2

[11] Monthly temperature, air humidity, precipitation, wind, shortwave, and infrared radiation at 10' spatial resolution (~10 km) are taken from the climate data provided by the Climate Research Unit, University of East Anglia, United Kingdom [*Mitchell et al.*, 2004; *Mitchell and Jones*, 2005]. Hourly data required to drive ORCHIDEE-STICS were produced from these monthly fields using a weather generator.

[12] Three simulations were carried out to separate the contributions of increasing CO_2, varying climate, and improved agricultural practices over the period 1901–2000. These simulations were all initialized for the year 1900 by a 10,000 years model spin-up until water and soil carbon pools equilibrate with the model forcing data: climate, CO_2, practices (simulation INIT in Table 1). In each simulation, the harvested grain and a fraction of the stems are exported out of the ecosystem each year, leaving only the belowground biomass and a fraction of the aboveground biomass to the soil as litter as being input for soil carbon decomposition.

[13] In the S1 simulation, only changes in atmospheric CO_2 are accounted for, with a rise from 300 ppm in 1901 to 370 ppm in 2000 (data from http://cdiac.ornl.gov/trends/co2/lawdome.html). In the S2 simulation, variable climate and rising CO_2 are prescribed, but practices are unchanged and remain at their ancestral value of 1901. To mimic ancestral practice, we assumed only organic fertilizers (2 t ha^{-1} of manure) to be applied on croplands corresponding to an average input of nitrogen of 32 kgN ha^{-1} a^{-1} and to an input of carbon of 500 kgC ha^{-1} a^{-1}, and there is no irrigation. Short-cycle varieties were used (*Récital* wheat for C3 crops and *Pactol* maize for C4 crops). The parameters of each variety are summarized in Table 2. Finally, the harvest index, defined as the ratio of yield to aboveground biomass, is 0.25 (N. Brisson, personal communication, 2003), typical of the early 20th century. There is no change in sowing dates (15 September for C3 crops, 15

Table 1. Three Model Experiments Carried Out With ORCHIDEE-STICS Over the Period 1901–2000[a]

Experiment	Atmospheric CO_2	Climate	Farming Practice
INIT	300 ppm	recycled 1900 climate until equilibrium is reached	organic fertilizers 2 t $ha^{-1}a^{-1}$ (500 kgC ha^{-1} a^{-1} and 32 kgN ha^{-1}) harvest index 0.25 short-cycle varieties for wheat and maize no irrigation decrease of soil carbon pools' turnover by 10% (to mimic ploughing)
S1	from 300 to 370 ppm	recycled 1900 climate	1901–2000 organic fertilizers 2 t $ha^{-1}a^{-1}$ (500 kgC ha^{-1} a^{-1} and 32 kgN ha^{-1}) 1901–2000 Harvest index 0.25 1901–2000 short-cycle varieties for wheat and maize 1901–2000 no irrigation 1901–2000 decrease of soil carbon pools' turnover by 10%
S2	from 300 to 370 ppm	1901–2000	1901–2000 organic fertilizers 2 t ha^{-1} a^{-1} (500 kgC ha^{-1} a^{-1} and 32 kgN ha^{-1}) 1901–2000 harvest index 0.25 1901–2000 short-cycle varieties for wheat and maize 1901–2000 no irrigation 1901–2000 decrease of soil carbon pools' turnover by 10%
S3	from 300 to 370 ppm	1901–2000	1901–1950 organic fertilizers 2 t ha^{-1} a^{-1} (32 kgN ha^{-1} a^{-1}) 1951–2000 mineral fertilizers from 32 to 150 kgN ha^{-1} a^{-1} 1951–2000 increase of harvest index (linear) from 0.25 to 0.45 1951–2000 increase irrigation (maize only) 1901–1980 short-cycle varieties for wheat and maize 1981–2000 long-cycle varieties for wheat and maize 1901–2000 decrease of soil carbon pools' turnover by 10%

[a]Experiments S1, S2, and S3 share the same initial state calculated by INIT. Experiment INIT is performed by repeating the climate of 1900 and the constant CO_2 concentration of 300 ppm, during 10,000 years, up until soil carbon pools have reached their asymptotic equilibrium values.

May for C4 crops) and sowing densities (130 pl m^{-2}). We accounted for ploughing in S2 in an idealized way by using a reduced turnover time for agricultural soil pools by 10% between 1901 and 2000.

2.2.3. Changes in Agricultural Practice

[14] In the S3 simulation, the evolution of agricultural practices between 1950 and 2000 is additionally accounted for, after *Boulaine* [1996]. Before 1950, we assumed only organic fertilizers (manure) to be applied on croplands as in S2. Between 1950 and 2000, mineral fertilizers are introduced while manure fertilizers are phased out. Accordingly, we prescribed nitrogen inputs increasing linearly from 32 kgN ha^{-1} a^{-1} in 1950 to 150 kgN ha^{-1} a^{-1} in 2000, and stopped any further carbon input.

[15] In France, the fertilizers inputs in 2000 are 170 kgN ha^{-1} a^{-1} for wheat, 157 kgN ha^{-1} a^{-1} for grain maize, and 78 kgN ha^{-1} a^{-1} for silage maize (French Ministry of Agriculture [*Chapelle*, 2003]). Note that our values for wheat in France are much higher than the FAO [2002] data. The FAO study concerned only a small part (3.2 10^5 hectares) of the total wheat area in France (4.897 10^6 hectares). The discrepancy between fertilizer statistics seems to concern only wheat in France. There is otherwise a good agreement between FAO [2002] and *Chapelle* [2003] for grain and silage maize in France. For other western European countries (Germany, Netherlands, United Kingdom, Ireland, Belgium), N fertilizers inputs between 150 and 180 kgN ha^{-1} a^{-1} are reported, in line with our prescribed values.

[16] The use of more productive cultivars, in the second half of the 20th century, obtained for instance by genetic selection, is modeled by lengthening the grain filling duration and by increasing the harvest index in STICS. Up until 1980, STICS is run with the parameters of a short-cycle variety (*Récital* winter wheat for C3 crops and *Pactol* maize for C4 crops), which is then replaced by a long-cycle variety (*Soissons* wheat for C3 crops and *DK-604* maize for C4 crops). The parameters of each variety are summarized in Table 2. Finally, the harvest index, defined as the ratio of yield to aboveground biomass, is assumed to increase linearly from 0.25 in 1950 to 0.45 in 2000 (N. Brisson, personal communication, 2003).

[17] Finally, irrigation is applied only to maize. It is assumed to increase linearly from zero in 1950 up to meeting the whole plant water demand in 2000. The FAO statistics of irrigated area do not reach back to 1950, but extrapolating the FAO trend between 1961 and 1970 back to 1950 confirms that maize irrigation was very

Table 2. Parameters of Phenological Development for the Different Winter Wheat and Maize Varieties Used in Experiment S3[a]

		Winter Wheat GDD, °C		Maize GDD, °C	
		Short-Cycle "*Récital*"	Long-Cycle "Soissons"	Short-Cycle "*Pactol*"	Long-Cycle "DK 604"
Phase 1	between emergence and end of the juvenile stage	227	237	400	400
Phase 2	between end of juvenile stage and maximum LAI	260	310	300	390
Phase 3	between maximum LAI and start of senescence	214	237	730	730
Phase 4	between start of senescence and physiological maturity	683	693	300	300
Total		1384	1477	1930	2020

[a]The duration of each successive phase of crop development is defined by Growing Degree Days (GDDs) sums. The main differences between modern and past varieties concern the duration of the early stage development, or Phase 2, following the juvenile period. Increasing the length of Phase 2 allows higher values of LAI to be reached earlier in the year.

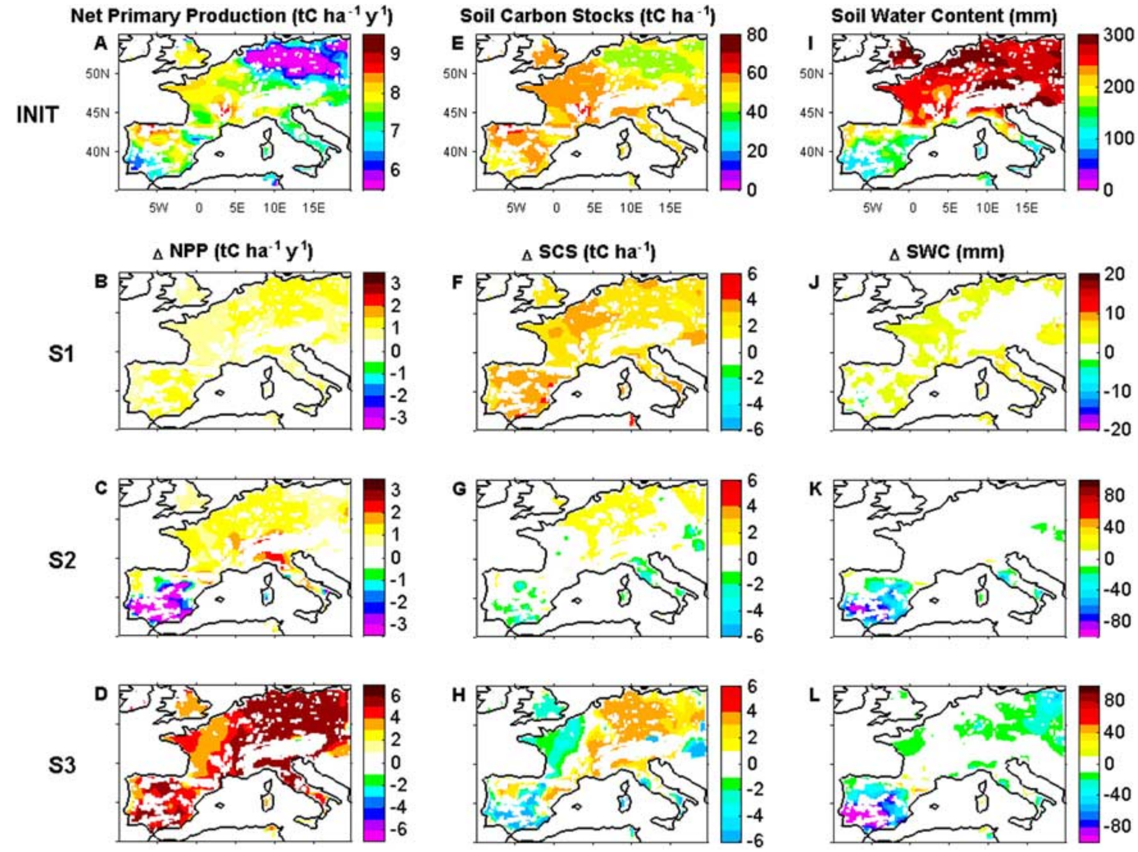

Figure 2. From left to right, distribution of winter wheat NPP (tC ha^{-1} a^{-1}), carbon stocks (tC ha^{-1}) of agricultural soils (wheat and maize) and soil water content (mm). From top to bottom, initial conditions corresponding to the period 1900 (experiment INIT in Table 1) and differences between final state (mean 1995–2000) and initial state INIT (1900) for each of the three model experiments S1 with rising CO_2 only, S2 with rising CO_2 and climate, and S3 with rising CO_2, climate and evolving farming practice.

low everywhere at that time, except in Spain and Italy. In STICS, irrigation is not systematically applied to maize, but it is triggered when the plant water stress reaches above a fixed threshold value of 0.85. In 2000, the comparison of the amount of irrigation calculated by STICS with the data of *Doll and Siebert* [2001] over Spain and with the *Agreste* [2002] irrigation census over France [*Gervois*, 2004] gives an agreement of 75% and 90%, respectively.

[18] In 2000, 5.50 Mha (70% of total maize area) are irrigated in western Europe in the simulation S3. Irrigated maize areas calculated by STICS are overestimated. If we consider only the grain maize, 1.087 Mha are modeled to be irrigated in S3 (62% of maize area) against only 0.78 Mha (44,5% of grain maize area) in the data [*Rabaud and Chassard*, 2007]. Irrigation materials are widespread only in regions where summer droughts are recurrent, whereas in STICS all maize fields could be irrigated in case of a water stress.

3. Changes in Productivity and Yield

3.1. Regional Change in Cropland NPP

[19] Figure 2a shows the annual Net Primary Productivity (NPP) of C3 crops (wheat) in 1900, while Figures 2b–2d shows changes between 1901 and 2000 for simulations S1 to S3. In the S1 experiment, the C3 crops NPP increases on average by 8.8% in response to rising CO_2 while the C4 crops NPP increases only by 5.1% (not shown). The NPP increase is quite uniformly distributed over the European domain considered. Note that the CO_2 driven increase in C4 crops yield is smaller than the regional increase of C3 crops yield because C4 photosynthesis is already efficient at lower CO_2 values, as implied by the *Collatz et al.* [1992] equations embedded in ORCHIDEE-STICS. In the S2 experiment, the C3 crops NPP increases on average by 12.4%, a bit more than in S1, but over Mediterranean regions, NPP decreases in response to dryer conditions (e.g., 19% in southern Spain). The drying reflects essentially a deficit of spring rains, which decreased by 35% during the past 60 years, especially over the Iberian Peninsula (Figure 2c). In contrast, the results of the S3 experiment show an increase of crop NPP (near 50% for the spatial mean over western Europe) in response to improved cultivation practices, offsetting the effects of drought in the Mediterranean regions (Figure 2d).

[20] The change in crop NPP (ΔNPP) between 1901 and 2000 in experiment S3 is not uniformly distributed over Europe (Figure 2d). It is smaller in France and in

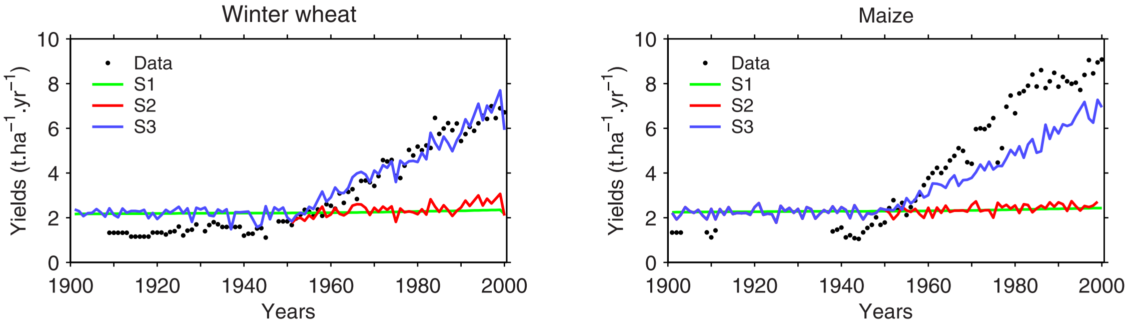

Figure 3. Simulated and observed winter wheat and maize yields in France between 1901 and 2000. The results are shown for experiment S1 with CO_2 effects only (green), for experiment S2 with CO_2 and climate (red), and for the more realistic experiment S3 where CO_2, climate and farming practice are varied (blue). Black dots are country averaged data from the "Institut International d'Agriculture–Services des Céréales" between 1909 and 1947 and from the Food and Agriculture Organization between 1948 and 2000.

Southern England than elsewhere. This is because we prescribed in 1900 for all European countries the parameters of the *Récital* wheat variety, a species already optimally adapted to the soils and climate conditions of France. Thus, starting from an already high NPP value over France and regions with similar climate (Figure 2a), the NPP increase obtained in 2000 due to improved practice is more limited over these regions than elsewhere (Figure 2d). In 1900, about a thousand of different local wheat varieties were cultivated in western Europe, for 15000 around the world [*Duby and Wallon*, 1977]. Assuming that each variety was at the time optimally adapted to its region of cultivation, our uniform model parameterization with a unique French variety *Récital* is thus likely to determine a systematic overestimate of the ΔNPP values in central and southern Europe. Note also that the spatial heterogeneity in the distribution of crop NPP in 1900 tends to smooth out as practice is improved through time. The ratio of the spatial standard deviation to the mean for C3 crops yield has decreased from 0.15 during the period 1901–1905 down to 0.09 during 1996–2000.

3.2. Comparison With Changes in NPP of Other Vegetation Types

[21] We also compared the modeled changes in NPP between croplands and naturals forests, being calculated by ORCHIDEE-STICS, during the whole period 1901–2000. In response to rising CO_2 alone (simulation S1) forests show everywhere a larger increase in NPP (+12.4%) than C3 crops (+8.8%) and maize (+5.1%). Including the effects of climate during 1901–2000 (simulation S2) further increases the forest NPP. Forests are more sensitive than crops to changes in CO_2 and climate. In Europe, the warming trends in spring and in fall have lengthened the growing season of trees, causing most of the increase in forest NPP in ORCHIDEE model [*Berthelot et al.*, 2005]. In contrast, the spring warming shortens the development of winter crops, the sum of degree days required for cereals growth being met earlier in the year, which acts to reduce NPP. Meanwhile, the autumn warming had no effects on winter crops (already harvested).

3.3. Comparison With Historical Yield Trends

[22] We evaluated the ORCHIDEE-STICS model results against historical yield data over France compiled by the Institut International d'Agriculture over 1909–1947 [*IIA*, 1947] and by the Food and Agriculture Organization (FAO, 2002) over 1948–2000. The results are shown in Figure 3 and given in Table 3. The rise in CO_2 alone was found to explain only 4.4% of the increase in winter wheat yield observed between 1901 and 2000. Adding climate change in experiment S2 did not further modify the yield trends, indicating that climate variations have had marginal effects on agricultural productivity. However, climate variability causes interannual variations in the yield (Figure 3), with dry and hot years being associated to drops in yield. The lowest abnormal yield values compared to the decadal mean occurred in 1923, 1947, and 1976. These are the three driest years of the 20th century [see also *Ciais et al.*, 2005, Figure 3]. On the other hand, the spectacular increase in wheat yield after 1950 appears to be almost uniquely driven by improved practices. Despite our simple parameterization of how practices have evolved in the past century, the modeled trend in wheat yield is in good agreement with historical observations from the IIA and the FAO.

[23] For maize, we obtained in experiment S1 a yield increase of 8.3% in response to rising CO_2. Like for wheat, the S3 experiment results show that improved practices are responsible for most of the recorded increase in maize yield over the past 50 years (+6.56 t_{DM} ha^{-1} or +465%). Unlike for wheat, however, the simulated maize yield for 1996–2000 over France is underestimated by 30% (Figure 3).

[24] A first possible cause is that we ignored the fact that grain maize grows predominantly in "optimal" southwestern regions of France (Aquitaine) where good climate conditions drive higher yields. In 2000 for instance, the maize yield in Aquitaine was 10% higher than the mean for France [*Agreste*, 2002]. In contrast, we distributed in the

Table 3. Evolution of Winter Wheat and Maize Yields in France, Between the Early 20th Century and Today for Model Experiment S1, S2, and S3

Simulation		Yield, $tC\ ha^{-1}\ a^{-1}$ INIT	Yield, $tC\ ha^{-1}\ a^{-1}$ 1995–2000	Yield Increase Above INIT, %	Percent of Yield Increase Compared to Increase in S3
S1	wheat	2.1	2.4	11%	5.0
	maize	2.1	2.2	8%	4.1
S2	wheat	2.1	2.3	11%	4.6
	maize	2.1	2.3	11%	5.4
S3	wheat	2.1	7.1	240%	100
	maize	2.1	6.3	200	100
Observed	wheat	1.3	6.9	440%	
	maize	1.4	8.0	470%	

model (section 2.2) the FAO national maize area evenly over the whole country cropland area, which is not realistic.

[25] A second cause for too low modeled maize yield is that we ignored silage maize (44% of the total cultivated maize area, dominant in the North of France). The parameters of grain maize are suboptimal for the north of France (too high GDD and too high optimal photosynthesis temperature). Silage maize would be better adapted, and would result into higher, more realistic, yields if it is accounted for.

[26] A third cause, is that the physiological and phenological parameters of maize in STICS, which were determined against INRA experimental data in the Poitou Charente region, are underestimating the yield. In fact, the modeled maize in the "optimal" region of Aquitaine are underestimated (8.2 $t_{DM}\ ha^{-1}$ instead of 9.8 $t_{DM}\ ha^{-1}\ a^{-1}$).

[27] For both wheat and maize, the simulated yields are overestimated until 1950. In the S3 simulation, the STICS model is parameterized for actual conditions. In particular, the sowing density (130 pl m^{-2}) is prescribed and herbicide and insecticide additions are implicitly taken account in that prescribed value.

4. Changes in Soil Carbon Stocks

4.1. Regional Distribution of Soil Carbon Changes

[28] Overall, we model a very small change of 1 tC ha^{-1} between 1901 and 2000, with an uncertainty of ±6 tC ha^{-1}. The current carbon balance over the last decade is a small sink of 0.16 tC $ha^{-1}\ a^{-1}$, with a range of 0 to 0.3 tC $ha^{-1}\ a^{-1}$. This sink is in the range of data compiled by *Lal et al.* [1998], reporting soil carbon gains due to mineral N fertilizer additions (0.1 to 0.3 tC $ha^{-1}\ a^{-1}$).

[29] Contrary to changes in NPP, the carbon stock change of agricultural soils (C3 and C4 crops) between 1901 and 2000 (ΔC) is not mostly determined by the increase of fertilizers and harvest index (Figures 2e–2h). In the S1 experiment, rising CO_2 causes only a small increase in agricultural carbon stocks (+3 tC ha^{-1}), because of enhanced NPP and litter input fluxes (Figure 2f). This is in agreement with the study of *Smith* [2005] who concluded to a limited increase of agricultural soil carbon due to rising CO_2 concentration. In the S2 experiment, changing climate partly opposes the effects of rising CO_2 because warmer temperatures cause an increase in mineralization. Between 1901 and 2000, the soil carbon stocks are found to decrease in experiment S2 between 3 to 5% over southern Europe (south of 42°N) because of the combined effects of decreased litter input and increased decomposition rates (see Figure 2g).

[30] The soil carbon stocks in experiment S3 increased in eastern Europe response to changing farmers' practice, CO_2 and climate (see Figure 2h), while it decreased (−2 to −4 tC ha^{-1}) in western France, southern Spain and southern England (Figure 2h). In these latter regions, the change in C3 crops NPP during the past 50 years were lower (2 to 4 tC ha^{-1}) than elsewhere. The spatial distribution of ΔC is mainly driven by the change in C3 crops litter input (except in southern Spain) rather than the change in maize input. This is first because the area covered by C4 crops in Europe is much smaller than the one of C3 crops (12% of the total arable land in our domain), and second because the increase of litter input to maize fields is compensated by higher mineralization rates in moister soils, as a consequence of assumptions about maize irrigation in ORCHIDEE-STICS.

[31] The simulated evolution of agricultural soil carbon stocks over Europe is qualitatively comparable to pointwise data that show either stable carbon stocks over time or a slight diminution with a large uncertainty [*Walter et al.*, 1995; *Fardeau et al.*, 1988].

4.2. Impact of Harvest Index and Fertilizer Additions

[32] We found that the stability of soil carbon pools between 2000 and 1901 in S3 results from a combination of processes opposing each other. The impacts on ΔC of the different farming practices embedded in all sensitivity experiments S3 were separated on the basis of model factorial experiment S3-A. The setting of these sensitivity tests is described in Table 4 and the results for ΔC averaged over Europe shown in Figure 4. The initial large carbon losses just after 1950 are due to replacing manure by mineral fertilizers. After roughly 20 years of losses, continued mineral fertilizer additions revert that trend and induce a build up of soil carbon via an enhanced NPP and litter input. The impact of higher harvest index and higher fertilizers amounts cannot be really separated, since both variables are positively correlated. A key to increasing crop yields in the late 20th century was not so much the selection of plants with high harvest indices, but the selection of plants that could respond to applied nitrogen by accumulating the nutrient and using the nitrogen in the production of grains [*Sinclair*, 1998].

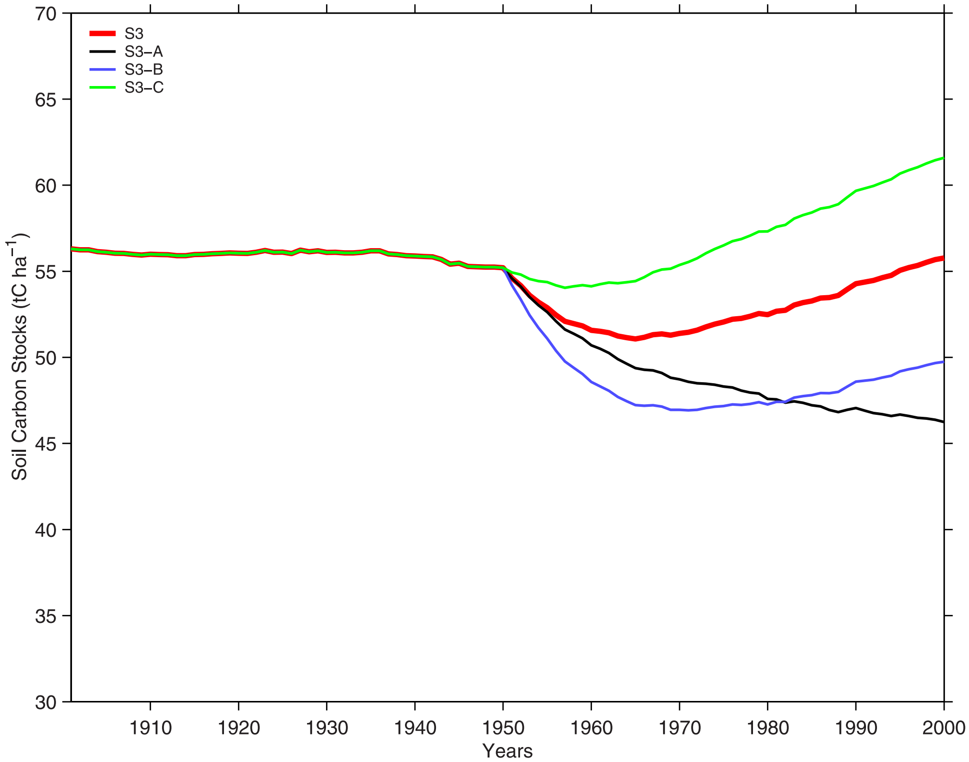

Figure 4. Evolution of soil carbon stocks during the 20th century in the control model experiment S3, together with sensitivity tests S3-A in which a minimum amount of N is provided by fertilizers and the harvest index is maintained at its value of 1950 (0.25) during the period 1950–2000, S3-B in which the ploughing intensity is 2 times higher than in S3, and S3-C in which there is no ploughing between 1950 and 2000.

[33] Nevertheless, the results of experiment S3-A suggest that increasing harvest index values in the model had a detrimental impact on ΔC, with a lesser fraction of biomass being returned to the soil. Higher-N fertilizers accompanied by higher harvest index values give a net increase in annual carbon return to the soil by 0.77 tC ha^{-1} a^{-1} which drives the estimated net sink of 0.16 tC ha^{-1} a^{-1}. We raise a caution flag on the fact that our large modeled impact of N fertilizers is 2 times the measured effects in long-term plot studies [*Arrouays et al.,* 2002]. In reality, the soil microbes activity (and thus the mineralization of soil carbon) increases with N additions. Thus, we likely overestimate the C sink in croplands, but even a twice smaller return to the soil would not change drastically the range of our results.

4.3. Impact of Ploughing

[34] Ploughing, by favoring soil oxygenation, accelerates the decomposition of soil organic matter. Ploughing practice is not included as a process in ORCHIDEE-STICS, in absence of any well-established parameterization and of pan-European historical data on ploughing depth and intensity. We accounted for ploughing in an idealized way by reducing the turnover time of agricultural soil carbon by 10% linearly between 1901 and 2000. The 10% value was tuned to give a good agreement with the data of *Arrouays et al.* [2002] showing that increased ploughing has caused carbon losses of ~0.1 tC ha^{-1} a^{-1}. *Arrouays et al.* [2002] estimated that increased ploughing has reduced soil carbon stores in France by 3–4 tC ha^{-1} during the period 1970–1998, by comparison with no-till C3 and C4 crops fields.

4.4. Sensitivity to Different Assumptions on Ploughing

[35] To gain insights on the impacts of ploughing before 1980, we designed two sensitivity tests (experiments S3-B and S3-C in Table 4). In experiment S3-B, we additionally decreased by 20% the turnover time of soil carbon after 1950, corresponding to an intensive mechanized ploughing scenario. In this test, the soil carbon losses during 1950–2000 are higher by 6.0 tC ha^{-1} (0.12 tC ha^{-1} a^{-1}) than under the moderate ploughing conditions of S3 (Table 4). This loss is (on the long-term) symmetric to the estimate of soil C gain due to reduced tillage of 0.2 tC ha^{-1} a^{-1} [*P. Smith et al.*, 2005]. If intensive ploughing had continued up until 2000 as in experiment S3-B, the European agricultural soil carbon stocks would have decreased by 12.2% (−6.9 tC ha^{-1}) below their 1950 value (Figure 4). In experiment S3-C, we assumed no till after 1950. In this test, soil carbon stocks increase by 8,3% (+4.5 tC ha^{-1}) after 1950. These two tests demonstrate that ploughing can cancel out the potential gains of soil carbon accompanying increasing crop productivity. Large uncertainties on the ploughing practices (frequency and depth) over the 20th

Table 4. Impact of Different Farming Practice on the Carbon Balance of Agricultural Soils[a]

		Input of Carbon to the Soil tC ha^{-1} a^{-1}			Soil Carbon Stocks tC ha^{-1}			NEP (>0 is Sink) tC ha^{-1} a^{-1}
Simulation	Description	INIT	1995–2000	Δ	INIT	1995–2000	ΔC	1991–2000
S3 (control)	mineral fertilizers increase[b] harvest index increase[c] ploughing intensity moderate[d]	3.51	3.80	0.29	56.2	55.3	−0.9	0.16
S3-A (test)	S3 but mineral fertilizers remain applied at a constant ancestral value of 32 KgN ha^{-1} a^{-1} between 1950 and 2000 and harvest index remain fixed at ancestral value of 0.25 between 1950 and 2000	3.51	3.04	−0.45	56.2	46.5	−9.7	−0.07
S3-B (test)	S3 but ploughing intensity is increased by additional shortening of soil carbon turnover by 20% between 1950 and 2000	3.51	3.80	0.29	56.2	49.3	−6.9	0.13
S3-C (test)	S3 but no ploughing between 1950 and 2000	3.51	3.80	0.29	56.2	60.9	+4.7	0.20

[a]The first three columns report the simulated carbon input to the soil at the beginning and in the end of the 20th century. The next three columns report agricultural soil carbon stocks and their difference between 1995 and 2001 and INIT. In fact, this difference is entirely realized between 1995 and 2001 and 1950, date at which many practices began to change in our scenario (see Table 2). The last column reports the derivative of the carbon stocks versus time curve, or net carbon balance (NBP). Factorial model experiments results are also given, where mineral fertilizer additions remain at their 1950 levels and harvest index values are maintained at their 1950 value of 0.25 (S3-A), and ploughing is intensified leading to accelerated soil carbon decomposition (S3-B), and there is no ploughing between 1950 and 2000 (S3-C).

[b]N fertilizers are applied over each cropland grid point after 1950, at the same rates given in Table 1 for experiment S3.

[c]Harvest index value assumed to increase linearly everywhere in Europe from 0.25 to 0.45 between 1950 and 2000, as indicated in Table 1.

[d]Turnover of all soil carbon pools is increased by 10% since 1901, as indicated in Table 1.

century currently limit our model ability to quantitatively reconstruct the carbon budget of agricultural lands.

4.5. Uncertainties

[36] From the range between S3-B and S3-C in Figure 4, we estimate an uncertainty of at least 12 tC ha^{-1}, that is 20% of the initial stocks on the modeled changes of soil carbon between 1901 and 2000. Uncertainties on the current carbon flux are also large. Ploughing practices are set in S3 to be constant between 1901 and 2000. However, some data [*Dellenbach and Legros*, 2001] suggest that ploughing was widespread and applied deeper and deeper between 1950 up until the early 1980s, after which this trend has reversed. Consequently, the current carbon sink may actually be higher than our mean value of 0.16 tC ha^{-1} a^{-1}. At face value, the soil carbon sink due to fertilizers may be overestimated (see section 4.2) in our study. Overall, the range of the S3-B to S3-C results suggests a cropland carbon sink comprised between 0.1 and 0.2 tC ha^{-1} a^{-1} (see Table 4). Thus, we reject both the notion that croplands are a huge carbon source [*Vleeshouwers and Verhagen*, 2002], and the view that they can be a large carbon sink [*Lal*, 2004].

5. Changes in Water Use Efficiency and in Soil Water Content

5.1. Crops Water Use Efficiency Increase

[37] Increasing CO_2 during the 20th century can be thought to have caused a better use of water by plants. This response of plants may have important implications if European countries will experience more droughts in the 21st century [*Seneviratne et al.*, 2006]. We computed the water use efficiency (WUE) of each crop as the ratio of the annual mean NPP in tC ha^{-1} a^{-1} to the annual planet transpiration, expressed in mm a^{-1}. ΔWUE values are displayed in Figure 5 for simulations S1 to S3. Experiment S1 shows a WUE increase of 14% in response to rising CO_2 between 1901 and 2000. Climatic change during the same time period did not significantly change the WUE at the European scale, since the warming led to parallel increases in both NPP and transpiration (S2 compared to S1). Experiment S3 shows a WUE increase between 1901 and 2000 of 19 ± 3% for forests, 19 ± 3% for grasslands, 37 ± 4% for wheat, and 33 ± 4% for maize, with the uncertainty being is the spatial standard mean deviation over Europe. The relative standard deviation is about 15% for noncrop vegetation and 10% for crops. True uncertainties are higher than these values, in presence of systematic errors both on NPP and on transpiration. The effects of improved cultivation practice in S3 have tripled the effects of CO_2 alone to further increase the WUE, despite an overall net increase in transpiration rate due to the introduction of more productive species and to the irrigation of maize. Interestingly, rising CO_2 is found in experiment S3 to contribute only 5% of the yield increase since 1901 (section 3), but contributes one third of the modeled WUE increase (deduced from comparison of S1 with S3 results in Figure 5).

5.2. Indirect Effects on WUE of Other Vegetation Types

[38] The agricultural practice driven increase in WUE for C3 and C4 crops has a negligible indirect effect on the WUE of adjacent forest and grasslands which share their deep water reserves with crops (see Figure 5). We also checked that maize irrigation do not increase artificially the transpiration of adjacent vegetation. Yet, when irrigation water is supplied in excess to the surface, water can infiltrate to the second deeper layer. If this was systematically the case, one would obtain a higher transpiration in S3

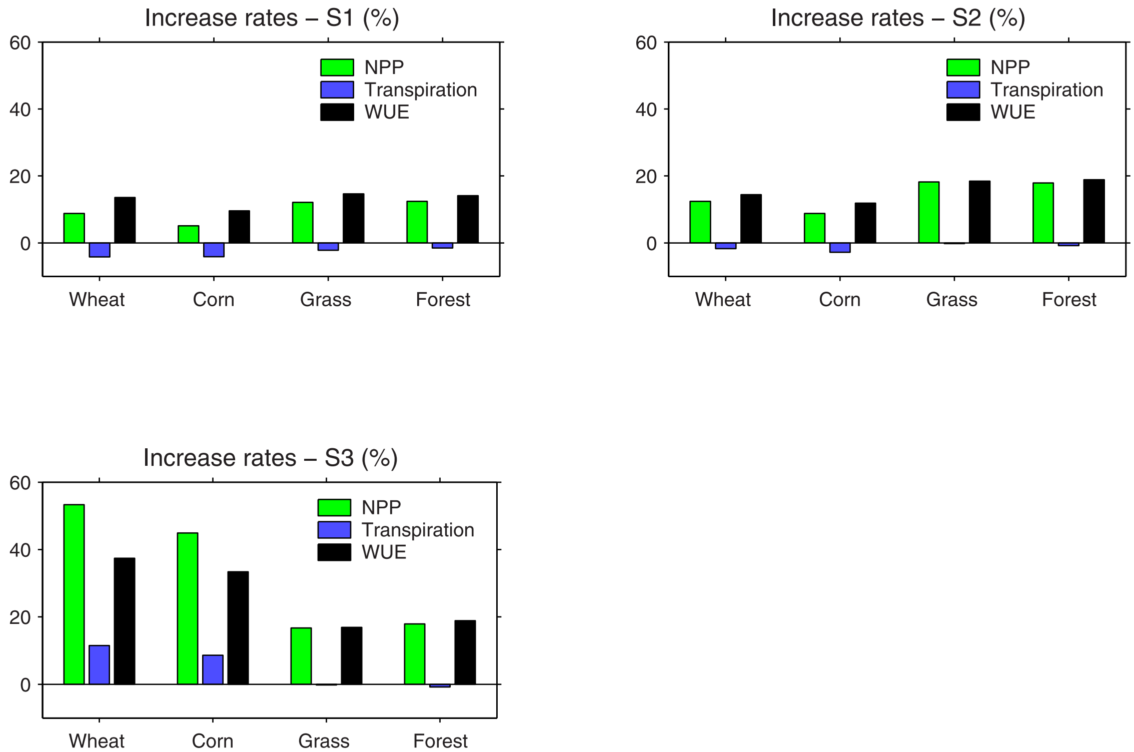

Figure 5. Percent change in NPP (green), transpiration (blue) and Water Use Efficiency (black) between 1995 and 2000 and 1900 (INIT), for each of the model experiment S1, S2, S3. The estimated quantities for winter heat and maize are calculated by ORCHIDEE-STICS, and are compared with the results of the DGVM ORCHIDEE for "natural" biomes C3 grasslands and forests.

for forests (roots in deep layer) than for grasslands (roots in surface layer), which is not the case in Figure 5.

5.3. Impacts of Changes in WUE on Soil Water Reserves

[39] We analyzed the changes in soil water content (ΔSWC) at the end of September, the period of the year usually experiencing the lowest seasonal amount of water. Contrary to the carbon variables, which are simulated separately for natural and cultivated ecosystems, the subsurface layer soil water reserves in ORCHIDEE are shared by all the vegetation types coexisting in each grid point. Thus the modeled ΔSWC is not a crop specific variable, but also reflects the response of natural ecosystem switch compete with crops for water. In experiment S1, rising CO_2 alone has the effect to save soil water. Lower transpiration rates (-17 mm a^{-1} over Europe) have a small impact (+2–3 mm) in augmenting SWC in September (Figure 2j), but they contribute to increase SWC (by +10 mm) in spring and winter when rainfalls are abundant. In experiment S2, climate change on the other hand is seen to determine a strong reduction in SWC, over the Mediterranean regions which experienced drying in spring over 1901–2000 (Figure 2k). Over the Iberian Peninsula, the decline in SWC induced by climate persists even when improved farming practice are included in ORCHIDEE-STICS (Figure 2l).

[40] In other regions, increased transpiration rates in response to warming cause only a small decrease in SWC (20% reduction in northern Europe) thanks to the enhanced plant water use efficiency. It is yet possible that the results of experiment S3 underestimate the climate induced soil water depletion between 1901 and 2000, because the water required for maize irrigation in experiment S3 was not withdrawn from the soil available water. In summary our study shows a qualitatively different response of soil water availability in croplands. In Mediterranean regions, climate changes are the primary driver of SWC, while in northern Europe practice changes have a stronger influence.

6. Concluding Remarks

[41] The coupled ORCHIDEE-STICS model was applied at the scale of western Europe during the period 1901–2000 in order to disentangle the impacts of rising atmospheric CO_2, climate variations and cultivation practices on the carbon and water balance of croplands (yet assuming constant agricultural area). A simple but robust parameterization of historical changes in cultivation practices was implemented in the model. This parameterization includes a shift toward mineral fertilizers, a selection of species with higher harvest indexes and earlier and shorter growing season, ploughing practice and irrigation for maize. All these practice changes begin in 1950. Each year, the timing of nitrogen fertilizer additions and the amount of irrigation for maize are self-computed by the crop model on the basis of physiological, not economical, requirements.

[42] In our model analysis, the improved agricultural practices account for 89 ± 6% of the large increase in crop

yield in Europe after 1950. Rising CO_2 was found to contribute a modest 11% to the total increase in C3 crops yield during 1901–2000, directly through augmented photosynthesis, and indirectly through water savings enabled by increasing water use efficiency. Drying in southern Europe did have a negative impact on yields, but management trends were larger and in the opposite direction.

[43] We found that increasing yields caused a build up of soil carbon stocks through increased litter fall. But the trend toward higher harvest index values during the second half of the 20th century combined with the intensification of ploughing and the replacing of manure by mineral fertilizers cancel out these benefits, so that European agricultural soils in 2000 are not really different from their initial stocks in 1901. In our most realistic simulation (S3), cropland soils act today as net carbon sinks to the atmosphere at a rate of 0.16 tC ha^{-1} a^{-1}, that is 53 TgC a^{-1} at the European continental level with a croplands area of 326 ± 32 Mha [from *Mücher et al.*, 2000]. This sink occurs in our model as resulting from the "rebound" of large carbon losses after 1950, which have progressively been offset by productivity-induced carbon gains. Our results are qualitatively different from those of *Sleutel et al.* [2003] based on an experimental study over croplands of Flanders, who concluded that croplands are a net carbon source to the atmosphere of 0.9 tC ha^{-1} a^{-1} for the period 1989–2000. *Vleeshouwers and Verhagen* [2002] using the CESAR model similarly found a large loss of carbon over European croplands (0.84 tC ha^{-1} a^{-1}). In the CESAR model, the area covered by each crop can change with time (being prescribed from FAO country-level statistics) unlike in ORCHIDEE-STICS where C3 and C4 crops area are set to be constant. However, in CESAR, the yield is simply diagnosed from the country-level FAO data to be uniform in each country and the yield to NPP ratio is estimated from Dutch agriculture data, and the same value applied everywhere. The effects of rising CO_2 are finally ignored. In ORCHIDEE-STICS, both the yield and the return of carbon to the soil are explicitly calculated for each grid point using information on practice, atmospheric CO_2, climate and soil properties. Recently, *J. Smith et al.* [2005] estimated with a modeling approach based upon LPJ [*Sitch et al.*, 2003] taking into account climate change and change in practice that soil carbon stocks of European croplands were stable over the time period 1990–2000. Their results are in relative good agreement with our simulations.

[44] It is fair to say that the uncertainty on our model-based estimate of the European cropland carbon balance is large. The largest source of uncertainty is insufficient information on how agricultural practice have evolved since the beginning of the 20th century. In particular, more information is needed on the effects of ploughing. In particular data from long-term field experiments that may allow to calibrate the soil decomposition module of ORCHIDEE in response to ploughing. Some studies conclude to a 50% increase of the mean residence time of the soil C between permanent pasture and conventional tillage plots [*Six et al.*, 1998; *Balesdent et al.*, 1990; *Ryan et al.*, 1995]. However, conventional practice being the most intensive type of tillage [*Paustian et al.*, 2000] and the tillage effects on organic matter being variable according to depth, intensity and frequency of soil disturbance, it is difficult to assess the impact of ploughing on soil decomposition through the 20th century.

[45] Other sensitive parameters which control the soil carbon budget, are the fate of crop residues after harvest, and the harvest index changes. How a given past change in each of these parameters is susceptible to shift today's cropland carbon balance from sink to source remains uncertain, and deserves more investigation using, e.g., more model factorial experiments. Regionally, we found that recent climate drying trends in southern Europe did reduce the yield and the return of carbon to and the soil C, and accelerated soil organic matter decomposition. However, this decrease in soil carbon was compensated by the effects of improved practice. Yet, climate trends cannot be ignored in estimating the carbon budget of croplands.

[46] Changes in the water balance are influenced (1) globally by rising atmospheric CO_2 with 30% more water savings in 1995–2000 than in 1901, (2) regionally by climate change trends with up to 80% less soil moisture in the Iberian peninsula caused by diminishing rainfall, and (3) regionally by practice changes causing a 20% decrease in soil water over northern Europe. In ORCHIDEE-STICS, higher transpiration rates caused by warming and by increasing leaf area index values are largely offset by a fourfold increase in crop water use efficiency throughout the 20th century.

[47] Extrapolating our results to the future, we may anticipate that there will be more spatial heterogeneities in the carbon balance than during the 20th century. Rising atmospheric CO_2 may contribute to a small increase in crop yield and soil carbon stores, but its effects will likely remain marginal. Furthermore, the recent assessment by *Long et al.* [2006] suggests that the impact of CO_2 fertilization on yield in current crop models is overestimated. The magnitude of regional climate change is on the other hand likely to be much larger during the 21st century than during the 20th century, with an expected +2.1 to +4.4°C warming in Europe compared to +0.8°C experienced so far [*IPCC*, 2001]. Warmer temperatures will likely enhance the water stress on productivity, especially for summer crops like maize which have a strong water demand. Soil respiration rates will also increase, shortening the residence time of soil carbon. The prediction of future rainfall remains particularly uncertain in climate models, but regional models consistently predict an increase in winter rains over northern Europe and a decrease in summer rains everywhere, with more extreme summer heat waves and more variable climate in general [*Seneviratne et al.*, 2006]. In this study, we have shown that drying trends in southern Europe already had a negative impact on crop yield. The yield of C3 crops and maize has already reached extremely high values in Europe, 8 t_{DM} ha^{-1} for wheat and 9.5 t_{DM} ha^{-1} for maize, respectively, after tripling over the past 40 years. Such productivity gains are unlikely to be sustained at such rates in the future, whereas climate change could have severe adverse effects. Climate change patterns are highly regional (see *Seneviratne et al.* [2006] for the future and our Figure 4 for the 20th century), and would require regional adaptation of practice to compensate for decreasing yields.

[48] Thus, from the point of view of both carbon and water balance, it is more likely that croplands will experience in the future more carbon losses than gains, unless practice adaptation can be developed and implemented. In addition, the possible effect of no-till activities might be important in the future [*J. Smith et al.*, 2005]. Our results show that if no-till had been sustained since 1950, the current cropland sink would be twice larger. Investigating interactions between climate changes and the current trends toward no-till should be given a high priority.

[49] **Acknowledgments.** This work was carried out at the Laboratoire des Sciences du Climat et de l'Environnement (Saclay, France). The computer time and the computing facilities were provided by the Commissariat à l'Energie Atomique.

References

Abrol, Y. P., and K. T. Ingram (1996), Effects of higher day and night temperatures on the growth and yield of some crop plants, in *Global Climate Change and Agricultural Production: Direct and Indirect Effects of Changing Hydrological, Pedological, and Plant Physiological Processes*, edited by F. Bazzaz and W. Sombroek, pp. 123–140, FAO, Rome.

Agreste (2002), *L'agriculture et l'agroalimentaire dans les régions, Coll. Graphagri Régions*, 330 pp., Agreste, Paris.

Agreste (2006), La forêt française préserve son avenir, *Agreste Primeur*, vol. 178, 4 pp., Agreste, Paris.

Arrouays, D., J. Balesdent, J. C. Germon, P. A. Jayet, J. F. Soussana, and P. Stengel (Eds.) (2002), *Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France?*, 332 pp., INRA, Paris.

Balesdent, J., A. Mariotti, and D. Boisgontier (1990), Effect of tillage on soil organic carbon mineralization estimated by ^{13}C abundance in maize fields, *J. Soil Sci.*, *41*, 587–596, doi:10.1111/j.1365-2389.1990.tb00228.x.

Bazzaz, F., and W. Sombroek (Eds.) (1996), *Global Climate Change and Agricultural Production: Direct and Indirect Effects of Changing Hydrological, Pedological, and Plant Physiological Processes*, 345 pp., FAO, Rome.

Berthelot, M., P. Friedlingstein, P. Ciais, J. L. Dufresne, and P. Monfray (2005), How uncertainties in future climate change predictions translate into future terrestrial carbon fluxes?, *Global Change Biol.*, *1*, 959–970, doi:10.1111/j.1365-2486.2005.00957.x.

Boulaine, J. (1996), *Histoire de l'agronomie en France*, 2nd ed., 448 pp., Coll. Tech-Doc, Lavoisier, Paris.

Brisson, N., et al. (1998a), STICS: A generic model for the simulation of crops and their water and nitrogen balances: I. Theory and parameterization applied to wheat and maize, *Agronomie*, *18*, 311–346, doi:10.1051/agro:19980501.

Brisson, N., M. Dorel, and H. Ozier-Lafontaine (1998b), Effects of soil management and water regime on banana growth between planting and flowering: Simulation using the STICS model, *Acta Horticul.*, *490*, 229–238.

Brisson, N., et al. (2002), STICS: A generic model for the simulation of crops and their water and nitrogen balance: II. Model validation for wheat and maize, *Agronomie*, *22*, 69–93, doi:10.1051/agro:2001005.

Brisson, N., et al. (2003), An overview of the crop model STICS, *Eur. J. Agron.*, *18*, 309–332, doi:10.1016/S1161-0301(02)00110-7.

Buttner, G., J. Feranec, and G. Jaffrain (2000), *Corine Land Cover Update 2000: Technical Guidelines*, *Tech. Rep. 89*, Eur. Environ. Agency, Copenhagen. (Available at http://reports.eea.eu.int/technical_report_2002_89/enl)

Chapelle, C. (2003) Des nitrates agricoles à l'Ouest et dans les plaines céréalières, *Agreste Primeur*, vol. 123, 4 pp., Agreste, Paris.

Choisnel, E. (1977), Le bilan d'énergie et le bilan hydrique du sol, *Meteorologie*, *6*(11), 103–133.

Ciais, P., et al. (2005), Europe-wide reduction in primary productivity caused by the heat and drought in 2003, *Nature*, *437*, 529–533, doi:10.1038/nature03972.

Collatz, G. J., M. Ribas-Carbo, and J. A. Berry (1992), Coupled photosynthesis-stomatal conductance model for leaves of C4 plants, *Aust. J. Plant Physiol.*, *19*, 519–538.

Dellenbach, P., and J. P. Legros (2001), Données historiques sur le développement du machinisme agricole en France, *Notes Acad. Sci. Lett. Montpellier*, *3763*, 16 pp., Montpellier, France.

de Noblet-Ducoudré, N., S. Gervois, P. Ciais, N. Viovy, N. Brisson, B. Seguin, and A. Perrier (2004), Coupling the soil-vegetation-atmosphere-transfer scheme ORCHIDEE to the agronomy model STICS to study the influence of croplands on the European carbon and water budgets, *Agronomie*, *24*, 397–407, doi:10.1051/agro:2004038.

Doll, P., and S. Siebert (2001), Global modelling of irrigation water requirements, *Water Resour. Res.*, *8*, 176–198.

Duby, G., and A. Wallon (1977), *Histoire de la France rurale*, 4 vol., Seuil, Paris.

Ducoudré, N., K. Laval, and A. Perrier (1993), SECHIBA, a new set of parametrizations of the hydrologic exchanges at the land/atmosphere interfaces within the LMD atmospheric general circulation model, *J. Clim.*, *6*, 248–273, doi:10.1175/1520-0442(1993)006<0248:SANSOP>2.0.CO;2.

Ewert, F., et al. (2002), Effects of elevated CO_2 and drought on wheat: Testing crop simulation models for different experimental and climatic conditions, *Agric. Ecosyst. Environ.*, *93*(1–3), 249–266, doi:10.1016/S0167-8809(01)00352-8.

Fardeau, J. C., C. Guiraud, J. Thiery, C. Morel, and B. Boucher (1988), Taux net annuel de minéralisation de la matière organique des sols de grande culture de Beauce. Conséquences pour l'azote, *C. R. Acad. Agric. Fr.*, *74*(8), 61–70.

Flenet, F., P. Villon, and F. Ruget (2004), Methodology of adaptation of the STICS model to a new crop: spring linseed (Linun unsitatissimum), *Agronomie*, *24*, 367–381, doi:10.1051/agro:2004032.

Gervois, S. (2004), Les zones agricoles en Europe: Évaluation de leur rôle sur les bilans d'eau et de carbone à l'échelle de l'Europe; sensibilité de ces bilans aux changements environnementaux sur le vingtième siècle, Ph.D. thesis, 252 pp., Univ. Pierre et Marie Curie, Paris.

Gervois, S., N. de Noblet-Ducoudré, N. Viovy, P. Ciais, N. Brisson, B. Seguin, and A. Perrier (2004), Including croplands in a global biosphere model: Methodology and evaluation at specific sites, *Earth Interact.*, *8*, doi:10.1175/1087-3562(2004)8<1:ICIAGB>2.0.CO;2.

Ghaffari, A., H. F. Cook, and H. C. Lee (2002), Climate change and winter wheat management: A modelling scenario for south-eastern England, *Clim. Change*, *55*, 509–533, doi:10.1023/A:1020784311916.

IIA (1947), *Annuaire international de statistique agricole: Années 1909–1947*, L'Inst. Int. d'Agricul., Rome.

IPCC (2001), *Climate Change: The Scientific Basis*, 598 pp., Cambridge Univ. Press, New York.

Juin, S., N. Brisson, P. Clastre, and P. Grand (2004), Impact of global warming on the growing cycles of three forage systems in the upland areas of south eastern France, *Agronomie*, *24*, 327–337, doi:10.1051/agro:2004028.

Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, P. Friedlingstein, P. Ciais, S. Sitch, J. Polcher, and C. Prentice (2005), A dynamic global vegetation model for studies of a coupled atmosphere-biosphere system, *Global Biogeochem. Cycles*, *19*, GB1015, doi:10.1029/2003GB002199.

Lal, R. (2004), Soil carbon sequestration impact on global climate change and food security, *Science*, *304*, 1623–1627, doi:10.1126/science.1097396.

Lal, R., J. M. Kimble, R. F. Follett, and C. V. Cole (1998), *The Potential of U. S. Cropland to Sequester C and Mitigate the Greenhouse Effect*, 128 pp., Sleeping Bear Press, Ann Arbor, Mich.

Leakey, A. D. B., M. Uribelarrea, E. A. Ainsworth, S. L. Naidu, A. Rogers, D. R. Ort, and S. P. Long (2006), Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO_2 concentration in the absence of drought, *Plant Physiol.*, *140*, 779–790, doi:10.1104/pp.105.073957.

Long, S. P., E. A. Ainsworth, A. Rogers, and D. R. Ort (2004), Rising atmospheric carbon dioxide: Plants FACE the future, *Annu. Rev. Plant Biol.*, *55*, 591–628, doi:10.1146/annurev.arplant.55.031903.141610.

Long, S. P., E. A. Ainsworth, A. D. B. Leakey, J. Nösberger, and D. R. Ort (2006), Food for thought: Lower-than-expected crop yield stimulation with rising CO_2 concentrations, *Science*, *312*, 1918–1921, doi:10.1126/science.1114722.

Mather, A. S., C. Needle, and J. Fairnbairn (1998), The human drivers of global land cover change: the case of forests, *Hydrol. Process.*, *12*, 1983–1994, doi:10.1002/(SICI)1099-1085(19981030)12:13/14<1983::AID-HYP713>3.0.CO;2-M.

Mazoyer, M. (2002), *Larousse agricole: Le monde paysan au XXème siècle*, 768 pp., Larousse, Paris.

Mitchell, T. D., and P. D. Jones (2005), An improved method of constructing a database of monthly climate observations and associated high-resolution grids, *Int. J. Climatol.*, *25*, 693–712, doi:10.1002/joc.1181.

Mitchell, T. D., T. R. Carter, P. D. Jones, M. Hulme, and M. New (2004), A comprehensive set of high resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100), *Working Pap. 55*, Tyndall Cent. for Clim. Change Res., July. (Available at http://www.tyndall.ac.uk/publications/working_papers/wp55.pdf)

Mücher, C. A., K. Steinnocher, F. Kressler, and C. Heunks (2000), Land cover characterization and change detection for environmental monitoring of pan-Europe, *Int. J. Remote Sens.*, *21*, 1159–1181, doi:10.1080/014311600210128.

Paustian, K., J. Six, and E. T. Elliott (2000), Management options for reducing CO_2 emissions from agricultural soils, *Biogeochemistry*, *48*, 147–163, doi:10.1023/A:1006271331703.

Pinter, P. J., Jr., B. A. Kimball, G. W. Wall, R. L. LaMorte, F. Adamsen, and D. J. Hunsaker (1997), Effects of elevated CO_2 and soil nitrogen fertilizer on final grain yields of spring wheat, in *Annual Research Report: U. S. Water Conservation Laboratory*, pp. 71–74, USDA, Agric. Res. Serv., Phoenix, Ariz.

Rabaud, V., and M. Chassard (2007), L'irrigation du mãuml;s mise à mal par les sécheresses, *Agreste Primeur*, vol. 194, 4 pp., Agreste, Paris.

Ramankutty, N., and J. Foley (1999), Estimating historical changes in global land cover: Croplands from 1700 to 1992, *Global Biogeochem. Cycles*, *13*, 997–1028.

Rosenzweig, C., A. Iglesias, X. B. Yang, P. R. Epstein, and E. Chivian (2000), *Climate Change and U. S. Agriculture: The Impacts of Warming and Extreme Weather Events on Productivity, Plant Diseases, and Pests*, 47 pp., Cent. for Health and the Global Environ., Boston, Mass.

Ryan, M. C., R. Aravena, and R. W. Gillham (1995), The use of ^{13}C natural abundance to investigate the turnover of microbial biomass and active fractions of soil organic matter under two tillage treatments, in *Soils and Global Change*, edited by R. Lal et al., pp. 351–360, CRC Press, Boca Raton, Fla.

Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär (2006), Land-atmosphere coupling and climate change in Europe, *Nature*, *443*, 205–209, doi:10.1038/nature05095.

Sierra, J., N. Brisson, D. Ripoche, and C. Noel (2003), Application of the STICS crop model to predict nitrogen availability and nitrate transport in a tropical acid soil cropped with maize, *Plant Soil*, *256*, 333–345, doi:10.1023/A:1026106208320.

Sinclair, T. R. (1998), Historical changes in harvest index and crop nitrogen accumulation, *Crop Sci.*, *38*, 638–643.

Sitch, S., et al. (2003), Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic vegetation model, *Global Change Biol.*, *9*, 161–185, doi:10.1046/j.1365-2486.2003.00569.x.

Six, J., E. T. Elliott, K. Paustian, and J. W. Doran (1998), Aggregation and soil organic matter accumulation in cultivated and native grassland soils, *Soil Sci. Soc. Am. J.*, *62*, 1367–1377.

Sleutel, S., et al. (2003), Carbon stock changes and carbon sequestration potential of Flemish cropland soils, *Global Change Biol.*, *9*, 1193–1203, doi:10.1046/j.1365-2486.2003.00651.x.

Smith, J., P. Smith, M. Wanttenbach, S. Zaehle, R. Hiederer, R. J. A. Jones, L. Montaranella, M. D. A. Rounsevell, I. Reginster, and F. Ewert (2005), Projected changes in mineral soils of European carbon croplands and grasslands, 1990–2080, *Global Change Biol.*, *11*, 2141–2152, doi:10.1111/j.1365-2486.2005.001075.x.

Smith, P. (2005), Limited increase of agricultural soil carbon and nitrogen stocks due to increased atmospheric CO_2 concentrations, *J. Crop Improvement*, *13*, 393–399, doi:10.1300/J411v13n01_19.

Smith, P., K. Andrén, T. Karlsson, P. Perälä, K. Regina, M. Rounsevell, and B. Van Wesemaels (2005), Carbon sequestration potential in European croplands has been overestimated, *Global Change Biol.*, *11*, 2153–2163, doi:10.1111/j.1365-2486.2005.01052.x.

Van de Geijn, S. C., and J. Goudriaan (1996), The effects of elevated CO_2 and temperature change on transpiration and crop water use, in *Global Climate Change and Agricultural Production*, edited by F. Bazzaz and W. Sombroek pp. 101–122, FAO and John Wily, New York.

Vleeshouwers, L. M., and A. Verhagen (2002), Carbon emission and sequestration by agricultural land use: a model study for Europe, *Global Change Biol.*, *8*, 519–530, doi:10.1046/j.1365-2486.2002.00485.x.

Walter, C., T. Bouedo, and P. Aurousseau (1995), *Cartographie communale des teneurs en matière organique des sols bretons et analyse de leur évolution temporelle de 1980 à 1995*, rapport final, 31 pp., Cons. Rég. de Bretagne–Agence Loire-Bretagne, Rennes.

Wheeler, T. R., P. Q. Craufurd, R. H. Ellis, J. R. Porter, and P. V. Vara Prasad (2000), Temperature variability and the yield of annual crops, *Agric. Ecosyst. Environ.*, *82*, 159–167, doi:10.1016/S0167-8809(00)00224-3.

N. Brisson, INRA, Unité Climat, Sol et Environnement, Site Agroparc-Domaine St Paul, 84914 Avignon CEDEX 9, France.

P. Ciais, N. de Noblet-Ducoudré, N. Viovy, and N. Vuichard, Laboratoire des Sciences du Climat et de l'Environnement, CEA Saclay, Bat. 712, Orme des merisiers, 91191 Gif-sur-Yvette CEDEX, France.

S. Gervois, Laboratoire d'Océanographie et de Climat, Expérimentation et Approche Numérique, Université Pierre et Marie Curie, Boite 100, 4 place Jussieu, 75252 Paris CEDEX, France. (sebastien.gervois@locean-ipsl.upmc.fr)