Biogeosciences Discuss., 11, 1561–1585, 2014
www.biogeosciences-discuss.net/11/1561/2014/
doi:10.5194/bgd-11-1561-2014

Biogeosciences
Discussions
Open Access

Future climate variability impacts on potential erosion and soil organic carbon in European croplands

M. van der Velde[1,*], J. Balkovič[1], C. Beer[2,3], N. Khabarov[1], M. Kuhnert[4], M. Obersteiner[1], R. Skalský[1], W. Xiong[1], and P. Smith[4]

[1]International Institute of Applied Systems Analysis (IIASA), Ecosystem Services and Management Program, Schlossplatz 1, Laxenburg, 2361, Austria
[2]Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Jena, Germany
[3]Department of Applied Environmental Science (ITM) and Bert Bolin Centre for Climate Research, Stockholm University, Sweden
[4]Institute of Biological & Environmental Sciences, University of Aberdeen, 23 St Machar Drive, Aberdeen, AB24 3UU, UK
[*]now at: European Commission, DG JRC, Institute for Environment and Sustainability, 21027, Ispra, Italy

Received: 18 December 2013 – Accepted: 14 January 2014 – Published: 23 January 2014

Correspondence to: M. van der Velde (marijn.van-der-Velde@jrc.ec.europa.eu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

We investigate the impact of future climate variability on the potential vulnerability of soils to erosion and the consequences for soil organic carbon (SOC) in European croplands. Soil erosion is an important carbon flux not characterized in Earth System Models. We use a European implementation of EPIC, driven by reference climate data (CNTRL), and climate data with reduced variability (REDVAR). Whether erosion regimes will change across European cropland depends on the spatial conjunction of expected changes in climate variability and physiographic conditions conducive to erosion. We isolated the effect of erosion by performing simulations with and without erosion. Median CNTRL and REDVAR erosion rates equalled 14.4 and 9.1 ton ha^{-1}, and 19.1 and 9.7, for 1981–2010 and 2071–2100, respectively. The total amount of carbon lost from European cropland due to erosion was estimated at 769 Tg C for 1981–2010 (from a total storage of 6197 Tg C without erosion) under CNTRL climate. Climate trend impacts reduce the European cropland SOC stock by 578 Tg C without – and by 683 Tg C with erosion, from 1981 to 2100. Climate variability compounds these impacts and decreases the stock by an estimated 170 Tg without erosion and by 314 Tg C with erosion, by the end of the century. Future climate variability and erosion will thus compound impacts on SOC stocks arising from gradual climate change alone.

1 Introduction

Erosion plays a vital role in the carbon cycle. Yet, Earth System Models generally do not include erosion. Erosion is especially important in the carbon cycling of croplands. The movement of soil and organic matter away from agricultural fields affects soil quality and crop production. Soil removal and subsequent sedimentation affect the overall terrestrial carbon budget, although the net effect of erosion and deposition on the carbon cycle remains difficult to quantify (Van Oost et al., 2007; Lal and Pimentel, 2008). At the same time, regional climate projections over Europe indicate that gradual changes in meteorological variables during this century will be accompanied by increasing variability and frequency of extreme events across different scales (Fischer and Schär 2010; Reichstein et al., 2013). This further necessitates analyzing the spatial conjunction of expected changes in climate variability and physiographic conditions conducive to erosion.

European croplands store a significant amount of carbon (Ciais et al., 2011). Overall, carbon budgets of European croplands are estimated to be close to zero in terms of net carbon emissions, with estimated net fluxes ranging from small carbon sources to small sinks depending on the data, methodology and model used (Ciais et al., 2011; Frank et al. 2014; and references therein), and uncertainty over past and present agricultural management practices. A better understanding of climate variability and subsequent impacts on erosion and carbon dynamics in European arable systems is needed. Here we investigate the consequences of the expected increase in the occurrence of extreme weather events on potential erosion, with implications for soil organic carbon storage of European cropland using the EPIC (Environmental Policy Integrated Climate; (Williams et al., 1989) agro-ecosystem model.

Tolerable natural soil erosion rates are generally below rates experienced in agricultural land. Current estimates of soil erosion rates in cropping systems are highly variable but about two to three magnitudes higher than soil is formed through weathering and dust deposition (Pimentel and Kounang, 1998; Brantley et al., 2007), and especially dependent on slope and tillage practices. At the field scale, erosion from tilled cropland has been reported at an average of $6\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ in the US (Wilkinson and McElroy, 2007) and up to $56\,\mathrm{t\,ha^{-1}\,yr^{-1}}$ in Europe (Verheijen et al., 2009). Crop residue retention and maintenance of a vegetative cover generally decrease soil erosion rates. The deposition and subsequent residence time of soil organic carbon (SOC) removed with eroded soil determines the actual contribution of SOC loss to CO_2 levels (van Oost et al., 2007; Lal and Pimentel, 2008). At the same time, an agricultural soil degraded through erosion and suffering from depleted nutrient and organic carbon

BGD
11, 1561–1585, 2014

pools will not be able to reach its production potential, thereby negating potential future carbon sequestration.

Heavy rain and storm events generally can have two effects affecting the carbon cycle. Firstly they can destroy above ground biomass by damage or destruction of the crop, and secondly they can lead to erosion and dislocation of soil, and consequently SOC. Extreme precipitation may affect crops catastrophically (van der Velde et al., 2012) or affect cropped land that is susceptible during fallow periods or relatively long times without canopy closure (Van Oost et al., 2007). Flooding at any stage during crop growth can lead to total crop failure in the areas affected. In addition to changes in the soil CO_2 fluxes and CO_2 uptake of plants during water logging phases, heavy rainfall can lead to important topsoil erosion due to its higher erosive power. Nearing et al. (2004) estimated a ratio of erosion increase to annual rainfall increase of approx. 1.7.

In the context of extreme events, it is important to consider the event-based nature of erosion as single events can have a substantial impact on sediment load totaled over a certain time period (e.g. Thothong et al., 2011). Importantly, exceptional rainfall events can trigger extreme runoff and widespread erosion in areas normally not considered to have a high erosion risk. For instance, erosion events ($> 100\,\mathrm{t\,ha^{-1}}$) in Norway resulted from a combination of extreme rainfall, agricultural management practices, low vegetation cover and a saturated soil overlying a frozen subsoil (Oygarden, 2003). In areas with an increased likelihood of extreme precipitation the event based nature of erosion events would suggest an increased transportation of soil and organic carbon away from impacted agricultural fields.

Extreme events may also impact carbon fluxes via partially lagged phenomena, such as increases in insect and pathogen outbreaks, or through a combination of separate extreme events compounding their impacts, for instance heavy rainfall after prolonged drought periods may lead to degradation via soil erosion (Reichstein et al., 2013). However, the relations between direct and indirect or lagged impacts in agro-ecosystems are often not straightforward. The difficulty in quantifying these interactions is further compounded by the adaptive actions farmers may take (Frank et al. 2014).

This paper aims to quantify the impact of future climate variability on potential soil erosion and the implications for soil organic carbon (SOC) stored in European croplands by specifically quantifying the contribution of erosion to the carbon losses that can potentially be expected. We examine the impacts of climate variability on the carbon cycle of wheat production systems across Europe. Specific objectives were (1) to quantify the impact of including the modeling of erosion on the carbon dynamics of European cropland; (2) to quantify whether the contribution of climate variability to erosion and SOC loss has and will change over time by comparing the time periods 1981–2010 and 2071–2100; and (3) to quantify the contribution of erosion due to changes in extreme weather to the overall soil carbon dynamics of European cropland.

2 Data and methods

To evaluate the impact of future day-to-day and inter-annual climate variability on soil organic carbon storage in European croplands we force our European EPIC (Environmental Policy Integrated Climate, Williams et al., 1989) implementation (Balkovič et al., 2013) with an artificial climate dataset (REDVAR) which represents reduced climate variability with conserved long-term means compared to the control climate data (CNTRL) as created by (Beer et al., 2014). The use of these two climate datasets allows us to perform a factorial modelling experiment isolating the effect of climate variability. To evaluate and isolate the contribution of soil erosion to the total carbon balance of cropped fields we performed simulations without and with erosion. It is important to keep in mind that the erosion simulated with EPIC is indicative for potential erosion and does not take account of further sedimentation processes as there is no routing in the model. Modelled crop yields of our European EPIC validation have been evaluated rigorously to reported regional yields (Balkovič et al., 2013). We report briefly on this in the section on Model performance and in Appendix A.

BGD
11, 1561–1585, 2014

2.1 Climate data

The climate datasets that were created using the statistical bias correction methodology described in Piani et al. (2010) have a spatial resolution of 0.25°, cover Europe (29 to 71° N and −24 to 45° E), and have a daily temporal resolution and a timespan from 1901 to 2100 (for details see Beer et al., 2014). The CNTRL input data consists of WATCH forcing data during 1901–1978, bias-corrected ERA-Interim during 1979–2010 (see http://www.eu-watch.org/data_availability), and bias-corrected A1B Remo results during 2011–2100 with transient [CO_2] based on the A1B emission scenario (Beer et al., 2014). The reduced variability (REDVAR) data conserves seasonal mean and trend changes in meteorological variables and in this sense it is identical to CNTRL but with reduced climate variability on daily and inter-annual scale (Beer et al., 2014). A full set of meteorological variables needed for modelling was altered and included minimum air temperature, maximum air temperature, downward short-wave radiation, downward long-wave radiation and specific humidity. The transformation also conserved the number of rain days per month. On average, extreme values were reduced by 15 % in the REDVAR climate dataset (for details see Beer et al., 2014). The atmospheric carbon dioxide concentratoins followed the CMIP5 protocol (Meinshausen et al., 2011).

2.2 Terrain and soil data

Digital terrain information was derived from SRTM (Shuttle Radar Topographic Mission, Werner, 2001) and GTOPO sources (Global 30 Arc Second Elevation Data; http://eros.usgs.gov). Soil data were obtained from the European Soil Bureau Database (ESBD v. 2.0), including the Soil Geographic Database of Europe, the Soil Profile Analytical Database of Europe, the Pedo-Transfer Rules Database and the Database of Hydraulic Properties of European Soils (Wösten et al., 1999). The initial SOC value was calculated from the Map of Organic Carbon Content in topsoils in Europe (Jones et al., 2005). It was subsequently partitioned into the passive and slow humus pools

BGD
11, 1561–1585, 2014

using 50-years of cultivation prior to the final simulation. Soil profiles were split into 10 vertical layers to appropriately address soil water and temperature regimes. Slopes and mean elevations were obtained from the SRTM and GTOPO data (for further details see Appendix A).

2.3 EPIC model performance

EPIC is an agro-ecosystem simulation model (Williams et al., 1989) integrating bio-physical processes in crop-soil production systems. Crop growth determines the accumulation of biomass and therefore is a crucial component determining carbon sequestration in arable soils. Therefore, the EPIC model performance was evaluated by comparing simulated crop yields against reported yields over Europe. We report here on the results obtained for wheat. We aggregated the simulated wheat yields (1997 to 2007) by NUTS2 (the European Nomenclature of territorial units for statistics) and regressed those against the EUROSTAT reported wheat yields. The goodness of simulation was assessed using the coefficient of determination for linear regression (R^2), which was tested by the F test, and the regression slope. Differences between mean values and standard deviations in simulated and reported yields were statistically evaluated using the two-tailed pair t test and the F test, respectively. The results are summarised in Table A1 . EPIC under-predicted both winter wheat means and standard deviations by 0.2 to 1.8 t ha^{-1} ($P < 0.05$ for all years) and 0.4 to 0.5 t ha^{-1} ($P < 0.05$ for five of the 11 yr), respectively. The R^2 goodness of fit between simulated and reported yields were between 0.64 and 0.81. Linear regression slopes varied from 0.63 to 0.94. The modelled and reported wheat yields demonstrate similar responses to the driving meteorological variables: they both decrease with increasing solar radiation and PET, increase with growing precipitation and aridity index, and show an optimum at about 11 °C.

BGD
11, 1561–1585, 2014

3 Results

3.1 Erosion

Average annual simulated erosion rates for 1981–2010 (Fig. 1a) range from near zero to more than 40 $t\,ha^{-1}\,yr^{-1}$. Obviously, areas characterized by little relief experience low erosion rates such as the highlands in Spain and large parts of northern Poland, Germany and Sweden. Regions with high erosion rates can be found in south-eastern Spain, the Italian Apennines and the Black Forest in Germany. Median potential rates in the EU27 equalled 14.5 $t\,ha^{-1}$ and 9.1 $t\,ha^{-1}$ from 1981–2010 for CNTRL and reduced climate variability respectively. These rates increase to 19.1 and 9.7 $t\,ha^{-1}$ in 2071–2100 for CNTRL and REDVAR respectively (Table 1). Erosion rates generally decrease over Europe with reduced climate variability (Fig. 1b). Note that transient CO_2 concentrations and trend changes in climate variables are equal for REDVAR and CNTRL, thus indicating that the relative impact due to variability increases in the future with median erosion rates lowered by 5.4 and 9.4 $t\,ha^{-1}$ due to reduced climate variability for 1981–2010 and 2071–2100, respectively.

Simulated biomass production ranges from about 5 to 17 $t\,ha^{-1}\,yr^{-1}$. The spatial pattern of biomass is very similar to the pattern of crop yields and reflects climatic suitability and inputs (data not shown). North-west Europe has the highest biomass production while it is lower in the Boreal regions, the Mediterranean area, and those countries where fertilizer input is lower (e.g. Bulgaria). Highest biomass production is simulated in the Atlantic region (median $\sim$ 15 $t\,ha^{-1}$); lowest values are obtained in the Boreal region (median $\sim$ 8 $t\,ha^{-1}$; see Table 1). Trend changes in climate are generally reducing biomass production (e.g. negative impacts from 1981–2010 to 2071–2100 for both CNTRL and REDVAR). The overall reduction is however lower with reduced climate variability (e.g. in the Atlantic region median reductions of 1.4 and 0.6 ton ha^{-1} in CNTRL and REDVAR simulation respectively; Table 1). Higher biomass production was calculated for REDVAR compared to CNTRL climate data for nearly the whole of Europe. This difference was amplified for the 2071–2100 period compared to the

BGD
11, 1561–1585, 2014

1981–2010 period. The highest increase (> 1.61 t ha^{-1} yr^{-1}) was predicted for the Atlantic region of Western Europe. These results indicate that higher inter/intra-annual variability and extreme events reduce wheat biomass production and will consequently reduce crop residue inputs into soils.

3.2 Impact of erosion

In the simulations without erosion differences in the topsoil organic carbon (SOC) are linearly related to the differences in the biomass input (BIOM, see Fig. 2a). Comparing the periods 1981–2010 with 2071–2100 indicates that both the absolute ranges and the within class variability of topsoil organic carbon are predicted to increase (Fig. 2a and b). Figure 2c and d shows the behaviour in the changes of SOC and BIOM when erosion is considered in the simulation runs with EPIC. When erosion is simulated, the relation between biomass and SOC changes. In contrast to Fig. 2a and b, Fig. 2c and d is not characterized by a linear relation, but now includes locations that are dominated by erosion processes. Increased erosion due to climate variability leads to a significant decrease in SOC stocks, comparing CNTRL with REDVAR simulations.

3.3 Impact on SOC

Resulting simulated soil organic carbon stocks in the topsoil ranges from below 20 to over 60 t ha^{-1} (data not shown). The largest SOC stocks generally occur in Northern Europe. The results indicate that increased variability in meteorological variables in CNTL reduced the SOC sequestration compared to REDVAR, especially in Atlantic and Continental regions. Carbon lost with sediment is a function of both the prevalent erosion rates and the local soil organic carbon stock. Loss of carbon with erosion is lower in the REDVAR compared to the CNTRL simulations in 1981–2010, but highest losses are associated with the 2071–2100 period for both simulations (data not shown). Potential erosion reduced the median SOC content from 55.5 (without erosion) to 25.7 and from 51.5 to 24.9 t ha^{-1} (or 54 and 60 %) in 1981–2010 and 2071–2100 respectively,

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

BGD

11, 1561–1585, 2014

Future climate variability impacts on potential erosion

M. van der Velde et al.

under the reference climate (45 and 53 % with reduced climate variability: see Table A2). Climate trend changes reduced the median European SOC by 20 % ($\sim$ 5.5 t ha^{-1}) with erosion and by 7 % ($\sim$ 3.9 t ha^{-1}) without erosion from 1981–2010 to 2071–2100. Expected climate variability reduced the median SOC by $\sim$ 20 % with erosion and by only $\sim$ 1.5 % without erosion; for both time periods, compared to the simulations with reduced climate variability (see Table A2).

The total amount of carbon lost from European cropland due to erosion under the CNTRL climate was estimated at 769 Tg C for the 1981–2010 period (from a total storage of 6197 Tg C without erosion). Climate trend impacts reduce the European cropland SOC stock by 578 Tg C without – and by 683 Tg C with – erosion from 1981 to 2100. Climate variability compounds these impacts and decreases the total European cropland SOC stock by an estimated 170 Tg without erosion and by 314 Tg C with erosion, by the end of the century.

3.4 Implications

Whether erosion regimes will change across European cropland depends on the spatial conjunction of expected changes in climate variability and physiographic conditions conducive to erosion. Figure 3 examines the impact of climate variability on SOC in the absence of erosion (Fig. 3a and c), and with the inclusion of erosion (Fig. 3b and d), for 1981–2010 and 2071–2100 and allows changes in SOC storage, due to erosion associated with expected climate variability, to be evaluated. Impact ratios of $[SOC_{REDVAR}]/[SOC_{CNTRL}]$ above 1 indicate areas with SOC loss due to climate variability.

4 Discussion

Absolute increases in erosion rates will be a function and spatial fingerprint of both the physiographic terrain characteristics (i.e. slope) and the expected and simulated occur-

BGD
11, 1561–1585, 2014

rence of climate variability and extreme events in that region. There are large regional contrasts related to topography (e.g. the Alps) as well as changing climatic conditions. Local within-basin contrasts exist. For instance, the Po basin in Italy is characterized by significantly higher erosion rates in the upper reaches of the basin under expected climate variability, compared to simulations with reduced variability, but with equal or lower erosion rates in the lower reaches of the basin. Changes in SOC that are already large due to climate variability alone will be amplified in certain areas, e.g. in France, while in other areas not strongly affected by climate variability impacts on SOC, e.g. Southern Germany and the Czech Republic, the impact of erosion will induce considerable SOC loss from the soil. Mountainous areas in regions where increases in climate variability will already lead to negative impacts on SOC through reductions in biomass production will experience an additional impact due to increased erosion rates.

Unravelling the spatial fingerprint and identifying the drivers that are locally the dominant factors in SOC cycling is not straightforward. Although climate variability generally leads to lower biomass production, intricate relations between the amount of precipitation and the occurrence of higher temperatures and their impact on crop production, as well as impacts on mineralization rates, in combination with higher erosion rates, lead to a variable picture at lower spatial scales. Soil erosion is related to topography, soil characteristics, vegetation cover, management practices etc., as well as to weather and its extremes such as droughts, heavy rainfall and storms or a combination of them. Soils are especially susceptible to erosion related to heavy rainfall or storms if vegetation cover is low, e.g. crop ecosystems at fallow stages. Climate change involves variably co-varying changes in rainfall and temperature characteristics. Biogeochemical processes driven by changes in precipitation amounts and intensities, number of days of precipitation, ratio of rain to snow, number of dry days, changes in minimum and maximum temperatures can simultaneously lead to increases in biomass production, accelerated mineralization rates, or greater erosion rates. Responses will differ depending on climate zone and local physiographic landscape characteristics. Even though the Mediterranean is already shaped by the strong seasonality of water avail-

BGD
11, 1561–1585, 2014

ability, our results indicate that changes in precipitation patterns with longer dry spells and more intensive precipitation events will lead to increased soil erosion, especially during periods with sparse vegetation cover. This will be further compounded by the high rates of land abandonment in the Mediterranean area (Weissteiner et al., 2011).

The possible ranges of autonomous adaptation actions taken by farmers and their impacts need to be characterized further. Even though co-benefits may occur, impacts on other ecosystem properties may also result from active interventions by farmers. For example, increased irrigation may lead to increased root biomass growth, higher microbial activity or increased erosion rates variably leading to increased or decreased SOC. Expected crop failure – for instance a corn crop affected by drought – can also lead a farmer to decide not to harvest the crop potentially leading to a larger incorporation of biomass in the soil. Quantifying which resulting effects will dominate in the agricultural system is a challenge that is dependent on location specific biophysical properties and social economic conditions.

Disturbance of the soil during an erosion event can enhance decomposition of organic matter and release of CO_2. However, the evaluation of the effect of erosion on the integrated carbon cycle needs to consider the fate of the eroded soil carbon. If this eroded carbon is not transformed to CO_2, but trapped in structures leading to longer residence times than in the original soil, soil erosion can also be a net sink (Van Oost et al., 2007). Hence the net effect of erosion on the carbon cycle is still controversial (Lal, 2009). In this manuscript we did not address the deposition of eroded material as routing is not included in EPIC. The use of hydrological models accounting for deposition and sedimentation may contribute in further quantifying the overall impact of increased climate variability on the net European carbon balance. Further analysis assessing the sensitivity of the soil organic carbon stored in arable systems to climate extremes should focus on both long-term and event-based impacts, as well as understanding the threshold impacts by the principle meteorological drivers.

BGD
11, 1561–1585, 2014

5 Conclusions

Erosion can be a dominant factor in carbon cycling of European cropland, especially in combination with expected changes in climate variability. The reduction in SOC due to erosion driven by increased climate variability can off-set regional gains in carbon stocks predicted to occur under gradual climate change alone (Gottschalk et al., 2012). Importantly, changes in SOC that are already large due to climate variability alone will be amplified in certain areas, and may induce considerable loss in areas that are otherwise not strongly affected by climate variability. The reduction in SOC due to erosion, driven by increased climate variability, may further impact carbon stocks in addition to impacts that will arise from gradual climate change alone. Soil protection policies in Europe can benefit from this new understanding.

Appendix A

Data and methods

Data sources: EU27 EPIC

We report in detail about the evaluation of our European EPIC implementation in Balkovič et al. (2013). The following data was used. Land cover information was taken from a combined CORINE 2000 and PELCOM map at 1 km resolution. Digital terrain information was derived from SRTM (Shuttle Radar Topographic Mission; Werner, 2001) and GTOPO sources (Global 30 Arc Second Elevation Data; http://eros.usgs.gov). Soil data were obtained from the European Soil Bureau Database (ESBD v. 2.0), including the Soil Geographic Database of Europe, the Soil Profile Analytical Database of Europe, the Pedo-Transfer Rules Database, the Database of Hydraulic Properties of European Soils (Wösten et al., 1999) and the Map of Organic Carbon Content in topsoils in Europe (Jones et al., 2005). Administrative regions were obtained from the Ge-

BGD
11, 1561–1585, 2014
Future climate variability impacts on potential erosion
M. van der Velde et al.

ographic Information System of the European Commission (GISCO) and watersheds from the European River Catchment Database, version 2 (ERC; provided by European Environment Agency, http://www.eea.europa.eu). Agricultural statistics on crop yields and fertilizer consumptions were retrieved from the Statistical Office of the European Communities (EUROSTAT, www.ec.europa.eu/eurostat).

EPIC model set-up

Six daily meteorological variables were used to run EPIC from 1901 until 2100: minimum and maximum temperature (°C), precipitation (mm), global radiation ($MJ\,m^{-2}$), relative humidity (fraction), and mean wind speed at 10 m ($m\,s^{-1}$). Each simulation unit (SimU) was attributed with a set of 13 soil properties, including soil organic carbon (%), sand, silt and clay (%), bulk density ($g\,cm^{-3}$), base saturation (%), cation exchange capacity and sum of base cations ($cmol_+\ kg^{-1}$), pH, stoniness (vol. %), saturated hydraulic conductivity ($mm\,h^{-1}$), and wilting point and field water capacity ($cm^3\,cm^{-3}$). All these variables are averages calculated from the ESDB separately for topsoil (0–30 cm) and subsoil (> 30 cm) horizons. Soil profiles were split into 10 vertical layers to appropriately address soil water and temperature regimes. The initial SOC value was calculated from the Map of Organic Carbon Content in topsoils in Europe. It was subsequently partitioned into the passive and slow humus pools with 50-years of cultivation prior to the final simulation. In addition, the SimU landforms were approximated with mode slopes and mean elevations obtained from SRTM/GTOPO.

Potential Heat Units (PHUs) were determined with the use of the PHU calculator developed at the Texas Blackland Research and Extension Center (BREC, 1990) using long-term minimum and maximum temperatures from the European Commission DG-JRC's Crop Growth Monitoring System (CGMS), optimum and minimum crop growth temperatures and the average number of days for the crops to reach maturity. For wheat, for instance, the length of vegetation period was set to 280, 300, 330, 290 and 265 days for Alpine, Atlantic, Boreal, Continental and Mediterranean regions, respectively. Sowing dates were estimated together with PHUs using the PHU calculator.

BGD
11, 1561–1585, 2014

Harvesting dates were then calculated by adding the time to maturity to the sowing date. Since harvesting dates are considered as the earliest possible dates of harvest, an automatic harvest was scheduled at 110 % of the calculated PHU to enable flexible harvesting based on annual heat unit accumulation and to take post-maturity drying of crops on the field into account.

Tillage operations were scheduled relative to the sowing and harvesting dates. These practices consisted of mouldboard ploughing and seed-bed preparation (field cultivator) three days prior to sowing and offset disking two days after harvesting. The mixing efficiency, which is the fraction of crop residue and nutrients that is mixed uniformly in the tillage depth, was 0.99, 0.30 and 0.75 for mouldboard ploughing, field cultivator and offside disking, respectively. The tillage depth was respectively 150 and 100 mm for ploughing and cultivators. The harvest efficiency was set to 95 %.

Phosphorus and potassium fertilizers were applied as rigid amounts together with tillage operation three days prior to sowing. N fertilization was triggered automatically until the annual N application rate was reached, allowing 20 % of plant N stress. The crop and regional specific annual N, P, and K application rates (kg ha^{-1}) were calculated by computing regional fertilizer balances at NUTS2 level. Fertilizer supply was calculated from NUTS2 livestock numbers and excretion coefficients as well as commercial fertilizer consumptions from EUROSTAT. Crop specific fertilizer demands at NUTS2 level were calculated using crop and forage yields and acreages from EUROSTAT as well as nutrient uptake coefficients (Balkovič et al., 2013).

Acknowledgements. This work emerged from the CARBO-Extreme project which was funded by the European Community's Seventh Framework Programme under grant agreement FP7-ENV-2008-1-226701.

BGD
11, 1561–1585, 2014

References

Balkovič, J., van der Velde, M., Schmid, E., Skalský, R., Khabarov, N., Obersteiner, M., Stürmer B., and Xiong, W.: Pan-European crop modelling with EPIC: implementation, up-scaling and regional crop yield validation, Agr. Syst., 120, 61–75, 2013.

Beer, C., Weber, U., Tomelleri, E., Carvalhais, N., Mahecha, M., and Reichstein, M.: Harmonized long-term climate data for assessing the effect of changing variability on land-atmosphere CO_2 fluxes, J. Climate, in review, 2014.

Brantley, S. L., Goldhaber, M. B., and Ragnarsdóttir, K. V.: Crossing disciplines and scales to understand the critical zone, Elements, 3, 307–314, 2007.

BREC: Blackland Research and Extension Centre, Potential Heat Units Program, available at: http://swatmodel.tamu.edu/, 1990.

Ciais, P., Gervois, S., Vuichard, N., Piao, S. L., and Viovy, N.: Effects of land use change and management on the European cropland carbon balance, Glob. Change Biol., 17, 320–338, 2011.

Fischer, E. M. and Schär, C.: Consistent geographical patterns of changes in high-impact European heatwaves, Nat. Geosci., 3, 398–403, 2010.

Frank, D., Reichstein, M., Bahn, M., Babst, F., Beer, C., Buchmann, N., Canadell, J., Ciais, P., Cramer, W., Frank, D., Ibrom, A., Mahecha, M., Miglietta, F., Poulter, B., Rammig, A., Seneviratne, S., Smith, P., Thonicke, K., Van der Velde, M., Vicca, S., Walz, A., Wattenbach, M., Zscheischler, J. and Zavala, M.: Effects of climate extremes on the terrestrial carbon cycle: concepts, observations and global implications, Glob. Change Biol., in review, 2014.

Gottschalk, P., Smith, J.U., Wattenbach, M., Bellarby, J., Stehfest, E., Arnell, N., Osborn, T. J., Jones, C., and Smith, P.: How will organic carbon stocks in mineral soils evolve under future climate? Global projections using RothC for a range of climate change scenarios, Biogeosciences, 9, 3151–3171, doi:10.5194/bg-9-3151-2012, 2012.

Jones, R. J. A., Hiederer, R., Rusco, E., and Montanarella, L.: Estimating organic carbon in the soils of Europe for policy support, Eur. J. Soil Sci., 56, 655–671, 2005.

Lal, R.: Challenges and opportunities in soil organic matter research, Eur. J. Soil Sci., 60, 158–169, 2009.

Lal, R. and Pimentel, D.: Soil erosion: a carbon sink or source?, Science, 319, 1040–1042, 2008.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J.-F., Matsumoto, K., Montzka, S. A., Raper, S. C. B., Riahi, K., Thomson, A., Velders, G. J. M., and van Vuuren, D. P. P.: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300, Climatic Change, 109, 213–241, 2011.

Nearing, M. A., Pruski, F. F., and O'Neal, M. R.: Expected climate change impacts on soil erosion rates: a review, J. Soil Water Conserv., 59, 43–50, 2004.

Van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C., McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., Da Silva, J. R., and Merckx, R.: The impact of agricultural soil erosion on the global carbon cycle, Science, 318, 626–629, 2007.

Oygarden, L.: Rill and gully development during an extreme winter runoff event in Norway, Catena, 50, 217–242, 2003.

Piani, C., Weedon, G., Best, M., Gomes, S. M, Viterbo, P., Hagemann, S., and Haerter, J.: Statistical bias correction of global simulated daily precipitation and temperature for the application of hydrological models, J. Hydrol., 395, 199–215, 2010.

Pimentel, D. and Kounang, N.: Ecology of soil erosion in ecosystems, Ecosystems, 1, 416–426, 1998.

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D. C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A., and Wattenbach, M.: Climate extremes and the carbon cycle, Nature, 500, 287–295, 2013.

Thothong, W., Huon, S., Janeau, J.-L., Boonsaner, A., de Rouw, A., Planchon, O., Bardoux, G., and Parkpian, P.: Impact of land use change and rainfall on sediment and carbon accumulation in a water reservoir of North Thailand, Agr. Ecosyst. Environ., 140, 521–533, 2011.

Van der Velde, M., Tubiello, F. N., Vrieling, A., and Bouraoui, F.: Impacts of extreme weather on wheat and maize in France: evaluating regional crop simulations against observed data, Climatic Change, 113, 751–765, 2012.

Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J., and Smith, C. J.: Tolerable versus actual soil erosion rates in Europe, Earth-Sci. Rev., 94, 23–38, 2009.

Weissteiner, C. J., Boschetti, M., Böttcher, K., Carrara, P., Bordogna, G., and Brivio, P. A.: Spatial explicit assessment of rural land abandonment in the Mediterranean area, Global Planet. Change, 79, 20–36, 2011.

BGD

11, 1561–1585, 2014

Werner, M.: Shuttle Radar Topography Mission (SRTM) mission overview, J. Telecommun. Network., 55, 75–79, 2001.
Wilkinson, B. H. and McElroy, B. J.: The impact of humans on continental erosion and sedimentation, Geol. Soc. Am. Bull., 119, 140–156, 2007.
Williams, J. R., Jones, C. A., Kiniry, J. R., and Spanel, D. A.: The EPIC crop growth model, T. ASABE, 32, 497–511, 1989.
Wösten, J. H., Lilly, A., Nemes, A., and Le Bas, C.: Development and use of a database of hydraulic properties of European soils, Geoderma, 90, 169–85, 1999.

BGD
11, 1561–1585, 2014

Table 1. Median biomass (BIOM, $t\,ha^{-1}\,yr^{-1}$) production, potential erosion rates (MUSLE; $t\,ha^{-1}\,yr^{-1}$) and SOC ($t\,ha^{-1}$) under control (CNTRL) and reduced (REDVAR) climate variability for simulations with and without erosion for 1981–2010 and 2071–2100.

climate	CNTRL	REDVAR	CNTRL	REDVAR	CNTRL	REDVAR	CNTRL	REDVAR
time	1981–2010	1981–2010	1981–2010	1981–2010	2071–2100	2071–2100	2071–2100	2071–2100
erosion	w	w	w/o	w/o	w	w	w/o	w/o
Median	**BIOM**	**BIOM**	**BIOM**	**BIOM**	**BIOM**	**BIOM**	**BIOM**	**BIOM**
Alpine	10.58	10.56	12.39	12.47	10.50	10.71	12.16	12.41
Atlantic	16.55	17.34	17.75	18.32	15.17	16.77	16.73	17.88
Boreal	8.03	8.05	8.43	8.50	7.47	7.70	7.52	7.70
Continental	10.74	10.83	12.18	12.18	10.45	10.91	11.91	12.20
Mediterranean	9.05	9.51	10.08	10.34	8.69	8.99	9.69	9.89
EU27	10.50	10.73	11.68	11.81	10.01	10.47	11.09	11.41
Median	**SOC**	**SOC**	**SOC**	**SOC**	**SOC**	**SOC**	**SOC**	**SOC**
Alpine	15.61	16.46	64.51	65.07	16.92	17.56	58.88	59.79
Atlantic	39.25	44.68	62.61	63.48	32.54	39.04	59.30	61.28
Boreal	85.56	88.53	101.62	102.02	70.19	73.52	89.94	90.64
Continental	29.13	35.00	63.88	64.56	21.27	26.40	58.74	59.78
Mediterranean	15.01	20.54	38.91	39.44	15.05	17.48	36.50	37.21
EU27	25.74	30.67	55.54	56.18	20.47	24.89	51.46	52.41
Median	**MUSL**	**MUSL**			**MUSL**	**MUSL**		
Alpine	158.88	130.84			178.79	142.90		
Atlantic	7.72	5.07			10.67	7.58		
Boreal	1.65	1.39			1.20	0.65		
Continental	14.35	9.57			19.21	9.87		
Mediterranean	37.42	16.02			42.55	19.10		
EU27	14.49	9.13			19.14	9.74		

BGD
11, 1561–1585, 2014

Table A1. Year-to-year comparison of simulated and reported annual crop yields and statistical model performance measures. *m* signfies number of NUTS2 regions used in the comparison, two-tailed pair *t* test and *F* test.

Year	*m*	simulated mean	simulated SD	reported mean	reported SD	test *t*	test *F*	Slope	R^2
1997	169	4.29	2.04	4.49	2.18	a	ns	0.79	0.71
1998	169	4.09	1.67	4.67	2.18	b	b	0.63	0.69
1999	202	4.45	2.00	5.01	2.41	b	b	0.74	0.79
2000	172	3.85	1.95	4.56	2.31	b	a	0.73	0.75
2001	171	4.13	1.99	4.49	2.17	b	ns	0.94	0.73
2002	170	3.95	1.90	4.63	2.19	b	ns	0.76	0.77
2003	199	4.07	1.87	4.58	2.33	b	b	0.72	0.81
2004	157	4.29	1.87	5.37	2.34	b	b	0.66	0.68
2005	135	4.00	2.06	4.81	2.34	b	ns	0.78	0.78
2006	143	4.00	1.84	4.75	2.16	b	ns	0.73	0.73
2007	129	4.17	2.04	4.61	1.98	b	ns	0.83	0.64

ns – not significant, [a] significant at $P < 0.05$, [b] significant at $P < 0.01$); all R^2 were significant at $P < 0.01$

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

BGD

11, 1561–1585, 2014

Future climate variability impacts on potential erosion

M. van der Velde et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◂◂ ▸▸
◂ ▸
Back Close
Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Table A2. Reductions in median soil organic carbon (SOC) storage in European cropland (% and $t\,ha^{-1}$) for combinations of simulations to calculate the impact of erosion, climate trend changes and climate variability on SOC storage (T1 = 1981–2010, T2 = 2071–2100, w = with erosion and w/o = without erosion).

	EU27 SOC reductions (%; $t\,ha^{-1}$) reference climate variability		reduced climate variability	
Impact of erosion	CNTRL(T1-w/o)-CNTRL(T1-w) −53.7 (29.8)	CNTRL(T2-w/o)-CNTRL(T2-w) −60.2 (31.0)	REDVAR(T2-w/o)-REDVAR(T2-w) −45.4 (25.5)	REDVAR(T2-w/o)-REDVAR(T2-w) −52.5 (27.5)
	with erosion		without erosion	
Impact of climate trend	CNTRL (T2-T1) −20.5 (5.3)	REDVAR (T2-T1) −18.8 (5.8)	CNTRL (T2-T1) −7.3 (4.1)	REDVAR (T2-T1) −6.7 (3.8)
Impact of climate variability	CNTRL (T1)-REDVAR (T1) −19.2 (4.9)	CNTRL (T2)-REDVAR (T2) −21.6 (4.4)	CNTRL (T1)-REDVAR (T1) −1.2 (0.64)	CNTRL (T2)-REDVAR (T2) −1.8 (0.95)

BGD
11, 1561–1585, 2014

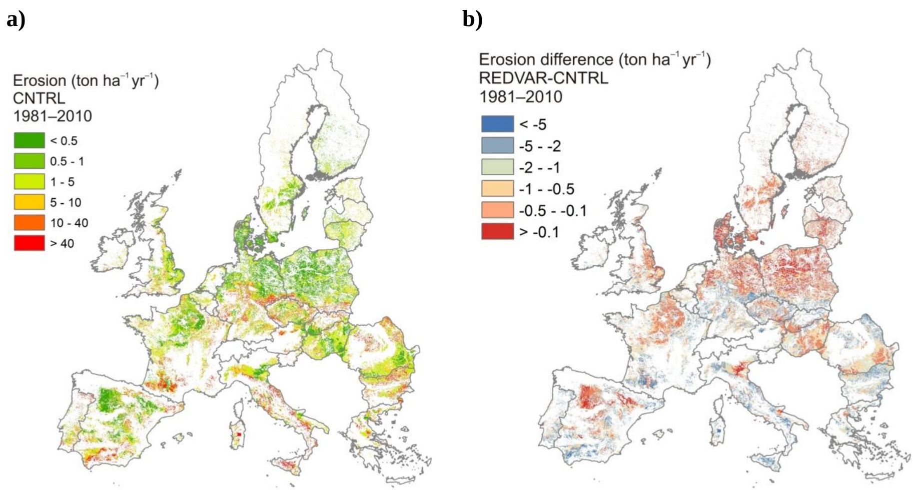

Fig. 1. Simulated erosion under reference CNTRL climate for 1981–2010 **(a)** and differences between erosion simulated with reduced climate variability (REDVAR) minus the simulation results of CNTRL climate data for 1981–2010; positive numbers (red colours) indicate higher erosion rates under CNTRL climate **(b)**.

BGD
11, 1561–1585, 2014

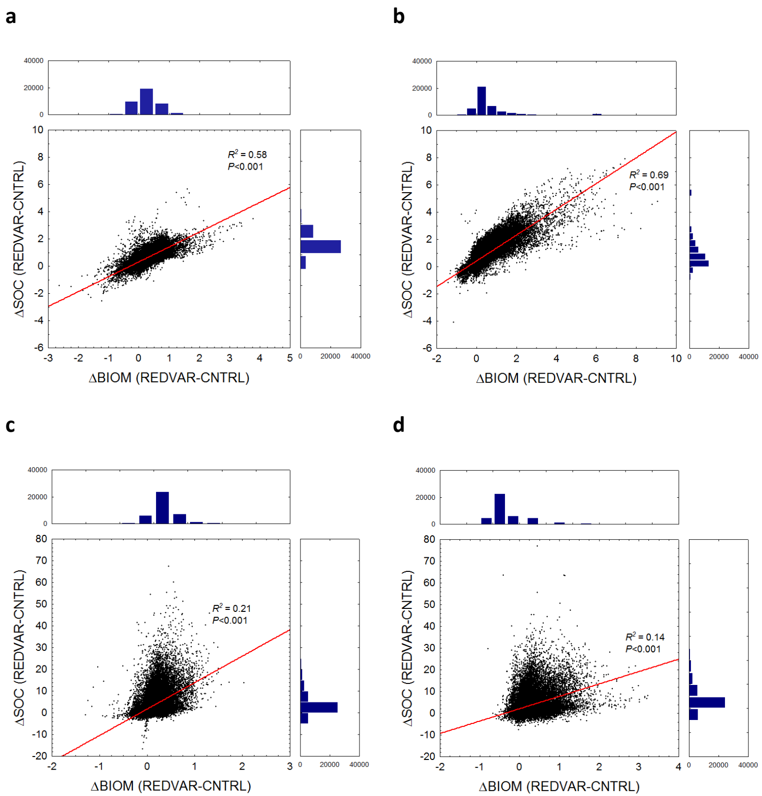

Fig. 2. Scatterplot of the differences between REDVAR and CNTRL biomass ($t\,ha^{-1}$) and soil organic carbon (SOC, $t\,ha^{-1}$) for **(a)** no erosion in 1981–2010, **(b)** no erosion in 2071–2100, **(c)** with erosion in 1981–2010, and **(d)** with erosion in 2071–2100 (red line describes regression). Histrograms indicate the distribution of the values of the variable along the corresponding axis.

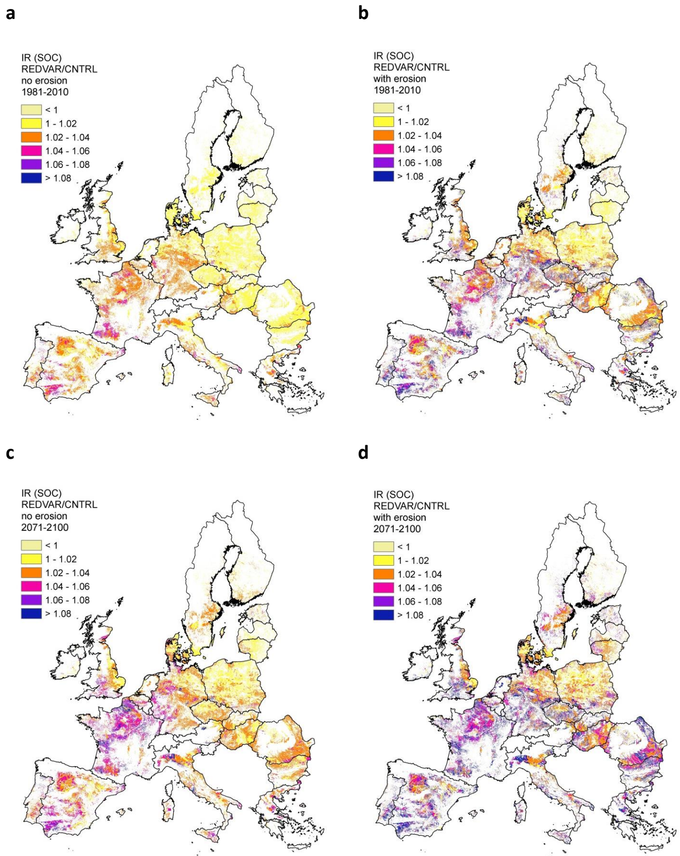

Fig. 3. Simulated impact ratio of reduced climate variability on SOC ($[SOC_{REDVAR}]/[SOC_{CNTRL}]$) **(a)** without and **(b)** with erosion for 1981–2010, and **(c)** without and **(d)** with erosion for 2071–2100.

BGD
11, 1561–1585, 2014