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Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices

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Abstract

Bottom–up estimates from long-term field experiments and modelling are the most commonly used approaches to estimate the carbon (C) sequestration potential of the agricultural sector. However, when data are required at European level, important margins of uncertainty still exist due to the representativeness of local data at large scale or different assumptions and information utilized for running models. In this context, a pan-European (EU + Serbia, Bosnia and Herzegovina, Montenegro, Albania, Former Yugoslav Republic of Macedonia and Norway) simulation platform with high spatial resolution and harmonized data sets was developed to provide consistent scenarios in support of possible carbon sequestration policies. Using the CENTURY agroecosystem model, six alternative management practices (AMP) scenarios were assessed as alternatives to the business as usual situation (BAU). These consisted of the conversion of arable land to grassland (and vice versa), straw incorporation, reduced tillage, straw incorporation combined with reduced tillage, ley cropping system and cover crops. The conversion into grassland showed the highest soil organic carbon (SOC) sequestration rates, ranging between 0.4 and 0.8 t C ha^{-1} yr^{-1}, while the opposite extreme scenario (100% of grassland conversion into arable) gave cumulated losses of up to 2 Gt of C by 2100. Among the other practices, ley cropping systems and cover crops gave better performances than straw incorporation and reduced tillage. The allocation of 12 to 28% of the European arable land to different AMP combinations resulted in a potential SOC sequestration of 101–336 Mt CO$_2$ eq. by 2020 and 549-2141 Mt CO$_2$ eq. by 2100. Modelled carbon sequestration rates compared with values from an *ad hoc* meta-analysis confirmed the robustness of these estimates.

Keywords: agricultural management, carbon sequestration, climate change, Europe, GHGs mitigation, land-use change, modelling

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Introduction

Globally, soils are the largest carbon terrestrial ecosystem sink or source of atmospheric CO$_2$ depending on land use and management practices (Houghton, 1999; Guo & Gifford, 2002). Lal (2004) estimated that the carbon sink capacity of the world's agricultural and degraded soils is 50 to 66% of the historical carbon loss of 42 to 78 Gt of carbon. At European level, several long-term soil monitoring networks have reported soil organic carbon (SOC) decreases (Bellamy *et al.*, 2005; Goidts & van Wesemael, 2007; Capriel, 2013; Heikkinen *et al.*, 2013), even if contrasting trends are evident in the past decades (Chapman *et al.*, 2013; Reynolds *et al.*, 2013). Weak SOC trends are likely to mask the intrinsic variability in SOC detection, especially as soils under cropland show currently a carbon balance close to a steady-state condition in Europe (Ciais *et al.*, 2010).

On the other side, direct greenhouse gas (GHG) emissions from the agricultural sector of the European Union (EU) are responsible for around 465 Mt CO$_2$ eq. yr^{-1}, around 9% of total emissions (EEA, 2013). Agricultural management is certainly a suitable and cost-effective way to mitigate GHG emissions compared to other technologies, with additional benefit for soil quality and food security (Lal, 2004). Long-term field experiments have demonstrated the possibility to sequester large amount of carbon in soils by adopting best management practices such as residue management, reduced tillage, optimized rotation schemes, etc. (Freibauer *et al.*, 2004). Smith (2012)reported a carbon sequestration potential of 200 Mt CO$_2$ eq. yr^{-1} using various practices, but an economic potential (i.e. the potential that could be realized at a given carbon price)

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of 20 Mt CO_2 eq. yr^{-1} in the EU27. Given that SOC may play a role in mitigating GHG emissions and in delivering major soil ecosystem services and functions (Ogle & Paustian, 2005), policymakers are increasingly focusing their attention on measures for SOC conservation. For instance, the decline in SOC is recognized as one of the eight soil threats that were identified in the European Union's Thematic Strategy for Soil Protection (EC, 2006, 2012). One of the key goals of the strategy is to maintain and enhance SOC levels.

In line with the Kyoto Protocol, the EU is committed to cut its emissions to 20% below of the 1990 levels by 2020, or to 30% if other major emitting countries commit to undertake their fair share of a global emissions reduction effort (EC, 2010). In addition, EU leaders have endorsed the more ambitious objective of reducing GHG emissions of 80% by 2050 compared to 1990 level.

Under this framework, the agricultural sector may provide a consistent contribution through carbon sequestration in soils although, currently, the land use, land-use change (LULUCF) sector is not part of the EU climate and energy package (EC, 2010), so called '20-20-20' target. The integration of LULUCF in the EU climate policy framework is currently going on through: 1) the harmonization of the LULUCF carbon accounting approaches across the Member States and 2) the possibility of including the mandatory reporting on cropland and grazing land management in the EU framework. These actions were adopted by the European Parliament and the European Council in May 2013 (EC, 2013).

In parallel, one of the main components in EU Common Agricultural Policy (CAP) for the 2014–2020 is the Good Agricultural and Environmental Condition (GAEC) standards. Through the GAEC scheme, soil erosion protection, soil structure maintenance and soil organic matter levels are recognized as minimum requirements to achieve a good condition of agricultural land (EC, 2009).

While there are considerable amounts of experimental data, soil inventories and SOC modelling at field-scale or regional level, consistent figures at European level are still scarce (Jandl *et al.*, 2014). At the same time, there is an urgent need for the development and implementation of higher tier methodologies that can be applied at fine spatial scales (Smith, 2012). Very recently, a high resolution platform of simulation was developed to simulate the agricultural SOC stock at pan-European level (Lugato *et al.*, 2014). This tool showed a good agreement between measured and simulated values, with uncertainty frequently less than 40% for specific administrative levels (i.e. NUTS2 regions).

Using this comprehensive pan-European modelling platform, this paper aimed to assess the impact of a number of alternative management practices (AMP) on SOC stock levels on arable soils namely, arable to grassland conversion (and vice versa), straw incorporation, reduced tillage, straw incorporation with reduced tillage, ley cropping system and cover crops. The platform coupled the CENTURY agroecosystem model with a series of pan-European harmonized data sets. The six AMP were projected to 2100 using two IPCC climate change scenarios. The goals of this work were to: (i) provide technical potential and realistic and highly disaggregated carbon sequestration rates at pan-European level; (ii) show the potentiality of the modelling tool for carbon accounting under a LULUCF framework; (iii) highlight the management practices which contributed to an increase in the SOC stocks of European arable land.

Material and methods

Model and input data set

This work is based on a recently developed pan-European simulation platform (Lugato *et al.*, 2014) (see Appendix S1 for the territorial definition). The simulation platform is built by integrating the well-known CENTURY agroecosystem model (Parton *et al.*, 1988) with several pan-European spatial and statistical databases.

CENTURY is a process-based model designed to simulate carbon (C), Nitrogen (N), Phosphorous (P) and Sulphur (S) dynamics in natural or cultivated systems, using a monthly time step (Parton *et al.*, 1988; Shaffer *et al.*, 2001). The soil organic matter submodel includes three SOC pools, namely active, slow and passive, along with two fresh residue pools, structural and metabolic, each with a different turnover rate. Soil temperature and moisture, soil texture and cultivation practices have different effects on these rates. The model is also able to simulate the water balance, using a weekly time step, while a suite of simple plant growth models are included to simulate C, N, P and S dynamics of crops, grasses and trees. For this study, the model was run with the coupled C-N submodels.

A full description of the input data management, model structure and initialization, as well as the model performance and uncertainty can be found in Lugato *et al.* (2014). In summary, soil data used by the model were derived from the European Soil Database (ESDB) (King *et al.*, 1994) available at the European Soil Data Centre (ESDAC-http://eusoils.jrc.ec.europa.eu/library/esdac/esdac_access2.cfm) (Panagos *et al.*, 2012). The properties considered for the topsoil layer (0–30 cm) included texture, bulk density, pH, drainage class and rock content. Although CENTURY has a simple water bucket model, the hydraulic properties (field capacity and wilting point) were estimated using a pedotransfer rule (Rawls *et al.*, 1982). These two parameters were corrected for the presence of rock according to the factor: [1-(Rv/100)], where Rv is the rock fragment content by volume. Data on soil depth or the presence of an impediment layer were derived from the ESDB and used to define the bottom boundary layer.

Climate data were taken from a 10′ × 10′ cell data set provided by the Climate Research Unit, University of East Anglia, UK (http://www.cru.uea.ac.uk/cru/data/hrg/) (Mitchell *et al.*, 2004). Monthly values were provided for the period 1900–2000, based on interpolated observed data. For the period 2000–2100, values were obtained from four different Global Climate Models (GCM) forced by four Intergovernmental Panel on Climate Change (IPCC) CO_2 emissions scenarios, as reported in the Special Report on Emissions Scenarios (SRES) (Nakicenovic *et al.*, 2000). For this study, two contrasting scenarios, HadCM3-A1FI ('world markets-fossil fuel intensive') and PCM-B1 ('global sustainability'), were selected as they encompass a wide range of climatic variations, the former more extreme and the latter more conservative (Figure S1). The CENTURY model can simulate the effects of increasing atmospheric CO_2 concentration (Parton *et al.*, 1988) by considering: (i) the increase in Net Primary Productivity (NPP) with a different response for C3 and C4 plant species; (ii) transpiration reduction in relation to a decrease in stomatal conductance and (iii) the C/N and shoot/root ratio change in grasses and crops. A linear growth rate in CO_2 concentration to reach 954 ppmv for the A1FI scenario and 540 ppmv for the B1 scenario was assumed for 2100 (Nakicenovic *et al.*, 2000).

Soil and climate layers were overlaid to identify homogenous soil–climate territorial units. The spatial extension of agricultural land use was derived from the Corine Land Cover (CLC) 2000–2006 databases (http://www.eea.europa.eu/publications/COR0-landcover). Then, each homogenous soil–climate unit previously identified was overlaid with the land cover data (CLC) and the area (ha) for the specific categories (arable, rice, vineyard, olive, orchard, pasture and complex systems) was calculated within each territorial unit.

Crop distributions within the arable class were calculated according to the statistics from the EU Statistical Office (EUROSTAT) on crop production area for NUTS2 regions – http://epp.eurostat.ec.europa.eu/portal/page/portal/agri_environmental_indicators/data/database). When building the crop rotations, space was substituted by time, hypothesizing a 4-year rotation in which each crop occupies 25% of the time (equivalent to 25% of the space). Each crop of the 4-year rotation was then allocated according to the 'relative' distribution data from the EUROSTAT statistics, adopting some approximation rules based on the proximity to the class limit. The schedules files for 18 arable or fodder crops (barley, wheat, maize grain, silage maize, soybean, sugar beet, sunflower, tobacco, ryegrass, alfalfa, rice, pulses, oilseed, rape, cotton, potato, tobacco, rice) were created. Management practices, including fertilization, tillage and irrigation, were implemented specifically for each crop, gathering information from several databases (see Lugato *et al.*, 2014 for a detailed explanation).

Model spin-up and alternative management practices (AMP) for SOC sequestration

The CENTURY model was spin-up through a series of management sequences encompassing the main agricultural technological stages of the last 2000 years, until the actual management representing the business as usual scenario (BAU) (Table 1). Some basic assumptions were necessary due to the impossibility to reconstruct past land use for such a broad territory. In particular, the main assumption was that the areas cultivated at present, being the most fertile, were likely to have been continuously cultivated (Lugato *et al.*, 2014). The first equilibrium sequence (Equil.1), spanning 1700 years, was characterized by a typical 3-year rotation with wheat-oats and a fallow period called 'maggese', that was undertaken to recover soil fertility ('maggese' derives the Latin '*maius*', May, the month the fallow field was tilled). This agricultural system was practised by farmers across Europe until the introduction of the 4-year rotation that was developed in Holland and introduced into Great Britain in the mid-1700s. This second equilibrium (Equil. 2) was characterized by the presence of a N-fixing crop (clover) and by equal amount of the rotation surface dedicated to livestock feeding (fodder crops) and food crops (mostly cereals). The R1 sequence consisted of the actual land use in each territorial unit, with some modifications related to input intensity (fertilization, tillage, etc.), including lower crop yields and higher presence of fodder crop in the rotation (Table 1). The R2 sequence was based on current management and land use/crop distribution. The evolution of crop productivity and harvest index in the last century was based on previous experience of model application in long-term experiments (Lugato *et al.*, 2007). Besides site-specific parameters, all the run time coefficients were left unchanged.

Table 1 Spin-up sequences simulated in each territorial unit

	Equilibrium 1	Equilibrium 2	R1	R2
Time	1700 years	300 years	1901–1960	1961–2010
Land use	3 years (W-O-F) + pasture	4 years (B-C-W-M) + pasture	Actual with more fodder crops in arable	Actual
Fertilization	Org	Org	Org + low Min	Org + Min
Tillage intensity	Low	Low	Moderate	Intensive
Irrigation	No	No	Yes	Yes

W-O-F = Low yield wheat-oat -fallow ('maggese') rotation typical of roman and middle-age agriculture.
B-C-W-M = Low yield barley-clover-wheat-meadow rotation introduced in XVII-XVIII century.
Org = Organic fertilization; Min = mineral fertilization.

The BAU conditions were projected on the basis of two climatic scenarios from 2013 until 2100, as well as the following common and feasible management practices (AMP) for carbon sequestration.

Conversion from arable to grassland (AR_GR_LUC)

This land-use change scenario hypothesized the conversion of the area currently under arable production to grassland. The term permanent grassland reflects a complex land use where grazing, hay making or mixed management practices are often applied. Due to the lack of databases defining local management, simplified management conditions were proposed that attempted to mimic the carbon balance that is likely to occur. In particular, the above ground biomass was removed to simulate three cutting events (May, July and September), while carbon restitution was implemented from manure application maintaining the actual rate of organic fertilization. No changes were made for animal livestock density.

The opposite scenario, simulating the conversion of grassland to arable (GR_AR_LUC), was also run.

Crop residue management (AR_RES)

In the BAU scenario, 50% of cereal straw is considered as being removed from the field (except for silage and grain maize in which above ground biomass and only grain were removed respectively). The alternative scenario was run considering the incorporation of all cereal straw.

Reduced tillage (AR_RT)

In the BAU scenario, the most common management practice is to apply a main tillage (mouldboard plough) after the crop harvest (generally between September and November) followed by a secondary and more superficial tillage before planting (depending on crop type). A reduced tillage scenario was based on the substitution of the mouldboard plough with a more superficial tillage that is modelled by the higher distribution of litter in the surface SOC pools and by the reduction in decomposition coefficient (i.e. 37% less than mouldboard) controlling SOC turnover.

In addition to the effect on SOC decomposition, the reduced tillage may influence SOC change by varying carbon inputs, as a consequence of different crop productivity with respect to the conventional management. However, as CENTURY showed a low sensitivity of crop yield response due to reduced tillage application, the potential yield parameters were decreased according to the results of two reviews on the effect of tillage on crop production in Europe (van den Putte *et al.*, 2010; Soane *et al.*, 2013):

- Maize potential productivity was decreased by 10% all over the Europe;
- Winter cereal (wheat and barley) potential yield was decreased by 5% in the area above 55°N latitude.

An additional scenario (AR_RET) combining the previous 100% straw incorporation and reduced tillage was also run.

Ley in rotation (AR_LEY)

The crop rotation system in BAU arable land use was designed as succession of marketable crops, according to their relative area distribution. The alternative scenario simulated a ley farming system by the inclusion of two consecutive years of a fodder crop in the BAU rotation. Specifically, alfalfa was incorporated in the simulation due to its ubiquity and its positive effect in enriching the soil N content. The alfalfa crop was cut four times per year and the biomass exported from field.

Cover crops (AR_CC)

As in the previous example, this alternative scenario simulated the insertion of cover crops in the rotation scheme, where the eventual biomass was totally incorporated into the soil before the successive main crop (e.g., green manure). In particular, two cover crop type categories were simulated:

- Mix grass (i.e. gramionid + clover) following winter cereals;
- Rye grass preceding spring–summer crops (i.e. maize).

Technical and realistic SOC sequestration potential

To understand the sink capacity of a soil and its persistence, AMP were simulated from 2013 until 2100 and SOC stock changes were evaluated as a difference with respect to BAU projections at the same time frame (2020, 2050, 2080 and 2100). In this context, carbon sequestration is defined as the change in SOC stock related to human-induced activity such as the agricultural management (UNFCCC, 2014). Each AMP was run hypothesizing the full conversion of the arable land (112.75 Mha for 76 200 SCL combinations), hence providing the biophysical potential SOC sequestration, hereafter called 'technical' potential in agreement with Smith (2012). Indeed, intermediate effects related to a lower allocation of each AMP (ha_AMP) could be obtained by a linear rescale with the total area (i.e. ha_AMP/total arable area).

Furthermore, to give a more realistic estimation of the role of the agricultural sector in offsetting GHG emissions, some combinations of AMP (Table 2) were proposed as potential policy oriented scenarios. The three scenarios have a different degree of economic and environmental focus. The first scenario S1 (more economical oriented) was characterized by the equal conversion of 12% of arable land to the six alternative practices. The S2 scenario involved 24% of arable land with differing proportions of AMP while in the third scenario S3 (the more environmental oriented) the land-use change 'cropland to grassland' was increased (10%) as well as the total arable land targeted for carbon sequestration (28%). The allocation of AMP was equally distributed among all the arable land (i.e. no geographical variation in the different AMP was simulated), as a preliminary analysis to understand the

Table 2 Proportion (%) of arable land area allocated to three combinations of alternative management practices under potential policymaker-oriented scenarios

Scenario	AR__GR_LUC	AR_RES	AR_RT	AR_RET	AR_LEY	AR_CC	Total
S1	2	2	2	2	2	2	12
S2	5	5	5	5	2	2	24
S3	10	2	2	2	5	7	28

magnitude of emissions that can be offset by carbon sequestration practices in agriculture.

Modelled and measured C sequestration rates comparison

A meta-analysis was performed to understand the model accuracy in simulating the above mentioned AMP. In particular, experimental rates of carbon sequestration were derived from long-term experiments (LTE) exclusively within the area under simulation. Only treatments comparable to the simulated AMP were taken into consideration (details of selected treatments are given in the Table S1). It should be noted that this is a very explorative exercise as experimental managements are highly site specific and treatments may vary significantly compared to the simulation of specific AMP at pan-European level.

Results

Technical SOC sequestration potential

The change in land use from arable to grassland (AR_GR_LUC) showed the highest technical carbon sequestration potential (Figs 1 and 2) with respect to all the others simulated AMP. Territorially, lower SOC gains (<20 t C ha^{-1}) by 2050 were predicted in the Mediterranean and Eastern Europe compared to north-western regions. The agroecosystems under conversion did not reach a steady-state SOC level at the end of the century, as showed by the cumulated sequestration trend (Fig. 2). Median annual rates of sequestration were higher than 0.6 t C ha^{-1} yr^{-1} in the short term (2020), decreasing only slightly thereafter (Fig. 3). Conversely, the conversion of grassland to arable (GR_AR_LUC) resulted in rapid SOC losses until 2050 (almost up to 2 Gt C) and a new stable situation thereafter (Fig. 2). Although two contrasting climatic scenarios were used (Figure S1), the effect of climate variability on SOC changes was very small.

The cereal straw incorporation scenario (AR_RES) depicted a marked regional variability in SOC changes (Fig. 1), related to both pedo-climatic conditions and availability of crop residues. The United Kingdom, northern France and Germany showed the highest technical potential as well as some Mediterranean regions where durum wheat and barley are regularly cultivated. The technical sequestration potential was below 0.5 Gt by 2100 (Fig. 2), with higher SOC accumulation following this AMP introduction (median values of 0.1 and 0.04 t C ha^{-1} yr^{-1} by 2020 and 2050 respectively) (Fig. 3).

Soil Organic Carbon changes under the reduced tillage (AR_RT) scenario were uniformly distributed and ranged from 1 to 5 t C ha^{-1} by 2050 (Fig. 1). The maximum pan-European sequestration potential was similar to that of the AR_RES scenario (Fig. 2), but with a slightly rapid dynamic as evident also by the annual sequestration rates (Fig. 3).

From a modelling perspective, the combination of reduced tillage and straw incorporation (AR_RET) across Europe was predicted to accumulate more than 0.5 Gt of C by 2050 (Fig. 2). At that time frame, SOC gains higher than 5 t C ha^{-1} were simulated both in the north and south of Europe (Fig. 1), while a lower effect was registered in Portugal, northern Italy and eastern regions. The annual sequestration rates were the highest among all other AMP simulated (excluding AR_GR_LUC) (Fig. 3), especially by 2020 when the 1st and 3rd interquartile values ranged between 0.16 and 0.31 t C ha^{-1} yr^{-1}.

The simulation of ley crops presence within the cash rotation (AR_LEY) lead to a constant SOC accumulation until 2050 (Fig. 2), which remained constant at around 0.5 Gt of C thereafter. Geographically, SOC changes were rather evenly distributed with some regions with lower carbon accumulation in central Spain and Poland (Fig. 1). Median rates of SOC sequestrated annually were 0.17 and 0.11 t C ha^{-1} yr^{-1} by 2020 and 2050 respectively (Fig. 3).

The cover crop scenario (AR_CC) had a similar sequestration potential magnitude as the AR_LEY, but with much higher variability related to climate change (Fig. 2). In particular, SOC trends under the more extreme scenario HadCM3-A1FI (thin dotted line) decreased slightly after 2050, while soils continued to accumulate carbon under the PCM-B1 (thick dotted line). SOC changes below 2 t C ha^{-1} by 2050 were detected in some Mediterranean regions (Fig. 1) (particularly in Spain) and in the sandy soils of northern Europe. The annual sequestration rates were comparable to that of AR_RET and AR_LEY (Fig. 3).

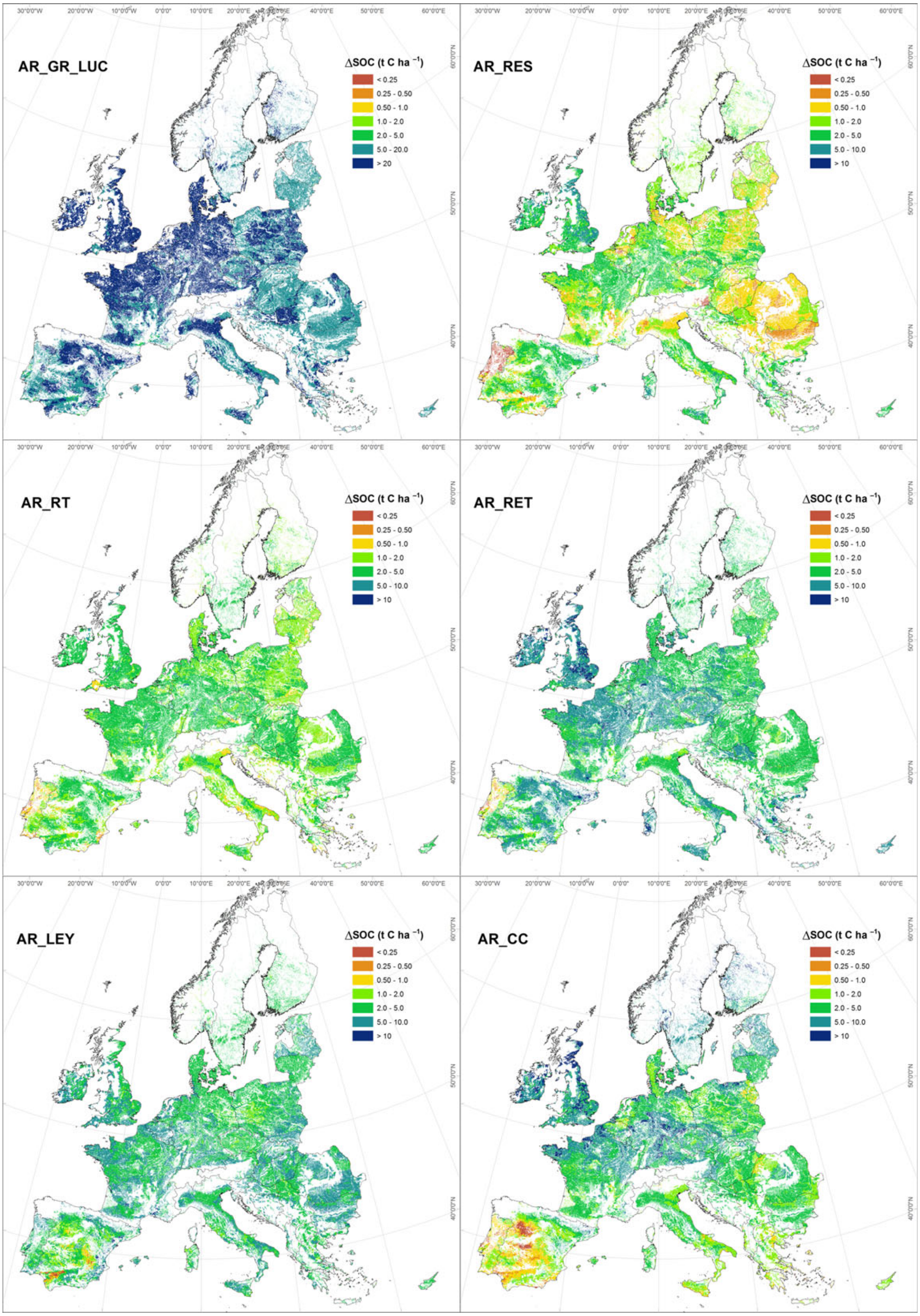

Fig. 1 SOC stock change (t C ha^{-1}) in the topsoil layer (0–30 cm) by 2050, under AMP simulated in the arable land: AR_GR_LUC = conversion from arable to grassland; AR_RES = crop residue management; AR_RT = reduced tillage; AR_RET = crop residue + reduced tillage; AR_LEY = ley in rotation; AR_CC = cover crops. The variance associated with these estimations is reported in the Figure S2.

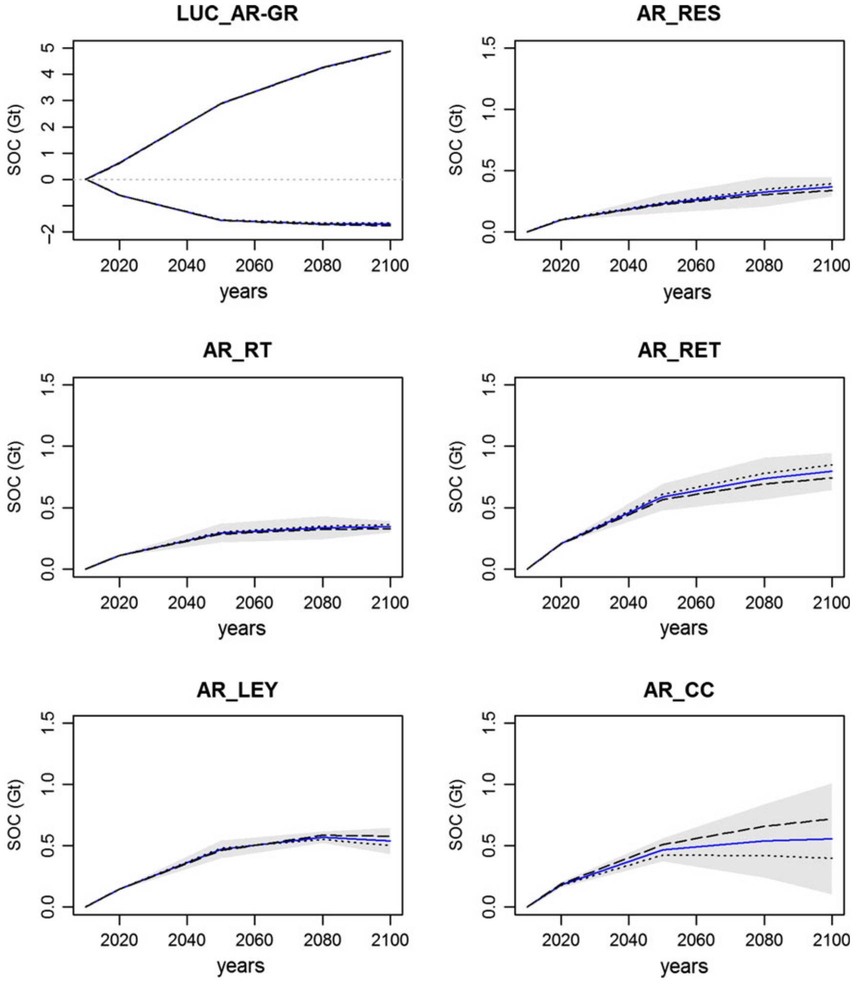

Fig. 2 Trend of cumulated SOC change (Gt of C) at pan-European level, in relation to the different simulated AMP. Thin and thick dotted lines correspond to HAD3_A1FI and PCM_B1 scenario respectively. The blue line is the average, while the grey region delimited the 2σ confidence interval.

The measured carbon sequestration rates derived from LTE (Fig. 3) ranged almost between 0 and 0.5 t C ha^{-1} yr^{-1} for all AMP considered, excluding the land-use change scenario. These values were within the variability in short (2013–2020) and long-term (2013–2050) sequestration rates estimated by modelling, with some exception of measured high rates in AR_RES, due to experimental high amount of crop residues applied to treatments.

Policy-oriented scenarios for SOC sequestration

Three simple scenarios were developed to illustrate to how AMP could eventually be implemented within a possible policy framework (Table 2 and Fig. 4). The cumulated values of carbon sequestered, expressed as CO$_2$ equivalent, were equal to 101, 217 and 335 Mt CO$_2$ eq. in 2020 for S1, S2 and S3 scenario respectively. Even allocating 12% of arable land (S1 scenario) to AMP, produced a mitigation effect in excess of 500 Mt CO$_2$ eq. given a very long-term perspective. Despite the S3 scenario involved only 4% more arable land than the S2 scenario, the inclusion of higher AR_GR_LUC proportion led to consistent differences (Fig. 4).

Discussion

Mitigation effect of the different AMP simulated

Among the AMP simulated, the change in land use from arable to grassland (AR_GR_LUC) was the most efficient in sequestering SOC (Figs 1 and 2). This is not surprising as many studies reported gains in the order of 20 t C ha^{-1} in the 0–30 cm topsoil layer within two to four decades after conversion (Conant *et al.*, 2001; Poeplau & Don, 2013). Conversely, the opposite

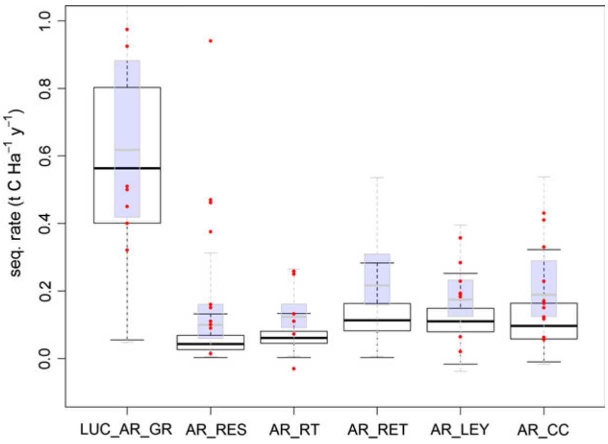

Fig. 3 Box plots of annual C sequestration rates (t C ha^{-1} yr^{-1}) by 2020 (solid box) and 2050 (empty box). Statistics were extracts using all the simulated combinations (76 200) in the arable land for each AMP. Red dots represent the C sequestration rates derived from LTE (Table S1).

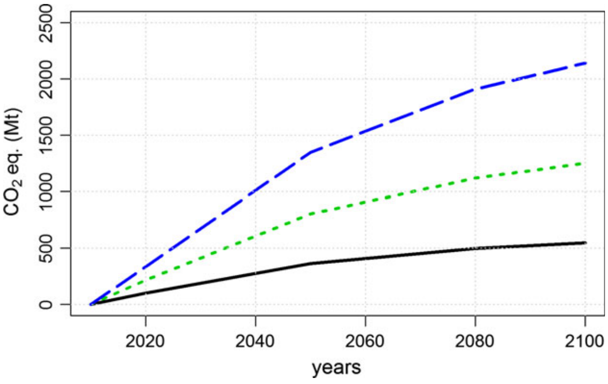

Fig. 4 Cumulated carbon sequestration rates (Mt CO_2 eq.) related to the application of the three policy-oriented scenarios. Black line = S1, green line = S2; blue line = S3.

practice (GR_ AR_LUC) highlights the importance of preserving permanent grasslands as a loss of 40% of the original SOC stock was detected after grassland to cropland conversion in temperate zones in less than 25 years (Poeplau *et al*., 2011). According to these simulations, even converting 5% of grassland areas to arable would lead to losses of more than 300 Mt CO_2 eq. over the next 50 years, strongly offsetting the benefits of implementing other AMP.

Interestingly, variability due to climate was very limited as the two climatic scenarios resulted in very close SOC trends (Fig. 2). The grassland model parameters are set to be less sensitive to climatic variation than other annual crops, as probably occurs at ecosystem level.

The increase in carbon input into soil is considered an effective way to accumulate SOC, with a different efficiency in relation to the amount and quality of carbon applied. Crop residue management, for instance, is one of the most feasible practices at farm level and its effect has been revised by many studies so far (Table S1). Recently, Powlson *et al.* (2011) reported only small or no SOC changes from the analysts of 25 LTE all over the world. Accordingly, long-term rates (e.g., by 2050) modelled in our scenario were generally below 0.1 t C ha^{-1} yr^{-1}, indicating an overall moderate potential of this AMP. However, as pointed out by Powlson, small changes in total SOC have disproportionately large impacts on soil physical properties (aggregate stability, water infiltration rate, etc.), thus policies recommending a large exploitation of residues cannot be accepted under the rationale of low SOC losses. The measured carbon rates resulted from the meta-analysis at pan-EU level (Fig. 3) showed in general low sequestration values but with some exception that are related to exogenous higher experimental inputs. It becomes clear that a tool, which could delineate the areas where an AMP could be more effective (Fig. 1), may help to design regional policies that optimize SOC sequestration.

Many field experiments have tested the effect of reduced tillage techniques on SOC accumulation and show positive effects but with high uncertainty (Lal & Kimble, 1997; Baker *et al*., 2007). Indeed, the biogeochemical feedbacks of tillage practices are several, encompassing changes in carbon input quantity and distribution along the profile and the effects on soil physical conditions, which in turn, govern SOC turnover. Some of these aspects were taken into account in the modelling exercise, as crop production patterns were adjusted according to the meta-regression analysis of van den Putte *et al.* (2010) to prevent overestimation of carbon input. Moreover, the CENTURY model allows the partition of living and standing biomass into surface litter or soil pools, which is dependent of the specific kind of tillage. What is still missing, as in the case of most of SOC models, is the ability to parameterize the variation in the physical properties of soil (e.g., bulk density, hydraulic properties, aggregation, etc.) that are empirically simulated by reducing the coefficient of decomposition of SOC pool. Despite these limitations and considering that a generic reduced tillage scenario was simulated, the annual rates of sequestration were within the range of variability in measured rates (Fig. 3).

When reduced tillage was associated with straw incorporation (AR_RET), the model predicted higher SOC accumulation values, double those of the single practices (AR_RES and AR_RT).

Modification in marketable rotations in ley cropping systems (AR_LEY) and introduction of cover crops (AR_CC) resulted in similar average SOC accumulation trends (Fig. 2), but with a higher variability in the latter. Moreover, the cover crops insertion boosted the yields of the main crops with respect to BAU, more in the PCM than the Had3 scenario (Figure S3). In fact the cover crops were entirely incorporated, likely recycling the nitrogen that was lost by leaching or gaseous losses when the intercropping period was left as bare fallow. This effect was limited under the increasing drought conditions predicted by the Had3 scenario (Figure S1), in which the water availability may be a limiting factor for plant growth. Experimental data of double cropping systems reported both higher water consumption (Meza *et al.*, 2008) and invariant water content and higher yields (Fouli *et al.*, 2012). It is clear that interactions and feedbacks between climate, rotations and carbon and nitrogen biogeochemical cycles are very complex, confirming the importance of developing a tool at high spatial resolution. The introduction of cover crops in southern Spain and Portugal seemed to be less competitive likely due to predicted increasing drought conditions, while recommendable in many area of north-east Europe (Fig. 1), where SOC gain were higher than 10 t ha^{-1} by 2050.

Technical and policy oriented scenarios for C sequestration

In the scientific context, there is an evident mismatch between carbon sequestration rates derived from long-term agricultural experiments (LTE) and large-scale estimates produced by modelling simulations. Networks created to valorize LTE (Powlson *et al.*, 1998; Smith *et al.*, 2002) often provide key data for policy development, but their representativeness is still debatable when possible policy actions involve millions of hectares. The impact of potential carbon sequestration measures was often assessed by applying sequestration rates from LTE to large pieces of land. One of the first examples was the study of Smith *et al.* (1997a), which estimated that 1.5 and 4 Gt of C could be potentially sequestered (for EU15) in a centennial time scale with residue management and ley cropping system respectively. Conversion of 100% of arable land (EU15) to no till (Smith *et al.*, 1998) was estimated to accumulate between 1.17 and 2.3 Gt of C in a time horizon of 50–100 years before reaching a new SOC equilibrium. Freibauer *et al.* (2004), including more data from LTE, estimated a realistic carbon sequestration for EU15 agricultural soils of 16–19 Mt yr^{-1} in the first Kyoto commitment period (corresponding to 0.08–0.095 Gt of C in total). However, the uncertainty related to the upscaling of field data to a large territory was not truly assessed in these studies, as the potential bias associated to apply linear rates to processes that are not linear, as SOC accumulation in soils. This bottom–up approach produces results of high interest for policy making at national level but more uncertain extrapolation to the whole continent.

Soil Organic Carbon models are valid tools to upscale the knowledge achieved at local scale as they mechanistically represent SOC dynamics in time, considering several feedbacks between climate, vegetation, carbon, nitrogen and anthropogenic intervention on homogenous pieces of land. Although they were extensively and successfully applied to predict measured data at field level (Smith *et al.*, 1997b), large-scale simulations are still scarce. Vleeshouwers & Verhagen (2002) developed a simple model at pan-European level (0.5 × 0.5°grid) to estimate carbon sequestration and emission in agricultural land. In their simulation, the conversion of arable to grassland yielded a sequestration of 1.44 t C $\text{ha}^{-1}\ \text{yr}^{-1}$, while incorporation of straw and reduced tillage yielded a gain of 0.15 and 0.25 t C $\text{ha}^{-1}\ \text{yr}^{-1}$ in the first Kyoto commitment period (2008–2012). Smith *et al.* (2005) estimated SOC changes in grassland and arable soils using RothC and IPCC climatic scenarios at European level; however, their projection was made for a BAU and a generic high soil carbon returns scenario.

Other studies were more recently published using agroecosystem models (e.g., Century, DNDC etc.) at regional level (Sleutel *et al.*, 2006; Álvaro-Fuentes *et al.*, 2011). Despite their value, the difficulty to create a synthesis at supranational level relies on the different models used, assumptions during the initialization, input data sets and scenarios design; although losing information and knowledge expert at local level, large-scale application may be more consistent in analysing the effect of AMP on a broad range of pedo-climatic conditions.

Six of the most representative AMP were selected to provide a robust starting point for a carbon sequestration policy discussion. Similar managements showed high mitigation potential in another study (PICCMAT, 2008) using a simpler *Tier 1* approach, in which measures such as catch crop, reduced tillage, residues management, rotation complexity and legumes introduction resulted in individual sequestration rates around 10 Mt CO_2 eq. yr^{-1} for EU27, when applied at 5–15% of the area (Smith, 2012). As a comparison, the sequestration potential of AMP simulated in this article (excluding LUC_AR_GR), ranged between 23.1 and 57.9 Mt CO_2 eq. yr^{-1} by 2050 when fully applied to arable land.

The platform described in this article attempts to create one of the most harmonized and spatially detailed simulation of carbon in arable soils. Although there are significant possibilities for further improvements, the previous validations against sampling network

(LUCAS) and national data sets (EIONET) (Lugato *et al*., 2014) and the proposed *ad hoc* meta-analysis confirmed the robustness and accuracy of the results. Current GHG emissions of the EU are about 4600 Mt CO_2 eq. (EEA, 2013), very close to the 20% target (4502 Mt CO_2 eq.) by 2020, to which the EU is committed in its climate and energy package (EC, 2010). According to the results obtained in the policy simulations, the allocation of 12% of arable land to different combinations of AMP would be sufficient to reach this target. Furthermore, the allocation of more land would strongly contribute to the optional 30% target that is fixed at 3940 Mt CO_2 eq.

Due to the feasibility of implementing additional management measures in the CENTURY model, this platform appears very promising and able to provide data at high spatial resolution and for long-term evaluations. However, biophysical results should be integrated into land use scenario and economic models, considering a range of market prices for carbon and the cost of AMP implementation, to eventually design the most cost-effective policy.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Nomenclature of the territorial extent under the modelling study.
Figure S1. Difference between the mean annual air temperature (°C) (upper figures) and annual precipitation (cm) (lower figures) in 1990–2000 and 2090–2100 decades, for the two climatic scenarios Had3_A1FI and PCM_B1.
Figure S2. Uncertainty of AMP effect calculated using the runs under different climate change scenarios. Values are expressed as 2σ.
Figure S3. Histograms of the crop yield difference between AMP and BAU under the two climatic scenarios simulated; the values are the average of 2090–2100 decade.
Table S1. Methodology and list of references used for the *ad hoc* meta-analysis.