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Including land management in a European carbon model with lateral transfer to the oceans

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ABSTRACT

The use of cover crops (CCs) is a promising cropland management practice with multiple benefits, notably in reducing soil erosion and increasing soil organic carbon (SOC) storage. However, the current ability to represent these factors in land surface models remains limited to small scales or simplified and lumped approaches due to the lack of a sediment-carbon erosion displacement scheme. This precludes a thorough understanding of the consequences of introducing a CC into agricultural systems. In this work, this problem was addressed in two steps with the spatially distributed CE-DYNAM model. First, the historical effect of soil erosion, transport, and deposition on the soil carbon budget at a continental scale in Europe was characterized since the early industrial era, using reconstructed climate and land use forcings. Then, the impact of two distinct policy-oriented scenarios for the introduction of CCs were evaluated, covering the European cropping systems where surface erosion rates or nitrate susceptibility are critical. The evaluation focused on the increase in SOC storage and the export of particulate organic carbon (POC) to the oceans, compiling a continental-scale carbon budget. The results indicated that Europe exported 1.95 TgC/year of POC to the oceans in the last decade, and that CCs can contribute to reducing this amount while increasing SOC storage. Compared to the simulation without CCs, the additional rate of SOC storage induced by CCs peaked after 10 years of their adoption, followed by a decrease, and the cumulative POC export reduction stabilized after around 13 years. The findings indicate that the impacts of CCs on SOC and reduced POC export are persistent regardless of their spatial allocation adopted in the scenarios. Together, the results highlight the importance of taking the temporal aspect of CC adoption into account and indicate that CCs alone are not sufficient to meet the targets of the 4‰ initiative. Despite some known model limitations, which include the lack of feedback of erosion on the net primary productivity and the representation of carbon fluxes with an emulator, the current work constitutes the first approach to successfully couple a distributed routing scheme of eroded carbon to a land carbon model emulator at a reasonably high resolution and continental scale.

Short abstract: A spatially distributed model coupling erosion, transport, and deposition to the carbon cycle was developed. Then, it was used to simulate the impact of cover crops on both erosion and carbon, to show that cover crops can simultaneously increase organic carbon storage and reduce particulate organic carbon export to the oceans. The results seemed persistent regardless of the spatial distribution of cover crops.

Author contributions

Conceptualization: ANF, PC, PP, PM, MC, BG, EL. Methodology: ANF, PC, PP, EL. Investigation: ANF, EL. Visualization: ANF, PC, PP, EL. Supervision: PC, PP, PM, MC, BG, EL, Writing—original draft: ANF, PC, PP, PM, MC, BG, EL. Writing—review: ANF.

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1. Introduction

Among the many management options for a more sustainable cultivation, the adoption of cover crops (CCs) has received increasing attention for its potential benefits (Scavo et al., 2022). CCs are grown during the fallow period and between two successive main crops, interrupting their cycle before competing with the next main crop. This practice, often associated with reduced tillage techniques, improves soil fertility through root exudates and the return of litter and biomass to the soil (Shackelford et al., 2019). In 2009–2015, CCs were reported to be one of the most common conservation agriculture practices in the United States of America (United States Government Accountability Office, 2017). In 2015, the European Union (EU) introduced the adoption of CCs in the Common Agricultural Policy as an option for the Ecological Focus Areas (EFAs). In its first year of application, 27.7% of the land devoted to EFAs in the continent were under CCs (Pe'er et al., 2017), and even though the new rules in 2023–2027 may reduce the area effectively covered by CCs in some farms, incentives to shift existing farms towards more sustainable systems are likely to increase the adoption of CCs in the future (Panagos et al., 2021).

CCs are known to affect agricultural fields in multiple ways. A recent compilation indicated that CCs significantly influenced 28 out of 38 soil indicators, with benefits including reductions on soil erosion, runoff and nutrient leaching (Jian et al., 2020; Stewart et al., 2018; Kaspar et al., 2011; Olson et al., 2014; Panagos et al., 2015b), and the mitigation of carbon dioxide (CO_2) emissions through increased albedo (Carrer et al., 2018). CCs can also have potentially synergistic effects, such as a joint increase in crop yield, soil functioning, and habitat provision for microorganisms after their adoption (Garland et al., 2021). In the context of nutrient cycling, CCs are reported to affect CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions significantly (Jian et al., 2020; Grados et al., 2022), although the effect on N_2O appears non-significant in other works (Grados et al., 2022; Han et al., 2017; Launay et al., 2022). CCs can increase soil organic carbon (SOC) stocks significantly (Jian et al., 2020) with an average topsoil accumulation rate of 0.32 MgC/ha/year (Poeplau and Don, 2015), an effect that can be attributed to the larger carbon input to the soil and the reduced C loss over arable land that would otherwise remain fallow or bare, susceptible to erosion (Guenet et al., 2020). Most of the studies in the literature, however, focus on relatively short timescales, and since the impact of CCs varies with the duration and the frequency of their implementation (Guenet et al., 2020), decades may be necessary to detect a significant increase in SOC concentrations (Syvitski, 2005).

Another relevant effect of CCs concerns the changes in the delivery of soil material to the oceans. Approximately 8.3–51.1 Pg of sediments are transferred to the world's oceans each year by erosion processes (Syvitski, 2005; Harrison, 1994), denuding the continent and affecting biogeochemical cycles (Walling, 2006). Organic carbon, for example, can be transferred to the ocean in particulate (POC) form, i.e. leaf litter, and debris, or in dissolved forms, i.e. soluble particles from the decomposition of eroded organic matter (Lal, 1995). The transfer of carbon to the oceans is considered critical for the proper constraint of biogeochemical land surface models (Blair and Aller, 2012), since they affect carbon stocks over different timescales (Galy et al., 2015). Such lateral transfers are controlled by the SOC stocks and, mostly, by the physical processes of soil erosion and particle detachment (Galy et al., 2015), two quantities that are affected by the adoption of CCs (Jian et al., 2020; Stewart et al., 2018; Olson et al., 2014; Poeplau and Don, 2015; Guenet et al., 2020).

The adoption of CCs affects the lateral transfers of carbon in two opposing directions: the additional carbon input and the increase of SOC stocks tends to enhance the lateral export to the oceans, but the reduction in particle detachment and transport contributes towards the opposite direction. Therefore, a relevant question is which of these two effects prevails. Answering this question is not straightforward, given the lack of sediment transport and deposition movements in land carbon models. Ideally, coupled land carbon and erosion models must represent both short-term local and long-term landscape processes, with the ability to be run through a sufficiently long time range and at a sufficiently high spatial resolution to capture the effect of terrain on erosion-related processes. However, no model has achieved such goals so far due to poor spatial generalization of parameters, and "immense computing power requirements" (Doetterl et al., 2016). Large-scale land surface models often adopt simplified approaches, such as omitting the representation of transport and deposition processes (Chappell et al., 2015; Lugato et al., 2016) or setting fixed ratios for the delivery rates (Lugato et al., 2018; Wang et al., 2017). Process-oriented carbon erosion models that compute a more realistic routing of the sediment along the landscape are often limited to small domains (Nadeu et al., 2015) or to lumped simulations and short time scales when upscaled for large domains (Walling, 2006).

The present work focuses on evaluating how CCs affect the carbon cycle over the European continent, by: i) improving the representation and understanding of the dynamics of POC export to the oceans at a continental level; ii) quantifying whether the enhanced input or the erosion reduction due to CCs prevails on controlling the export of POC to the oceans; and iii) quantifying how a hypothetical policy scenario of widespread CC adoption could affect the SOC budget. To do so, first the lateral transfers of carbon and sediments were quantified at the continental level from early industrial levels (i.e., 1860) to 2050 at a daily temporal resolution with monthly forcings and 10 × 10 km spatial resolution. Then, two scenarios of CCs adoption under the current climate and land use conditions were simulated with the recently developed CE-DYNAM model (Naipal et al., 2020; Fendrich et al., 2022), which couples a spatially-explicit routing scheme to the carbon cycle of the detailed biogeochemistry land surface model ORCHIDEE (Krinner et al., 2005) to represent both ecosystem carbon fluxes and lateral movements in a spatially distributed manner (see SM). The strength of the approach used comes from the combination between empirically calibrated erosion rates, detailed ecosystem carbon exchange, and process-based lateral fluxes, which vary according to the terrain geomorphology and changes on the climatic and land use forcings, as well as on management activities represented through spatially-explicit maps of cover crops adoption.

2. Materials and Methods

2.1. Study area

The study area of this work encompasses the 27 Member States (MSs) of the European Union, plus the United Kingdom, Switzerland and the Balkan States, totaling 491 million hectares. CCs are included within the Good Agricultural and Environmental Conditions (GAECs) standards of Common Agricultural Policy, and the Farm Field Survey of Eurostat indicates that the adoption of CCs increase from 6.5 to 8.9% of all agricultural lands of the 27 MSs in the period from 2010 to 2016 (Borrelli and Panagos, 2020). For its environmental benefits, increasing attention has been given to CCs in the EU.

2.2. Modeling

This work used the CE-DYNAM (v3) model to quantify the impacts of erosion, transport, and deposition (ETD) on the carbon cycle from 1860 to present, plus the subsequent CC adoption from present day to 2050. CE-DYNAM couples: i) an emulator of the land-surface model ORCHIDEE (Krinner et al., 2005), ii) the RUSLE-2015 (Panagos et al., 2015a) erosion model developed for Europe and adapted to include carbon erosion, and iii) a sediment routing scheme describing the lateral movement of eroded soil and carbon in the landscape, including the transfer of particulate organic carbon to the ocean (Fig. 1). In each model time step (i.e., one day), the topsoil carbon in each grid cell is eroded proportionally to the erosion rate calculated. Such eroded

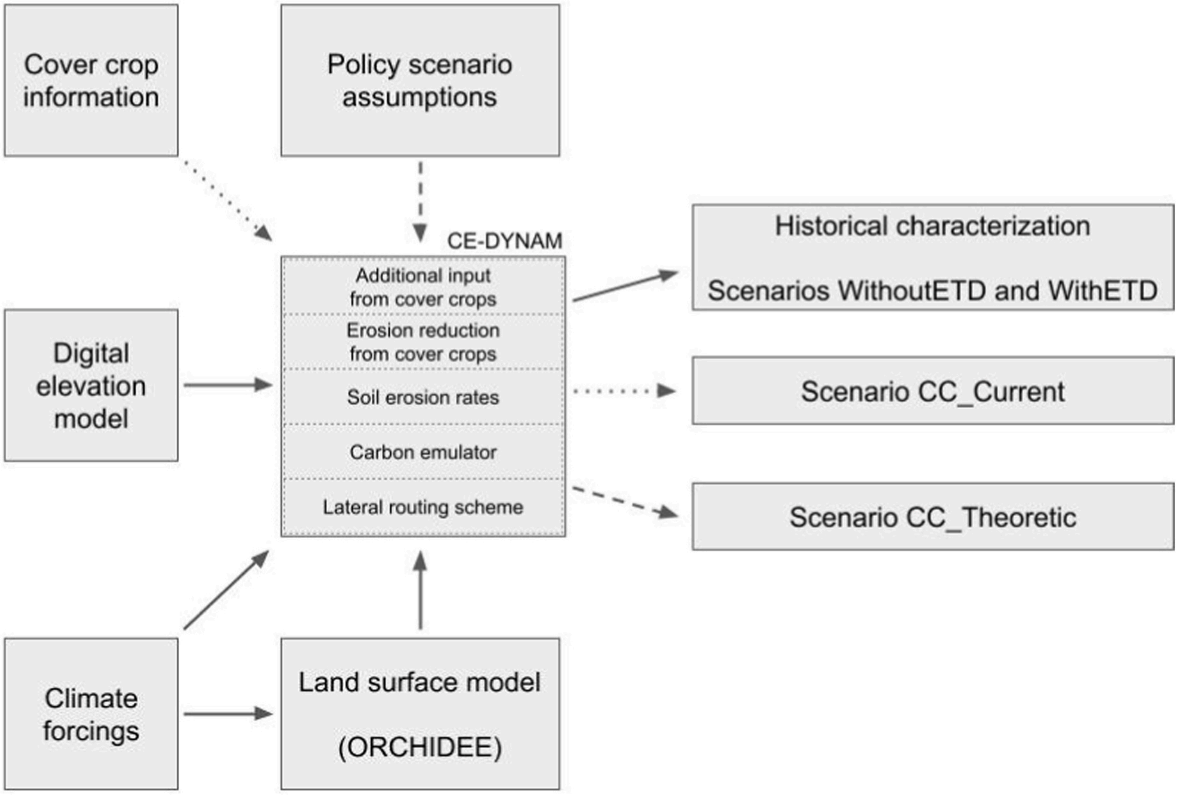

Fig. 1. Schematic representation of the methodology. The inputs represented with continuous arrows were used for all calculations, while those in dashed and dotted arrows were used for the dashed and dotted outputs only, respectively.

material is then either routed downstream according to the terrain configuration or redeposited in place. When lateral movement happens from a source to some target cells, both SOC dynamics are affected. In the source, soil material is moved from the deeper layers to the surface, representing the exposure of subsoils after erosion. In the targets, part of the topsoil carbon is transferred to the subsurface, representing the burial due to the arrival of upstream material. In practice, both dynamics co-occur in most cells, and the soil material is routed in a cascade effect across the landscape until a part of the gross eroded material reaches the so-called ocean cells, which correspond to sites in the boundaries of the simulation domain whose only function in the model is receiving upstream soil material.

CE-DYNAM was set up to run from 1860 to 2050 at a daily temporal resolution, monthly forcings, and 10 × 10 km spatial resolution. Such a spatial granularity is consistent with the highest resolution available for climate reconstruction datasets (CEA/LSCE, 2023), which represents a compromise between the fine scale of hydrological processes and the large scale of most carbon models. A calibration was done to ensure that simulated values of sediment in rivers approximate both sediment discharge observations in river stations from the GEMSTAT database (UNEP, 2018) and the aggregated ocean POC output values derived from (Borrelli et al., 2018). The strength of the model is that climate, land cover, soil characteristics, and management practices directly affect all model components and their interactions. The model results were then summarized in terms of the exports of POC to the ocean. More information about the model and its limitations are presented in the Supplementary Material.

For the calculation of future simulations (Table 1), the target spatial distribution of CCs in CC_Current was defined to be the high-resolution observation-based map of (Fendrich et al., 2023) for 2016, resulting in a total area of 13 Mha. Such a scenario attempts to mimic the actual rate of CC adoption in Europe since the creation of the Nitrates Directive, known to be an important policy driver for this practice (Kathage et al., 2022). In CC_Theoretic, the expansion of CCs occurred over all croplands where erosion rates exceed 2 t/ha/year or located inside the Nitrate Vulnerable Zones (Kathage et al., 2022), reaching a much larger hypothetical CCs area of 118 Mha. The threshold of 2 t/ha/year is often considered the limit below which European soils are still under healthy conditions. It was included, for example, in the Proposal for a Directive on Soil Monitoring and Resilience made by the European Commission in the context of the European Green Deal (European Commission, 2023).

Table 1
Description of the four scenarios simulated in this work.

Scenario	ETD enabled	CCs adoption	CCs spatial distribution
WithoutETD	✖	✖	–
WithETD	✓	✖	–
CC_Current	✓	✓	Fig. S5 (left)
CC_Theoretic	✓	✓	Fig. S5 (right)

Variations in the carbon budget and lateral fluxes were calculated for all scenarios and compared. The additional litter input from CCs, which cannot be modeled by ORCHIDEE, was diagnosed from a separate simulation with DayCent (Lugato et al., 2018), which provided spatially explicit gridded values (1 km resolution) at monthly temporal resolution. Such a simulation included CCs by adding an additional crop (i.e., permanent ryegrass) to the rotation when a period of at least 2 months was expected between the harvest of a cash crop and the sowing of the next cash crop. The attempt to overcome the unavailability of climate and land use forcings until 2050 consisted of repeating the data for 2010–2017 in a loop until 2050. It must be noted, however, that even though such a modeling decision consists of a practical solution to allow extending simulations in time, it has the important consequence of not representing the future variations in rainfall regimes due to climate change. The magnitude of such changes, when accounted for, could create enhanced erosion fluxes across the continent (Panagos et al., 2021).

To isolate the impact of CCs, two analyses were made. The first analysis consisted of pooling together the results of CC_Current and CC_Theoretic to calculate the relative increase of their SOC stocks and the changes of ocean exports compared to simulation WithETD. These two CCs scenarios were pooled together for this analysis to search for common patterns that appear despite their different spatial distribution (Fig. S5). Then, the model's response on SOC stocks and on the lateral fluxes to the ocean were calculated. For the SOC stocks, calculations were grouped per classes of CCs application at the pixel level. The rate of SOC change per year was then calculated to assess the variation of the CC impact over time. For the ocean exports of POC, the results were grouped according to the average share of CC application on each basin. The second analysis consisted of calculating the SOC budget for each scenario separately, which allowed the quantification of impacts at the continental scale.

3. Results

3.1. Historical and present-day simulations

The first set of results are CE-DYNAM simulations of the impacts of erosion, transport, and deposition (ETD) on the carbon cycle from 1860 to present. Those impacts include the exposure of subsoil organic carbon due to the transfer of detached particles to downstream areas and the corresponding burial of particles at the target locations. Apart from

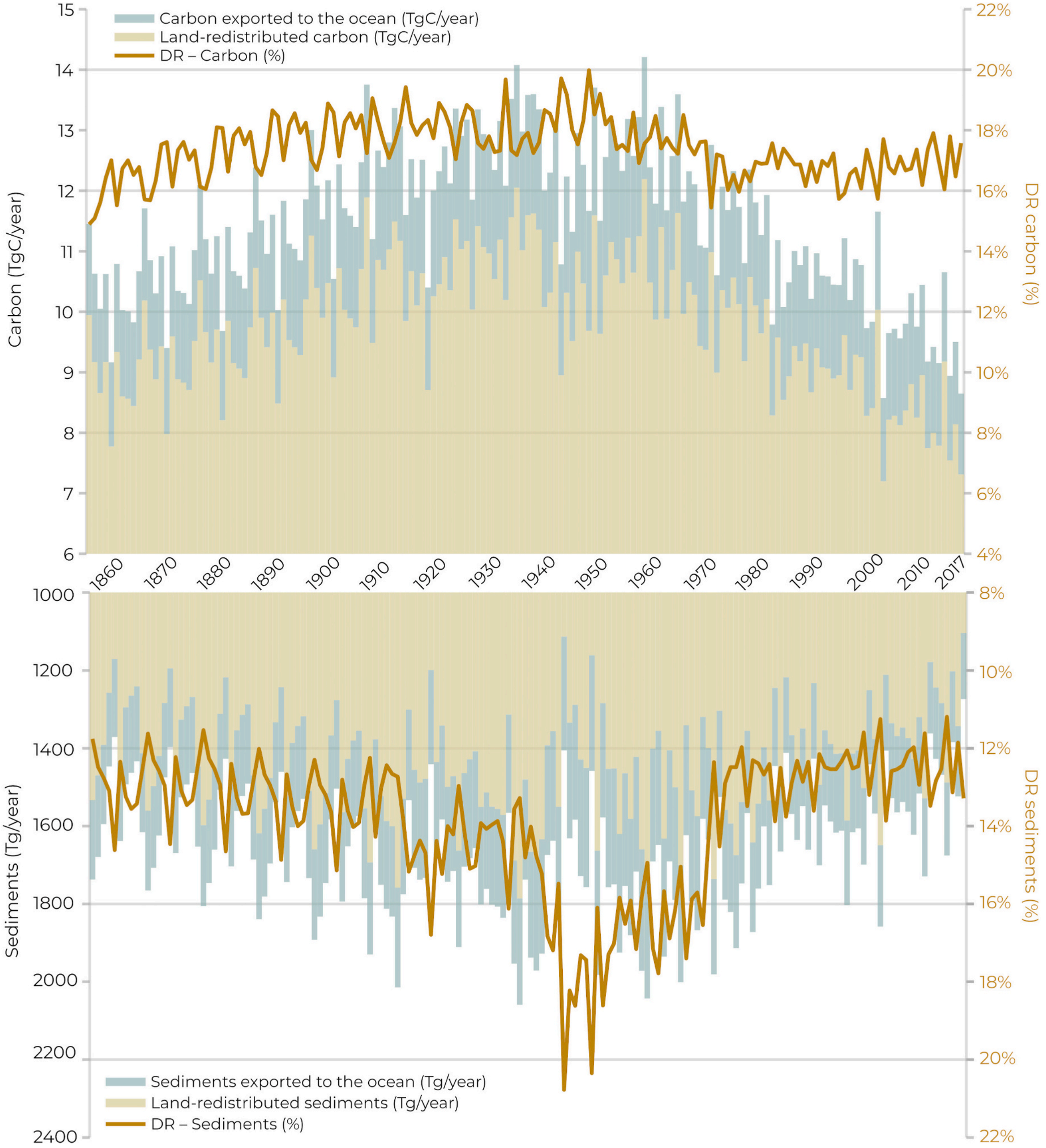

Fig. 2. The variation of carbon (top) and sediment (bottom) export through time. The land-redistributed carbon can be either buried, laterally displayed or respired (for carbon). The total is the sum of redistributed and exported, and the delivery rate (DR) is calculated as the fraction of exported over the total flux redistributed on land and exported to ocean.

cropland management practices, erosion rates and ocean export are affected by rainfall regime variations and land cover change (Panagos et al., 2015a,b), with the spatial distribution of these factors playing an important role. The height of the bars in Fig. 2 equals the total amount of eroded material in each year. The total value is split between a fraction redistributed within the land (yellow) and another part that reaches the oceans (blue). The orange line depicts the evolution of the delivery rate (DR, defined as the share of the eroded soil material flowing to the ocean). The results indicate that the DR ranges from 14.9 to 19.9% for carbon, and from 11.1 to 20.8% for sediments, respectively. For both sediment and carbon, a peak of DR between 1940 and 1960 coincides with a period where low erosion rates happened (Fendrich et al., 2022). This pattern indicates the existence of a time delay in the response of lateral movements to a reduction in the erosion rates.

The map of lateral fluxes (Fig. 3) shows the local imbalance between erosion removal, transport, and carbon export to the oceans. Since most CE-DYNAM cells simultaneously gain and lose carbon during the lateral transfer, areas with a higher net loss (i.e., in red tone in Fig. 3) correspond to those where the topsoil removal by erosion exceeds the gains of sediment material from upstream sites. The figure also shows the magnitude of the flux of POC export to the oceans, represented with gray circles. It can be seen that most carbon lost to the ocean comes from a reduced number of regions, namely Great Britain, Italy, Greece, the Balkan States at the Adriatic Sea, and the south of Spain. In all cases, the regions belong to the Mediterranean or North Atlantic basins (see SM), inducing their large ocean export. Out of the total average of 1.95 TgC/year exported for 2000–2017, the contribution of each group of basins corresponded to 46.09% for the North Atlantic Ocean, 43.44% to the Mediterranean, 8.06% to the Baltic Sea, 1.98% to the Black Sea and 0.43% to other regions (Fig. S1). The proximity between regions with high erosion rates and the coast suggests that catchment elongation plays an important role in controlling ocean export. Another element that supports this explanation is that the opposite effect can be perceived in the Black Sea, where the high losses do not necessarily convert into a high export to the sea for these basins. However, other factors such as landscape connectivity can not be discarded since their effect is not properly captured at the spatial resolution adopted.

3.2. *The future impacts of cover crops*

Four scenarios were designed to evaluate the impact of ETD with and without CCs on soil carbon fluxes and stocks until 2050. In scenario WithoutETD, a default land surface model simulation was used, therefore not including ETD or CCs. Then, WithETD included the soil erosion

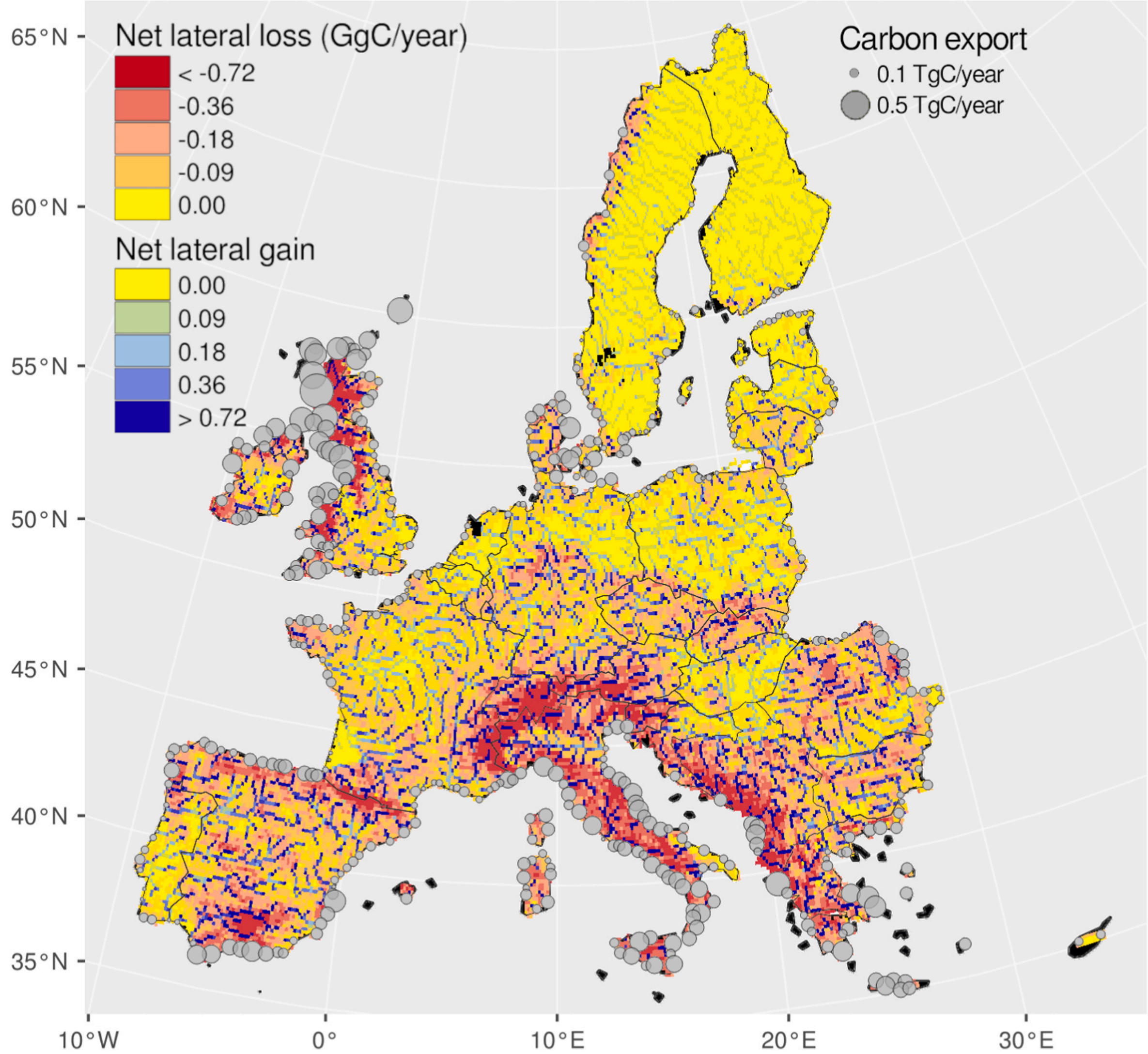

Fig. 3. Net lateral carbon transport and carbon export to the oceans, average for the period 2010-17. Results refer to the simulation WithCC with an enrichment factor equal to 1 (see SM). To enhance visualization, the diameter of each circle is proportional to the carbon export raised to the power of 1/3. Carbon export ranges from 0 (no circle) to 0.5 (largest circle) TgC/year.

rates and the ETD processes but no CCs. The comparison of the results of WithoutETD and WithETD allowed us to isolate the effect of ETD processes. Then, the scenario CC_Curent consisted of WithETD plus a realistic application of 13 Mha of CCs. Finally, scenario CC_Theoretic assumes a maximum CC expansion up to 118 Mha based on (Panagos et al., 2021), corresponding to a strong policy incentive to reduce soil losses of soil and prevent eutrophication (Shackelford et al., 2019; Jian et al., 2020; Martin, 2019). Table 1 in the Materials and Methods section summarizes the characteristics of each scenario, and more information can be found in the SM.

Fig. 4 shows the relative change of SOC stocks during the CCs expansion period. The left image shows the cumulative increase, while the right one shows the annual SOC rate of change for different classes of CC application in percent coverage of arable land. The continuous lines representing the averages indicate higher increases in SOC stocks for higher rates of CC application. The uncertainty bands presented correspond to the standard deviation of 15 sensitivity simulations run (see SM). The increase of SOC induced by CCs is more uncertain for CC fractions below 30%. Above this level, the number of pixels in CC_Current is low, leading to a lower inter-scenario variability and therefore to narrower uncertainty bands. For CC fractions higher than 30%, the average additional increase of SOC in the CC scenarios compared to WithETD reaches 34.5 ± 0.4 ‰ after 50 years. Such an increase is, however, not linear. The yearly average rates of change show that the SOC sequestration rate induced by CCs increases to reach a maximum after 10 years, and then declines. This means that SOC continues to accumulate, albeit at a slower rate, even after CC has reached its maximum expansion.

63.5 ± 2.4% out of the total additional storage in Fig. 4 happened after 2017, when the fraction of CCs had already reached its maximum expansion. For pixels with high CC fractions, a peak of additional SOC sequestration rate at 1.3 ± 0.1‰/year was obtained around 10 years after the beginning of their application. After the peak, the sequestration rate decreases gradually until the end of the simulation period. Combined, the narrow uncertainty band for such a result and the fact that the CCs scenarios are pooled together indicate that the effect is significant and does not depend on other factors that vary spatially across the continent. Overall, applying CCs at the current rate would have a maximum increase of 0.03‰/year and applying them at a maximum rate would peak at 0.19‰/year. In a country level, the two countries with the overall highest increases in CC_Current would be Denmark and Poland, with peaks of 0.23 and 0.20‰/year, respectively, while in CC_Theoretic those countries would be Hungary and Italy, with peaks of 1.23 and 0.84‰/year, respectively.

For ocean export, Fig. 5 shows a clear inverse relationship between the average rate of CCs application and the carbon export to the oceans. Analogously to the case of SOC stocks, the decrease in carbon export stabilizes at some point. After around 13 years of CCs application, the decrease of C export stabilizes at around −43.1 ± 24.8 ‰ compared to the WithETD scenario when the basins contain more than 15% of CCs in croplands. It must be noted that, similarly to the SOC stocks, the classes below 15% have narrower uncertainty bands due to a lower inter-scenario variability. The results indicate a delayed response of the ocean export compared to the 10 years response time observed for the peak of SOC storage. When the scenarios are considered separately, the same plateau is reached on the class above 15% of CCs in croplands, but amounting to −20.9 ± 4.1 ‰ in CC_Current and −65.3 ± 12.5 ‰ in CC_Theoretic.

The SOC budgets for all scenarios in Fig. 6 show that, compared to WithoutETD, WithETD has a slightly lower soil respiration rate (933.22 vs. 932.75 TgC/year) due to the continuous removal of carbon from the topsoil by ETD processes. Scenario WithETD also sets up reference values that can be compared against CC_Current and CC_Theoretic. The gross eroded carbon in WithETD, CC_Current and CC_Theoretic are 14.13, 14.06 (−0.5%) and 13.09 TgC/year (−7.4%), indicating a more considerable decrease when more CCs are adopted. The same relationship is found for ocean export, which remains equal to 1.95 TgC/year for WithETD and CC_Current but decreases up to 1.84 TgC/year (−5.6%) in CC_Theoretic, and for burial and subsoil exposure. The former varies from 12.18 TgC/year in WithETD to 12.11 and 11.23 TgC/year (−0.6% and −7.8%, respectively) in CC_Current and CC_Theoretic, respectively, while the later reduces from 7.68 TgC/year in WithETD to 7.65 TgC/year (−0.2%) in CC_Current and to 7.19 TgC/year (−6.4%) in CC_Theoretic. Two fluxes that increase in CC_Current and CC_Theoretic are the litter input and respiration rates due to the enhanced input caused by adding a new species to the crop succession. In WithoutETD

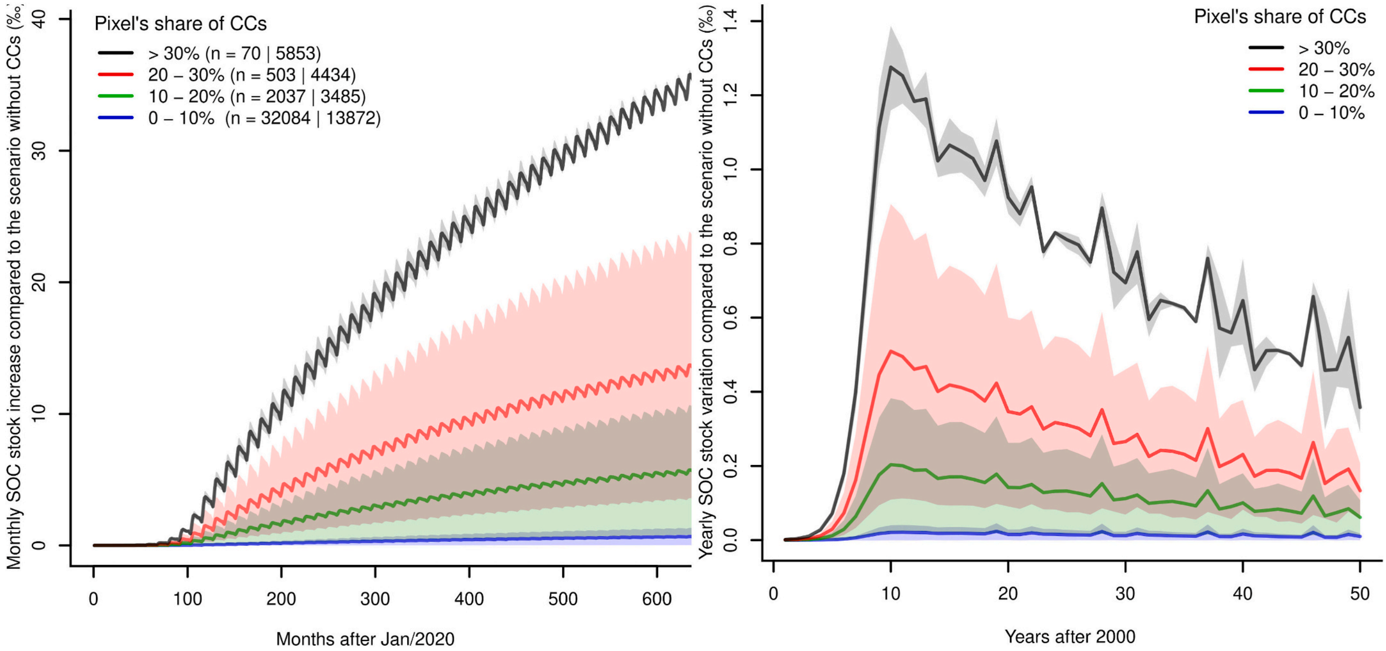

Fig. 4. SOC stocks variation as a function of the pixel's share of cover crops (CCs): relative cumulative increase per month (left) and annual changes (right). The bands around the mean are the standard deviation of the 15 parameters' sensitivity simulations (see SM). The number of pixels in each class is reported as: (n = <number in CC_current> | <number in CC_Theoretic>).

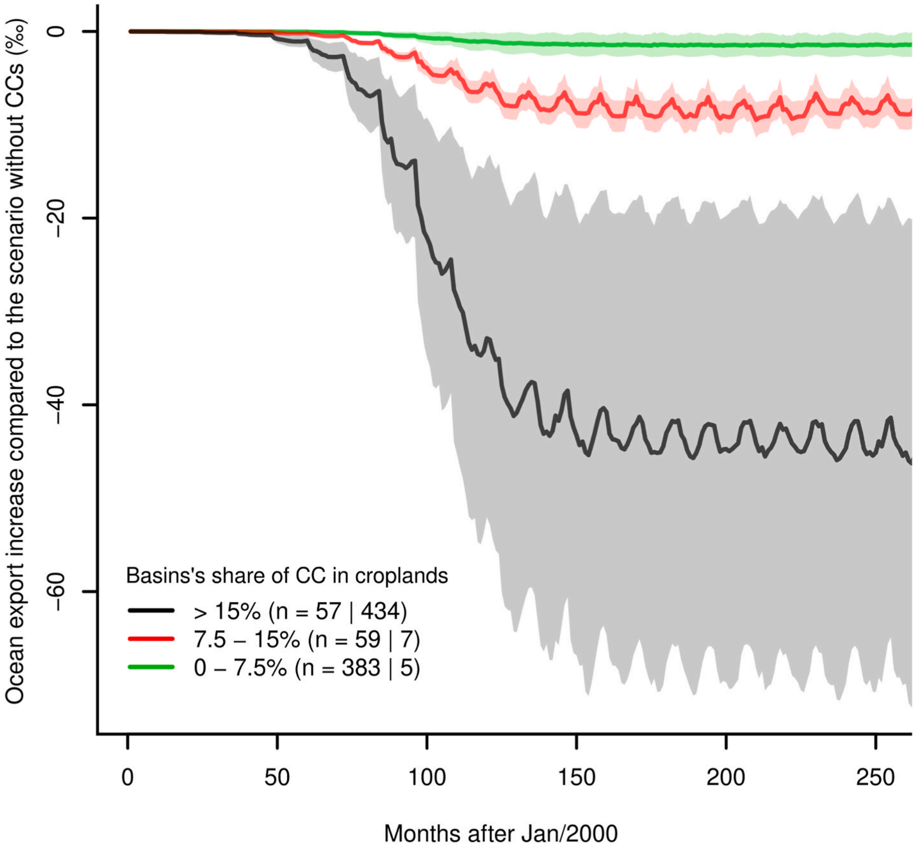

Fig. 5. Carbon export variation as a function of basins' share of cover crops (CCs). The bands around the mean are the standard deviation of the 15 simulations incorporating uncertainty on model parameters (see SM). The period corresponds to 2000 to 2020, the period 2021–2050 was removed due to lack of relevant changes in the pattern displayed. The number of basins in each class is reported as: (n = <number in CC_current> | <number in CC_Theoretic>).

and WithETD, the litter input equals 989.61 TgC/year (2.01 MgC/ha/year), and increases +1.49% to 1002.37 TgC/year (2.04 MgC/ha/year) in CC_Current and +7.96% to 1065.77 TgC/year (2.17 MgC/ha/year) in CC_Theoretic.

4. Discussion

In the historical and present simulations, the DRs ranging from 14.9 to 19.9% for carbon and 11.1–20.8% for sediments are similar to other reported in large-scale studies. At a global scale, (Lal, 2003) estimated a DR of 10%, and in Europe, (Borrelli et al., 2018) calculated a DR of 15.3% using the spatially-explicit Watem-SEDEM model at a 100 m spatial resolution. A similar average of 11% was adopted by (Lugato et al., 2018) for agricultural land in Europe using the DayCent model. The difference in range between sediment and carbon DRs (Fig. 2) arrives from a combination of two factors. The first factor is the mismatch between areas with high erosion rates and those with high exposed SOC stocks. Figs. S6 and S7 show that carbon-rich soils often have low erosion rates and vice-versa. Three particularly relevant regions where the agricultural area increased from 2000 to 2017, and where both SOC stocks and erosion rates are predominantly high, are Bosnia and Herzegovina, Montenegro and Albania (Fig. S7), contributing to the high export to the Mediterranean Sea (Fig. S1). The same pattern is also found in the United Kingdom and Ireland (Fig. S7). The second factor affecting the DR of carbon distinctly from sediment is the fact that after particle detachment, the carbon transported and buried off-site is partially released to the atmosphere through respiration by microorganisms. Such an effect is particularly relevant in inland mountain regions such as Switzerland (Fig. S6), which are far from the ocean and have high losses of carbon (Fig. 3). In these regions, burial and respiration happen during the journey of eroded carbon along the landscape, before reaching the rivers and the ocean.

When cover crops are considered, the period of 13 years for POC export stabilization (Fig. 5) indicates the presence of a delayed effect compared to the peak in SOC increase rates after 10 years (Fig. 4). A possible explanation can be the time needed for particles to reach the ocean after erosion events. Their residence time varies across the landscape, as its stability relates to geomorphological characteristics (Hoffmann et al., 2013). The results indicate that in the tradeoff between the enhanced carbon input versus the reduction of soil losses from erosion, the second factor prevails over the first in controlling ocean POC exports. Even though the model is sensitive to climatic, pedologic, and watersheds' morphological properties, this result seemed persistent despite the different spatial distribution of CCs application in the scenarios considered. These spatial factors, as well as the configuration of CCs, seem to affect only its magnitude but not its direction. Despite this result, it can be noted that the effect Fig. 5 also contains a large uncertainty band, which arises from the three erosion reduction factors used to simulate the impacts of CCs on the erosion rates in the sensitivity simulations (SM). Such a high uncertainty has two implications. First, it indicates that the reduction of POC export does not depend only on whether cover crops will be adopted, but also on how (e.g., which species and scheme) they will be implemented. Secondly, it indicates that although sensitivity simulations (SM) have tried to capture some uncertainties by varying empirical parameters (i.e. the spatial allocation of CCs, the effect of CCs on reducing erosion, and the enrichment factor), only further work on the mechanistic representation of the relationship between CCs and soil erosion in land models can lead to more accurate answers.

The increases in carbon input of Fig. 6 can be compared to the target

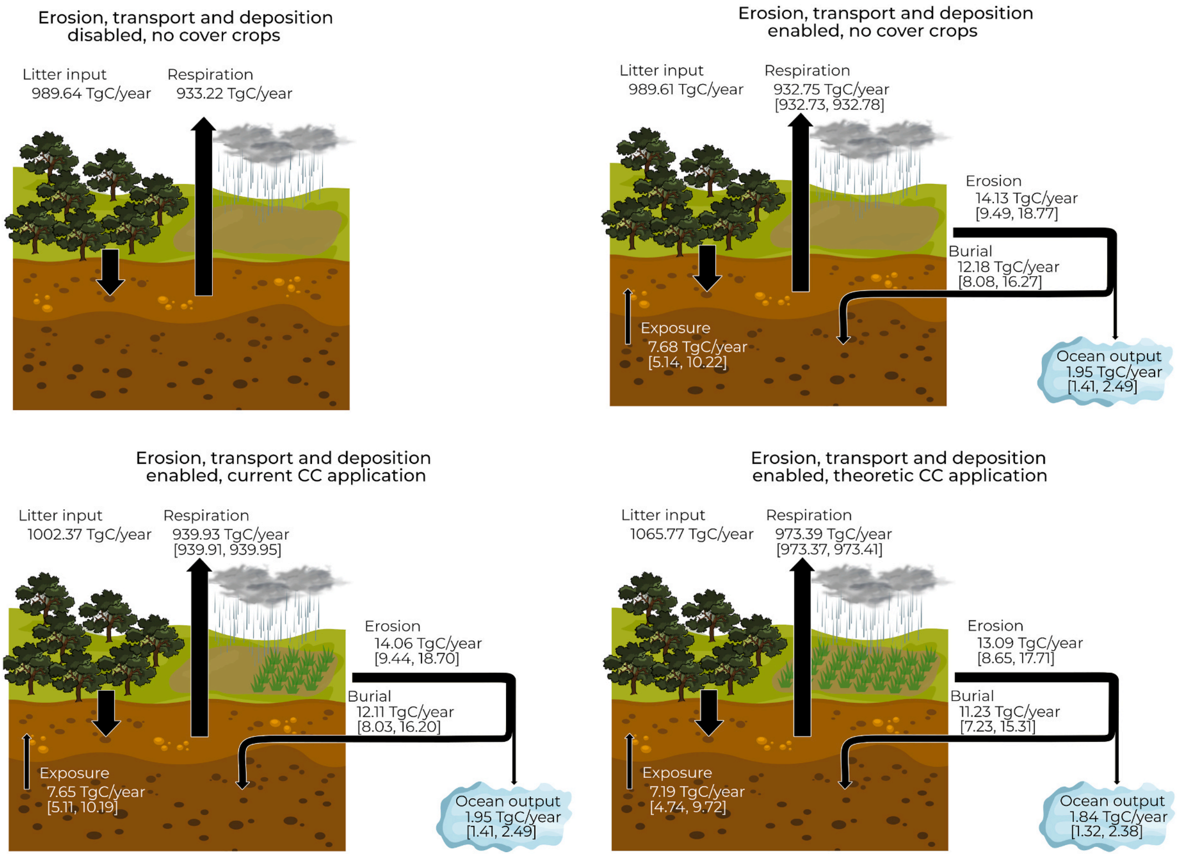

Fig. 6. SOC budget for scenarios WithoutETD (top left), WithETD (top right), CC_Current (bottom left) and CC_Theoretic (bottom right). Values are reported as: "average [min, max]" of the 15 parameters' sensitivity simulations (see SM).

of the 4‰ initiative, which aims at increasing SOC stocks by 0.4% per year. Generally, our results indicate that the effects of CCs are very low compared to the estimated increase of 30–93% (Bruni et al., 2022; Martin et al., 2021; Riggers et al., 2021) necessary to achieve this target. The maximum annual contribution when the CC fraction exceeds 30% (Fig. 4) is only approximately one-third of the 4‰ initiative's target. Overall, the maximum annual increase would correspond to 0.75% of the target in the scenario with a realistic CC application and 4.75% in the scenario with a theoretic application. With the highest increase at the country level, Denmark and Poland would have a maximum additional SOC storage of 5.75 and 5% of the 4‰ target in CC_Current, while Hungary and Italy would reach a maximum of 30.75% and 21% of it in CC_Theoretic. Furthermore, the highest increase in inputs obtained here, of 0.16 MgC/ha/year in CC_Theoretic (Fig. 6), is also very low compared to reference absolute values for the 4‰ initiative, amounting to only half the lower uncertainty bound estimated by Riggers et al. (2021).

Therefore, the results presented in this work reinforce the idea that CCs are insufficient to achieve the 4‰ targets without other additional measures (Minasny et al., 2017, Bruni et al., 2021). These measures may involve practices that provide a permanent additional input to the soils beyond that of CCs, such as adopting agroforestry systems, improving crop rotations, and including crops with high belowground biomass (Bruni et al., 2022). When taking these options into account, different policies must be established for areas with high SOC stocks and erosion rates (Fig. S7). The former requires higher inputs of C to sustain a target of yearly increase in stocks, and the latter may cause degradation and depletion of SOC stocks that would need to be restabilized before any increase (Bruni et al., 2022). In this sense, even though CCs are not sufficient for the 4‰ target, exploring the synergies with other management options that simultaneously address SOC storage and erosion control can be a strategic policy alternative.

5. Conclusions

The impact of CCs on the transport of soil particles and the SOC cycle changes in space and time, leading to a dynamic that is not yet fully captured by most land surface models. The approach proposed in this work constitutes the first attempt to represent such dynamics with a spatially distributed approach at a continental level, allowing a more detailed understanding of the fluxes from the detachment of particles until their export to the oceans. In this sense, the present results aimed at characterizing the impact of erosion itself on the SOC cycle since the early-industrial period and the corresponding changes when CCs are added according to different scenarios. It was found that the progressive implementation of CCs tends to increase SOC stocks and have a nonlinear dynamic through time, indicating a need to better understand the long-term effects of the adoption of CCs. For instance, the results of this work indicate that the induced increase in SOC storage continues even after the area of CCs reaches its maximum, although at a lower rate. CCs also reduce POC export to the ocean compared to the scenario without CCs, indicating that their role in reducing erosion prevails over the induced increase in SOC stocks. Despite model sensitivity to climatic, pedologic, and watersheds' morphological properties, the results were found to be persistent for different spatial distributions of CCs adoption. Further work is still needed to understand the generalizability of these findings for other regions of the world. Despite the limitations of the current work, the results attempt to shed some light on the fluxes involved in carbon transport from the land to the ocean. Additionally, it must be noted that increased rainfall variability due to climate change may significantly impact the results reported in this work, potentially creating lateral carbon fluxes in the same order of carbon farming activities. Increasing knowledge on the integrated carbon cycle is fundamental to properly separate real net removals from the confounding effect of carbon displacement.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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