Maximising climate mitigation potential by carbon and radiative agricultural land management with cover crops

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Abstract
To reach the Paris climate targets, the mitigation capacity needs to be maximized across all components of the Earth system, especially land. Mitigation actions through land management, such as cover crops in agricultural soils, are often evaluated in terms of their carbon sequestration potential, while radiative forcing related to surface albedo changes is often ignored. The aim of this study was to assess the mitigation potential of cover crops, both as changes in biogenic greenhouse gas fluxes (CO₂ and N₂O) and albedo-driven radiative forcing at the top of the atmosphere (TOA). To achieve this, we have integrated a biogeochemistry model framework running on approximately 8000 locations across the European Union with detailed soil data, supplemented with time series of albedo measurements derived from satellite remote sensing. We found that carbon sequestration remained the dominant mitigation effect, with 1th and 3rd interquartile of 5.2–17.0 Mg CO₂e ha⁻¹ at 2050, and negligible changes in N₂O emissions over that time-horizon. Cover crops were generally brighter than bare soils, hence, the reflected shortwave radiation at TOA ranged between 0.08–0.22 Wm⁻² on average, broadly equivalent to a removal of 0.8–3.9 Mg CO₂e ha⁻¹. Through scenarios analysis, we further showed how the mitigation potential could be substantially increased by growing a high albedo chlorophyll-deficient cover crop. This radiative land management option has an additional benefit of providing its mitigation effect more rapidly than carbon sequestration, although additional studies might be warranted to evaluate local and non-local associated climatic effects, such as changes in patterns of surface temperature and precipitation.

1. Introduction
The European Union (EU) has set ambitious emission reduction targets in order to meet the Paris agreement, with a decrease of at least 40% of greenhouse gases (GHG) by 2030 [1]. This was further increased to 50%–55% under the EU Green Deal, which aims for carbon neutrality by 2050 [2]. In this context, the land use and land use change and forestry sector (LULUCF) has been formally included in the effort-sharing regulation for the 2021–2030 period [3], with a binding commitment that emissions accounted from land use should be entirely compensated by an equivalent removal of CO₂ in the sector (the so called ‘no debit’ rule). The overarching objective is to incentivize a more climate-friendly land use, for instance, reducing CO₂ emissions from the cultivation of organic soils (~70 Tg y⁻¹ of CO₂e) or by generating carbon credits that could compensate for N₂O emissions from agricultural soils, currently in the order of 130–140 Tg y⁻¹ of CO₂e [4]. Because most agricultural mineral soils are likely to be close to an equilibrium for soil organic carbon and far from their saturation capacity [5], the regulation could offer a motivation to adopt management practices that enhance atmospheric CO₂ uptake through soil carbon sequestration.

In the EU, the Common Agricultural Policy (CAP) is one of the main policy instruments to implement such measures, due to the high share of financially-supported agricultural compared to total land. The current reform of the CAP (2021–2027) sets high ambitions on environmental and climate change actions [6], but it requires clear scientific indications to prioritize its investments towards those most effective.
Conservation, restoration or improved land management actions, which increase carbon storage or avoid greenhouse gas emissions [7], are promoted under the concept of Natural Climate Solutions (NCS) [8]. One such NCS involves the practice of planting cover crops in arable lands that have an off-season fallow period. This practice extends the period during which photosynthesis occurs and, hence, the carbon sink capacity of the agroecosystem. The introduction of cover crops is recognized as a good practice to increase the soil organic carbon stock [9, 10], while improving soil quality and fertility [11]. So far the cost-effectiveness and the mitigation potential of this solution has been evaluated predominantly in terms of their impact on the main biogenic fluxes of GHGs such as CO₂, N₂O and CH₄ [8, 12, 13].

Conversely, cover crop adoption also changes the ground cover and the surface properties, such as albedo, which themselves affect the climate by: (1) inducing a local cooling or warming effect, due to the change in the radiation balance at the surface and in the partition of available energy between sensible and latent heat fluxes [14, 15]; (2) changing the radiation budget at the top of the atmosphere (TOA; i.e. about 100 kilometers above the surface, where the Earth’s energy budget is defined) by affecting the fraction of shortwave radiation reflected at the surface (albedo). The latter effect can be expressed as CO₂ equivalence, which provides a measure of the globally averaged TOA radiation change relative to emissions of CO₂ over a specified timeframe. It is worth to point out that this is a broad measure of the scale at which the Earth’s energy budget is perturbed by albedo change relative CO₂ emissions, but it does not account for important regional differences between albedo and CO₂ in terms of their spatial pattern of energy flux changes, associated feedback mechanism, or resulting spatial patterns of warming or cooling.

Several studies have suggested the preferential mitigation benefits of cropland albedo management, through practices such as reduced tillage or crop biogeoengineering [16–18], that may lead to an energy imbalance at TOA. For instance, a recent study suggests that the introduction of cover crops can increase the albedo compared to a bare soil. In turn this generates a negative radiative forcing (i.e. cooling effect) at TOA that is of the same order as that of carbon sequestration when converted to CO₂ equivalent [19]. Bearing in mind the finite capacity of soil to store carbon, the potential vulnerability of soil carbon stocks to land degradation and the need to maintain this storage, accounting for biophysical processes in the spatial and temporal extent of the total mitigation potential is a relevant consideration for policymakers in order to develop the most appropriate and cost-effective climate actions. Yet, there are no studies that combine both the biophysical and biogeochemical aspects of cover crops adoption in a consolidated way.

In order to produce a comprehensive, robust and spatially explicit assessment of the net climate impact of cover crops, we ran a state-of-the-art biogeochemistry model DayCent [20] on approximately 8000 locations, classified as arable, from the most extensive harmonized land use and soil inventory network available for the EU (LUCAS survey) [21, 22]. To account for radiative budget changes at the surface and at the TOA, remote sensing data were used to calibrate a function relating albedo with ground cover at each LUCAS sampling point. This locally-adjusted relationship allows the simulation of different modelling scenarios, either with or without cover crops. The difference in ground cover is taken into account on a daily basis, both in terms of the radiative forcing caused by changes in GHG fluxes and in albedo. Finally, an additional pair of simulations were generated that considered a chlorophyll-deficient mutant cover crop that has a much higher albedo, and thus a higher potential to mitigate climate change.

2. Data and methods

The model framework is based on the integration of the most extensive harmonized land use and soil inventory network of the EU (i.e. LUCAS) [21] and the well-known ecosystem model Day-Cent [20]. This platform was thoroughly described in previous work [10, 22, 23], therefore, only a succinct overview is provided here. The additional step in this work was to couple remote sensing information to account for albedo changes under alternative agricultural management practices (supplementary figures S1 and S2 (available online at stacks.iop.org/ERL/15/094075/mmedia)).

2.1. LUCAS dataset

Through a combination of remote sensing and direct field observations, the LUCAS survey gathers harmonized data on land use and land cover across the EU, including changes over time. It includes a soil component based on 10% of the survey control points, thereby providing approximately 20,000 sampling locations in 2009. The survey was repeated in 2015 over most of the same sampling points. Topsoil samples (0–20 cm) were taken from all land use and land cover types, with a slight bias for agricultural areas. The samples were analysed in a single ISO-certified laboratory for: particle size distribution, coarse fragments, pH, soil organic carbon (SOC) content, carbonate content, phosphorus (P) content, total nitrogen (N) content, extractable potassium content and cation exchange capacity. For the purpose of this study, we included only the agricultural land classified as arable under rotational forage crops.

2.2. Daycent model and implementation

DayCent, the daily time-step version of the biogeochemistry Century model, was designed to simulate
soil C dynamics, nutrient flows (N, P) and gas fluxes (CO₂, CH₄, N₂O, NOx, N₂) between soil, plants and the atmosphere. Sub-components include soil water content and temperature by layer, plant production and allocation of net primary production (NPP), decomposition of litter and soil organic matter, mineralization of nutrients, N gas emissions from nitrification and denitrification, and CH₄ oxidation in non-saturated soils. The model is driven by daily meteorological data, site characteristics and the management practices such as crop rotation, tillage, grazing, irrigation, organic and mineral fertilization inputs.

The inputs needed to run the DayCent model were derived by using: (1) information on soil properties available for LUCAS points, which was considered very accurate and directly used as input parameters without an uncertainty range; (2) information from official statistics not available at point-level and subjected to an uncertainty analysis, depending on the sensitivity of modelled C and N₂O fluxes to their variation. The soil properties included the initial SOC, particle size distribution and pH. Hydraulic properties such as field capacity, wilting points and saturated hydraulic conductivity were estimated using a pedotransfer rule based on texture and SOC content [24]. Hydraulic properties (i.e. field capacity and wilting point expressed in volume) were corrected for the presence of stones, while soil bulk density was also calculated with an empirically-derived pedotransfer function [25]. Management information was derived from official statistics (Eurostat, 2019) and included crop shares at NUTS2 level (administrative borders, which represent the EU basic regions for the application of regional policies) and mineral N consumption at national level. The amount of mineral N at national level was partitioned according to the regional crop rotations and agronomic crop requirements. Organic fertilizations and irrigated areas derived from the ‘Gridded Livestock of the World’ FAO dataset [26], and the assimilation of irrigated areas from the FAO-AQUASTAT product of [27].

To ensure that initial SOC values in the modelling framework correspond to the measured ones, the simulations were set to start in 2009, the year of the LUCAS sampling. Meteorological data were taken from the E-OBS gridded dataset (www.ecad.eu/). The dataset provides daily data of maximum and minimum temperature and precipitation on a grid with a spatial resolution of 0.25°. For the climatic projection, the general circulation model CNRM-CM541 run with an RCP4.5 emission scenario [28] and dynamically downscaled with the Regional Climate Model CCLM4-8-17, available from the WCR-CORDEX portal (https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/), was used. Average annual atmospheric N deposition (2006–2010) from the EMEP model (rv 4.5) [29], providing both wet and dry spatially distributed deposition, were also implemented.

For the arable land use, the following crops were available in the DayCent model: winter and spring barley, winter and spring wheat, forage and grain maize, oilseed rape, potato, sugar beet, soybean, sunflower, pulses and cotton. The planting and harvesting dates for each crop were based on the crop calendar map, available at the SAGE Center [30]. An R script was created to automatically assemble crop rotations from the above-mentioned datasets, creating the DayCent schedules files for each LUCAS location. The LUCAS survey does not provide information about the specific management, therefore conventional agro-techniques were assumed to be in place; these included a primary (mouldboard) and secondary tillage and mineral N application split in two events (depending also on crop type).

The ‘baseline’ scenario is characterized by current agro-ecosystems conditions with regard to soil status, crop rotation, management and climate. The model was run from 2009 to 2015 with the observed climate, to allow equilibrium in the soil profile of the fast SOC and N pools and the water status. For the period 2016–2100 the simulation was extended with the RCP4.5 climate scenario. The baseline scenario was used as a comparison for the cover crop alternative scenarios simulated.

The cover crop scenario (CC) involves the introduction of a grass cover (rye grass) replacing the fallow period between the harvest and the planting of two consecutive main crops, when this fallow lasted for at least two months. In this scenario, the mineral N fertilization was also reduced by 20% assuming some N recycling by cover crop uptake [23], which was completely incorporated into the soil before the following cash crop.

### 2.3. Remote sensing approach

The objective of this paper is to estimate the change in albedo that would occur if the bare soil would be replaced by a cover crop, for every LUCAS point. To do so, we assume that the albedo of the hypothetical cover crop can be represented by the albedo of the actual crop grown over the LUCAS point during the growing season. This albedo can then be compared to the albedo of the bare soil observed in the absence of cover crop to obtain the expected albedo change due to adopting the practice of cover cropping over that point. The challenge lies in getting the correct albedo measurements for all LUCAS points and for various years, given the condition that the only available albedo product with the adequate properties (i.e. high enough repetitivity to get the timing right, wide enough coverage to cover all the EU, and a long enough archive to span several years), has at best a spatial resolution of 500 m (using the MODIS instrument on both Terra and Aqua satellites). As a result, most pixels over the EU are mixed, containing information from various fields at different growth stages.
The strategy we adopt to solve this problem is to establish a local relationship between albedo and the Normalized Difference Vegetation Index (NDVI), an indicator of green vegetation density, that is calculated from the same instrument as the albedo. The time series of both Albedo and NDVI are collected around every LUCAS point in a radius of 3.5 km. Then a series of filtering operations are carried out to ensure that a robust NDVI-Albedo relationship is established.

A first spatial filtering ensures that time series are only selected from the land mapped as arable land in the CORINE Land cover classification map of 2012 (https://land.copernicus.eu/pan-european/corine-land-cover). A second, more sophisticated filtering step is done to identify time series that have a more spatially homogeneous footprint. This is done by calculating a temporal signal-to-noise ratio (SNR) from time series of daily multi-angular NDVI observations from the MODIS instrument using the methodology described in [31]. SNR can thus be mapped and higher values indicate the location in which ‘purer’ time series can be expected. SNR is here calculated with 500 m MODIS data for every growing season (from October 1 until September 30 of the following year), and only times series coming from areas where SNR is above 25 are retained. A third filtering ensures that all measurements involving snow are removed from the time series, as the snow would mask the cover crop and strongly alter the albedo. From the mean NDVI of all retained time series, the time of the maximum is identified as the latest limit to consider values for the albedo-NDVI relationship. This avoids including albedo values corresponding to crop senescence, which is not representative of conditions for the cover crop. The earliest limit to consider values is fixed to 150 d prior to the date of the maximum of the ensemble mean NDVI.

After all filtering operations, a linear regression is applied on all remaining values for every LUCAS point and for every growing season between autumn 2003 and summer 2018, multi-annual averages are calculated to ensure more robust estimates. Prior to averaging, the filtering a procedure based on minimal criteria (adj.R\(^2\) > 0.1 and n > 30) was applied, resulting in the selection of 7263 points.

The change in albedo (\(\delta\alpha\)) was calculated as the albedo difference between the cover crops (CC) and baseline scenario: \(\delta\alpha = \alpha_{CC} - \alpha_{base}\).

To understand the potential radiative impact of a very bright mutant cover crop, we ran an additional scenario assigning to it an \(\alpha_{max}\) of 0.28. We also considered a productivity reduction, derived from field experiment testing a mutant soybean with reduced chlorophyll content [33]. For analogy, we made the assumption that a possible mutant cover crop had the same productivity decrease of 20%.

Furthermore, we elaborated the following approach in order to have an estimation of the potential impact including the snowpack on the cover crop scenarios simulated:
Figure 1. Albedo and radiative forcing changes under the cover crop adoption scenarios. (a) Mean snow water equivalent (cm) of the period December to January, calculated by DayCent with the RPC4.5 scenario utilized. (b) Bare soil albedo. Mean albedo change due to cover crops introduction under the (c) snow and (d) snow-free scenario. Radiative forcing (W m^{-2}) due to cover crop introduction under the (e) snow and (f) snow-free scenario. For c to f, the values are daily mean over the period 2016–2100. Positive values of albedo radiative forcing indicate higher outgoing reflected radiation at the TOA. The overall mean (µ) and standard deviation (σ) of all LUCAS point are indicated below each map.
(a) we converted, on a daily basis, the snow water equivalent (cm) simulated by the model (figure 1(a)) into snow height, assuming a density of 0.3 g cm\(^{-1}\);

(b) when the calculated snow height was between 0.045 and 21 cm, we apply equation (2) changing the bare soil albedo (\(\alpha_{\text{bare}}\)) with that of snow (0.65). This assumption strongly penalizes the cover crop presence, since it assumes that plants always emerge from snow (‘worst case scenario’). Above 21 cm of snow height, we assumed that cover crops were completely buried [34].

Next, we collected daily data of shortwave incoming radiation at the surface (\(SW_{in}\)) and at the top of the atmosphere (\(SW_{TOA}\)) from the climatic projections used in section 2.2. The atmospheric transmittance (\(T_a\)) was calculated as the ratio \(SW_{in}/SW_{TOA}\) following the approach of [19], which assumes that upward and downward \(T_a\) are equal. We then calculated the albedo-induced radiative forcing at TOA (Wm\(^{-2}\)) multiplying the daily quantity (\(SW_{in} \times T_a\)) by the albedo change (\(\Delta \alpha\)):

\[
RF_{\Delta \alpha}(t, I) = \left( \frac{1}{dd} \sum_{i=1}^{dd} SW_{in} \times T_a \times \Delta \alpha_i \right) \frac{A}{A_{\text{Earth}}}
\]

were where \(RF_{\Delta \alpha}(t, I)\) is the annual mean radiative forcing at (annual) time step \(t\) (W m\(^{-2}\)) calculated at daily time step over the 2016–2100 period (\(dd = 31,045\)) at each \(I\) location, \(A\) is the local perturbed area and \(A_{\text{Earth}}\) is the area of the earth (5.1 \times 10\(^{14}\) m\(^2\)).

In the last step, the radiative forcing was converted to CO\(_2\) equivalent in order to make a spatial and temporal comparison of both biogeochemical and biophysical mitigation potentials. We used a method based on the global warming potential (GWP) [35], as reported in the equation:

\[
GWP_{\Delta \alpha}(TH, I) = \frac{\sum_{t=0}^{TH} RF_{\Delta \alpha}(t, I)}{k_{CO_2} \sum_{t=0}^{TH} y_{CO_2}(t) dt}
\]

where \(RF_{\Delta \alpha}(t, I)\) is the discretized annual mean instantaneous radiative forcing from an albedo change (equation (3)), \(k_{CO_2}\) is the radiative efficiency of CO\(_2\) (1.76 \times 10\(^{-13}\) Wm\(^{-2}\) kg\(^{-1}\) at 389 ppmv), and \(y_{CO_2}(t)\) is the CO\(_2\) Impulse Response Function.

For the biogenic fluxes, the CO\(_2\)-C flux was multiplied by 44/12 and N\(_2\)O-N flux by 44/28 GWP\(_{N_2O}\), where GWP\(_{N_2O}\) is the global warming potential of N\(_2\)O equal to 265 in a 100-year horizon [36].

We also defined the albedo forcing ratio as: \(ofr = \left| \frac{GWP_{\Delta \alpha}(TH)}{GWP_{N_2O}(TH)} \right|\), where CO\(_2\) and N\(_2\)O are the cumulative soil CO\(_2\) and N\(_2\)O direct emissions/removal at the time horizon TH (all as Mg CO\(_2\)).

While the biogeochemical modelling is a more consolidated component and already subject to extensive uncertainty and validation [10, 23], the remote sensing outcomes and their integration with the biogeochemical part remained unexplored. Therefore, we performed a global uncertainty and sensitivity analysis using a Montecarlo approach on the following parameters: intercept (\(int\)) and exponent (\(exp\)) of the equation converting aboveground biomass into coverage (equation (1)), \(\alpha_{\max}\) and \(\alpha_{\text{bare}}\) (equation (2)) and kCO\(_2\) and yCO\(_2\) used to convert the radiative forcing to CO\(_2\) equivalent (equation (4)).

First, the total variance was obtained by randomly sampling (1000 drawings) the probability density functions of all the parameters and looking at long-term radiative forcing as output (GWP\(_{\Delta \alpha}\)); then, the sensitivity of each of them was assessed keeping constant one parameter at time (varying the others) and comparing its relative contribution to the total variance (see supplementary information).

3. Results and discussion

3.1. Cover crops radiative impact

The radiative impact of a cover crop fully depends on the difference in broadband albedo between the canopy and the bare soil that it is going to shade, together with the radiation load during the cover crop. Given the importance of bare soil albedo, we assessed its spatial pattern using satellite remote sensing. On average, bare soil albedo (\(\alpha_{\text{bare}}\)) across the arable LUCAS locations was 0.14 ± 0.03, with some marked variability territorially (figure 1(b)). Spain, in particular, showed the brightest soils with values mostly above 0.2, as reported in other studies [19]. Although \(\alpha_{\text{bare}}\) varies in time with soil moisture, our local relationship, based on multi-annual time series, implicitly accounted for average conditions for the season when the soil is bare.

The global sensitivity analysis (supplementary figure S3) clearly shows that \(\alpha_{\text{bare}}\) plays a key role in determining the efficacy of albedo-based mitigation options, highlighting the importance of having accurate estimates of this parameter in space and time. Ideally, these estimates could be improved by combining high resolution remote sensing with observation performed at the surface.

The albedo at full canopy (\(\alpha_{\max}\)) was 0.18 ± 0.02, and was correlated (\(r = 0.56\)) to bare soil albedo (see supplementary figure S4). This correlation is likely to stem from the fraction of bare ground that can be seen through the canopy (e.g. inter-row space, gaps between leaves) and by ancillary landscape elements (e.g. roads, drainage ditches). This second aspect is particularly relevant in the case of this study, because the spatial resolution of the satellite sensor used to extract the albedo at the time of maximum vegetation cover (MODIS) [37] is relatively coarse with
respect to the size of the fields in European landscapes (see Methods for more details). These contamination errors would result in both under and overestimation of albedo-induced change by cover crops in darker and brighter soils, respectively. However, since the distribution of \( \alpha_{\text{bare}} \) is right-skewed (skewness = 0.96) toward higher albedo values across the EU, the predominance of cases where the vegetation would have been even brighter than soil makes our results conservative.

On average, the presence of cover crops in the simulated rotations induced an albedo increase of 0.0043 \( \pm \) 0.0036 (figure 1(d)), equal to a radiative forcing of 0.22 \( \pm \) 0.2 Wm\(^{-2}\) (figure 1(f)). In almost all LUCAS points, the spectral signature of the vegetation was equal or brighter than the bare soil, with some evident exceptions in several Spanish regions where soils are particularly bright.

Previous studies, estimating cover crops radiative mitigation potential by albedo change in the EU, have only considered a snow-free bare soil conditions \([11, 19]\). Since snow has a very high albedo (generally around 0.65), the presence of cover crop canopy above the snowpack could induce both local warming and negative change in radiative budget at TOA. Yet, a recent study \([38]\) suggests that the presence of cover crops increases wintertime temperature by up to 3 °C in central North America by decreasing albedo in regions with variable snowpack. However, these results were recently contested by another study \([34]\), suggesting no significant local warming if the same scenario had been run with a more realistic agro-technique and cover crop morphology.

Indeed, the albedo change varied markedly when comparing the snowpack to the snow-free scenario in our simulations (figures 1(a), (c)). In snowy areas, such as Scandinavia, the albedo increase was marginal since cover crops were completely buried by snow, according to our assumptions. Instead, the soil surface was darker particularly in a central–eastern belt extending between 45 and 50 degree of latitude and in the regions neighboring Denmark. Across the EU, the average albedo change due to cover crops adoption resulted in negative values although, when multiplied by the \((SW_{\text{in}} \times T_a)\) term (supplementary figure S5), the radiative forcing was positive (0.083 W m\(^{-2}\)) but about three times lower than the snow-free scenario (figure 1(e)). While we recognized that this reduction is dependent on a single climatic scenario and a conservative snow effect assumptions (see methods), it highlights the possible trade-offs of radiative management in certain areas and the possibility to adopt agro-techniques to minimize them (e.g. low height and low leaf area index cover crops).

Another important aspect is that the positive radiative imbalance at TOA is also concomitant with local non-radiative biophysical effects. For instance, cover crops may produce local surface cooling by enhanced evapotranspiration \([39]\). While the quantification of these local effects on temperature are outside the scope of this paper, the promotion of cover crops in water-limited environments should

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**Figure 2.** Mitigation potential of cover crops introduction. (a), (d) Cumulative trend of biophysical (albedo-driven) and biogeochemical (\( \text{CO}_2 \) and \( \text{N}_2\text{O} \)) emissions (Mg \( \text{CO}_2 \text{e} \) ha\(^{-1}\)) over the 21st century, using either a normal crop (a) or a chlorophyll-deficient cover crop (d). The thick lines are the average of all locations simulated, while the shaded areas the interquartile range. Positive and negative emissions indicate an atmospheric source and sink, respectively. (b), (c), (e), (f) Spatial distribution of the albedo forcing ratio \( (\alpha_f) \) at 2050 for normal and bright cover crops, under the snow (b), (e) and snow-free scenario (c), (f). The potential productivity of the chlorophyll-deficient cover crop was reduced by 20% than the normal one and the albedo set to 0.28. Values equal to 1 indicate that the GWP from albedo is equivalent to the net soil GHG flux in the absolute term.
be evaluated with care as they may deplete the soil water reservoir compromising the yield of the following cash crops [38]. Indeed, a recent research [40] suggest that a higher soil water retention, related to a long-term use of cover crops and their improvement on soil properties, may balance the higher evapotranspiration.

It is important to stress that biophysical impacts on climate are occurring both at a local scale (i.e. at the location where the changes in surface properties have occurred) and, as a secondary effect, at a larger scale due to non-local impacts on the boundary layer, the water cycle, etc [41]. The magnitude of non-local effects are dependent on the overall area interested by the variation in surface characteristics; for instance, if cover crops are applied over a large area then the consequential increased evapotranspiration may have the extra indirect contribution of stimulating cloud formation [42], which further brightens the planetary albedo and increase precipitation. The quantification of non-local biophysical effects needs to be addressed with high-resolution coupled land-climate models, but these climate feedbacks are still far to be understood and their representation in model schemes is critical. In addition, current Earth System Models do not have a sufficiently fine spatial resolution and detailed management schemes to represent local practices

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**Figure 3.** Cumulative national mitigation potential in the EU member states. Emissions of biogeochemical and albedo radiative forcing at TOA (Tg of CO\(_2\)) under the full application of cover crops in the arable land by 2050, under snow (a), (c) and snow-free (b), (d) scenario. The balance is reported for the normal and (a), (b) chlorophyll-deficient cover crop (c), (d). The numbers in the square represents the EU whole mitigation potential. Positive and negative emissions indicate an atmospheric source and sink, respectively. Arable land area was gathered from EUROSTAT (table S1), and multiplied by the mean values of all predicted values within each member states, for the three component. MS nomenclature and arable area is reported in table S1.
[34], making the overall biophysical effects less accountable.

3.2. Biogenic and total mitigation potential

Our results show that the incorporation of cover crop biomass into the soil allowed a rapid SOC accumulation followed by a more asymptotic trend in the second half of the century. The cumulative sequestration rates ranged generally (1st and 3rd interquartile) between 5.2 to 17.0 Mg CO$_2$e ha$^{-1}$ (0.15 to 0.47 per year) by 2050 (figure 2(a)), which are in line with values reported by meta-analysis and previous modelling studies [9, 23]. The N$_2$O emissions were slightly lower than the baseline in the medium term, also due to the nitrogen fertilization reduction implemented assuming a recycle by cover crops uptake (figure 2(a)). Only in the long-term did N$_2$O emissions increase slightly driven by the higher SOC, resulting in a cumulative atmospheric source in some countries that never offset the carbon sequestration (figure 3). The uncertainties related to N$_2$O measurements and inventories [43] and the parameters governing model equations are still very high [44]. Meta-analyses seem to suggest that higher mean annual temperature and soil organic carbon content may increase N$_2$O emissions [45], which are two of the conditions prescribed and simulated by the model, respectively. Therefore, more research is needed to investigate those complex biogeochemical–climate-management interactions, especially for a GHG with such a powerful global warming potential [36]. Overall, the cumulative emissions (CO$_2$ + N$_2$O) were $-12.4$ Mg CO$_2$e ha$^{-1}$ on average by 2050 ($-9$ and $-13.9$ Mg CO$_2$e ha$^{-1}$ by 2030 and 2100, respectively).

The radiative mitigation potential of cover crops is an instantaneous effect, with interquartile values ranging from $-2.0$ to $-5.7$ Mg CO$_2$e ha$^{-1}$ in the snow-free scenario by 2050 (figure 2(a)). Under the snow scenario, these values were equal to 2.5 and $-4.3$ Mg CO$_2$e ha$^{-1}$, with some countries (Romania, Bulgaria, Hungary) showing cumulative equivalent positive emissions by change in radiative forcing at TOA (figure 3(a)).

To quantify better the relative contribution of the albedo with respect to the biogenic soil fluxes, we defined the albedo forcing ratio ($\alpha$fr) (see methods) in which, values close to 0 indicate the dominance of the biogeochemical component, while values approaching 1 indicate an equal contribution of both the biophysical and biochemical components. We found that by 2050, carbon sequestration was the dominant mitigation effect (figure 2(b)), which was progressively reducing its strength because of the finite soil capacity of accruing organic carbon. On the other hand, the albedo-induced radiative forcing is an instantaneous effect, which can have a cumulative long-term mitigation effect in some part of the EU of a similar magnitude to those due to biogeochemical processes. While the two activities might have an equal TOA radiative effect when globally averaged, we would like to stress, again, that the spatial pattern of that forcing is much more concentrated in space for albedo, leading to different effects on the climate at regional and local scales.

The simulations show that a full application of cover crops at member state level allows an estimated biogeochemical mitigation potential of 1336 Tg of CO$_2$e by 2050, with an additional contribution from albedo change likely between 99–430 Tg of CO$_2$e (snow and snow-free scenarios, corresponding to a removal of 2.8–11.9 Tg yr$^{-1}$ of CO$_2$e, respectively). The latter contribution resulted in a slightly lower share of total removals by the end of the century, since the continuous small strength of soil carbon sink (supplementary figures S6).

Bio-engineering to increase crop albedo may be a way to foster the radiative cooling of cover crops while maintaining all the benefits associated with higher soil organic carbon and, therefore, achieve an overall stronger mitigation potential. In fact, when we ran a scenario under a cover crop with high albedo we obtained a much higher $\alpha$fr by 2050 (figures 2(d)–(f)), indicating that the biophysical response generally overtook the biochemical component over the EU. Even in the most conservative snow-scenario, the overall mitigation potential at the EU level was 2541 Tg of CO$_2$e by 2050 (figure 3(c)). This scenario may be not so futuristic as a tested chlorophyll-deficient soybean mutant, although being still less productive, may be further modified to achieve the same yield in the near future as reported in [46].

According to this study, the use of a chlorophyll-deficient soybean with respect to a commercial variety allowed a radiative forcing of 1 Wm$^{-2}$, corresponding to a removal of 27 Mg ha$^{-1}$ CO$_2$e. For comparison, the high cover crop albedo scenarios resulted in a mean radiative forcing of 0.81 and 0.94 Wm$^{-2}$, equal to a GWP of $-18$ and $-21$ Mg ha$^{-1}$ CO$_2$e in the snow and snow-free scenarios, respectively.

4. Conclusion

The EU is ramping up its ambition to take bold climate change actions. This is seen both specifically in the agricultural sector, with the current planning of the post-2020 Common Agriculture Policy, but also in the broader scope of the European Green Deal. Accordingly, the EU is committed to reach GHG emission neutrality by 2050, which requires large investments and immediate cost-effective solutions, such as carbon sink from land management, to abate the current emissions (4483 Tg of CO$_2$ in 2017, www.eea.europa.eu/data-and-maps/indicators/greenhouse-gas-emission-trends-6-assessment-3). We have demonstrated that land management practices, such as the large-scale adoption of cover crops, could provide up to 1336 and 99–430 Tg of CO$_2$e by 2050 of mitigation potential with both
biogenic and biophysical effects, respectively. However, there is a fundamental difference between those strategies, which has a strong implication for policies. In fact, mitigation based on the uptake or reduced emissions of biogenic GHGs has a global diffused effect on temperature, since CO$_2$ and N$_2$O are well mixed in the atmosphere, hence making the trade of credits and debits globally equivalent, at least in principle. On the contrary, even if biophysical effects impact the mean TOA radiative forcing, they trigger predominantly local variation in temperature, in addition to poorly predictable non-local effects due to teleconnection in the climate system (e.g. mediated by clouds, advection of heat, etc.).

While different drivers are commonly converted in radiative forcing by metrics, some idealized experiments suggested the non-additivity between land use change and GHG effect [47]. We recommend that the additional mitigation capacity from albbedo changes, we estimated by cover crop adoption, should not be treated as CO$_2$ accountable quotes equal to those generated by GHG reduction, but rather as an indication where and how much the biophysical effect can generate additional benefit or trade-off to biogenic GHG exchanges.

Finally, further research is certainly needed to maximize the adoption of cover crops, taking into account soil moisture regimes, snow presence, carbon sequestration capacity and the color of bare soil. Cover crop can also decrease soil erosion and carbon displacement, inducing feedbacks on carbon cycle that are still unclear and poorly constrained [48]. This paves the way to a more comprehensive assessment of climate performance of other carbon sequestration practices, such as the management of residues, biochar addition, soil drainage, that can further alter the surface cover properties.

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Author contributions

E L and G D developed the research concepts; E L, G D, G C conducted the modelling and analyses; E L, G D, A J and A C performed the data interpretation. G D did the figures. E L took a lead on writing the paper with contributions from all authors.

Data and materials availability

All data needed to evaluate the conclusions in the paper are available at the European Soil Data Centre (ESDAC) of the European Commission—Joint Research Centre: http://esdac.jrc.ec.europa.eu/. Additional data related to this paper may be requested from the authors.

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