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Compaction induced losses in soil services in Europe under future climate

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Supplementary material for this article is available online

Abstract

Soil compaction has negative impacts on soil ecosystem services, such as food production, groundwater recharge and climate regulation. The extent, magnitude, and spatio-temporal variability of the environmental and economic impacts of compaction remain unknown. In this study, we develop a novel framework that couples a soil-compaction-agroecosystem model with climate projections from the Coupled Model Intercomparison Project (CMIP6) to systematically predict changes in crop yield, nitrogen losses, soil carbon stocks and surface water runoff from compacted arable land across Europe. Simulations were conducted at 0.11’ spatial resolution under the high emissions Shared Socioeconomic Pathway (SSP585) scenario. This was done for winter wheat, the most widespread crop in Europe, by considering an ensemble of three compaction levels (representing wheel loads of 4, 6 and 8 Mg) and projections from five climate models. The simulation outcomes were used to estimate the economic costs of compaction. We compared compaction induced changes in variables related to soil ecosystem services for the Near Future (NF, centred about year 2030), Mid-term (MT, 2050) and End of Century time horizons (EOC, 2090). We estimated annual compaction induced economic cost due to losses of crop yield, carbon and nitrogen for Europe to be approximately 7 ± 0.3, 5 ± 0.5 and 2.7 ± 0.3 billion € per year for the NF, MT, and EOC, respectively, with the decreasing trend attributed to overall decreasing yields due to climate change. In addition, the continental economic cost of flooding by soil compaction induced increase in runoff were estimated as 3 ± 0.7, 3.1 ± 0.6 and 3.2 ± 0.5 billion € for the NF, MT and EOC, respectively. Our simulations indicate the negative impact of soil compaction on soil services under future climate scenarios, adding additional challenges for sustainable future agroecosystems. This further highlights the need to develop policies that protect soil by mitigating soil compaction through improved traffic management practices, soil recovery measures, and the development of new agricultural machinery.

1. Introduction

Soil compaction is a major threat to soil functioning in modern agriculture, affecting soils across multiple regions and climates (Hamza and Anderson 2005, Nawaz *et al* 2013, Chamen *et al* 2015). Cropland soil compaction is typically caused by heavy agricultural machinery, with risks increasing when operations occur under structurally weak soil conditions that reduce soil bearing capacity. More than three decades ago, Oldeman (1992) estimated that 68 Mha of agricultural lands worldwide, including 33 Mha in Europe, had already been subjected to compaction. In response to rising food demands from a growing global population, the size and weight of agricultural vehicles has increased (Van Dijk *et al* 2021, Keller and Or 2022), likely contributing to greater levels and wider extent of soil compaction (estimates range between 25% and 45% of all agricultural land; Brus and Van Den Akker 2018, Keller *et al* 2019).

Soil compaction reduces soil water and gas transport properties (Pulido-Moncada *et al* 2022) and increases soil mechanical resistance (Ruiz *et al* 2015), which, in turn, impacts soil functions (Rabot *et al* 2018) and soil ecosystem services (Chamen *et al* 2015). There is abundant experimental evidence that soil compaction can lead to crop yield decline (Obour and Ugarte 2021) and increased nitrous oxide emissions (Hernandez-Ramirez *et al* 2021). However, evidence on how compaction affects nitrate leaching and carbon stocks is limited, and the underlying mechanisms remain unclear (Romero-Ruiz *et al* 2026). Investigations of the decline of soil ecosystem services due to compaction are limited to small ranges of climate and soil types (Hernandez-Ramirez *et al* 2021, Pulido-Moncada *et al* 2022), and most of these studies are conducted over relatively short periods of time (Håkansson *et al* 1987, Keller *et al* 2021), which limits their ability to assess the long-term effects of soil compaction under different pedoclimatic conditions. Compaction costs accumulate over time, which makes it challenging to assess the long-term costs. Few studies, typically using Life Cycle Assessment modelling and focusing on crop yield, have examined long-term compaction impacts at continental or global scales, with some suggesting that topsoil and subsoil compaction may reduce global crop yields by about 15% (Sonderegger and Pfister 2021).

The impact of soil structure and its degradation on soil functioning, although widely acknowledged, has only recently been considered in agroecosystem modelling, where it has been applied in studies on tillage effects (Jarvis *et al 2024)*, soil structure development by biological activity (König *et al* 2023), and soil compaction (Romero-Ruiz *et al* 2026). Applying climate projections to suitable models would offer valuable insights into the severity and extent of current and future compaction induced soil function loss at country and continental scale. In this context, the results of the Coupled Model Intercomparison Project (CMIP, Eyring *et al* 2016) have been used in agroecosystem models to predict the impact of climate change on soil services in croplands at global or continental scales. This approach has been integrated in food security studies on crop decline (Asseng *et al* 2015, Luchtenbelt *et al* 2024), nitrogen management in agricultural systems (Bodirsky *et al* 2014, Springmann *et al* 2018), irrigation and water security (Jägermeyr *et al* 2015, Wang *et al* 2021), greenhouse gas emissions (Li *et al* 2024), and land-use change and socio-political drivers of agriculture (Popp *et al* 2017, Springmann *et al* 2018). Despite the uncertainties in climate projections and crop models (Müller *et al* 2021, 2024), these studies have provided valuable information on global agricultural systems that guide policy-making. Acknowledging the significant adverse impacts of soil compaction on soil functioning, as well as the on-going trend towards larger and heavier machinery that likely enhances compaction risks in the future, information on how anthropogenic soil compaction influences soil ecosystem services under climate change is needed to guide the development of sustainable agroecosystems and secure future crop production.

In the present climate, soil compaction has a generally negative impact on soil ecosystem services (Nawaz *et al* 2013, Graves *et al* 2015), but the current severity and spatial patterns as well as their evolution under climate change remain unclear. In this study, we used an agroecosystem model that explicitly simulates compaction effects together with climate projection ensembles to assess the impacts of soil compaction on soil services in Europe.

2. Methods

We used a 1D process-based soil structure modelling framework that combines a compaction model with a model that simulates crop growth, and carbon and nutrient cycling (section S2 in SI). This model was used to simulate winter wheat (*Triticum aestivum* L.) growth across cropland in Europe using continental soil and climate data and to predict four key variables linked with soil ecosystem services: crop yield, soil organic carbon stocks, and nitrous oxide (N_2O) emissions and nitrate (NO_3) leaching from soil; and surface water runoff that is closely linked with flooding risk (figure 1).

2.1. Agroecosystem modelling approach

The RLM-SCC model developed by Romero-Ruiz *et al* (2026) was used in this study. The framework couples (i) an agroecosystem model (the Rothamsted Landscape Model, RLM; Coleman *et al* 2017) and (ii) a soil compaction model (Romero-Ruiz *et al* 2023). This coupled soil-compaction agroecosystem model simulates vehicle traffic compaction effects on soil processes related to crop growth and carbon and nitrogen cycling. By systematically integrating information about soil compaction induced changes in bulk density, macroporosity and saturated hydraulic conductivity, this framework allows quantification of impacts of compaction on soil states and related soil ecosystem services. The RLM-SCC employs the dual domain representation of water retention and hydraulic properties, modelled using the approach by

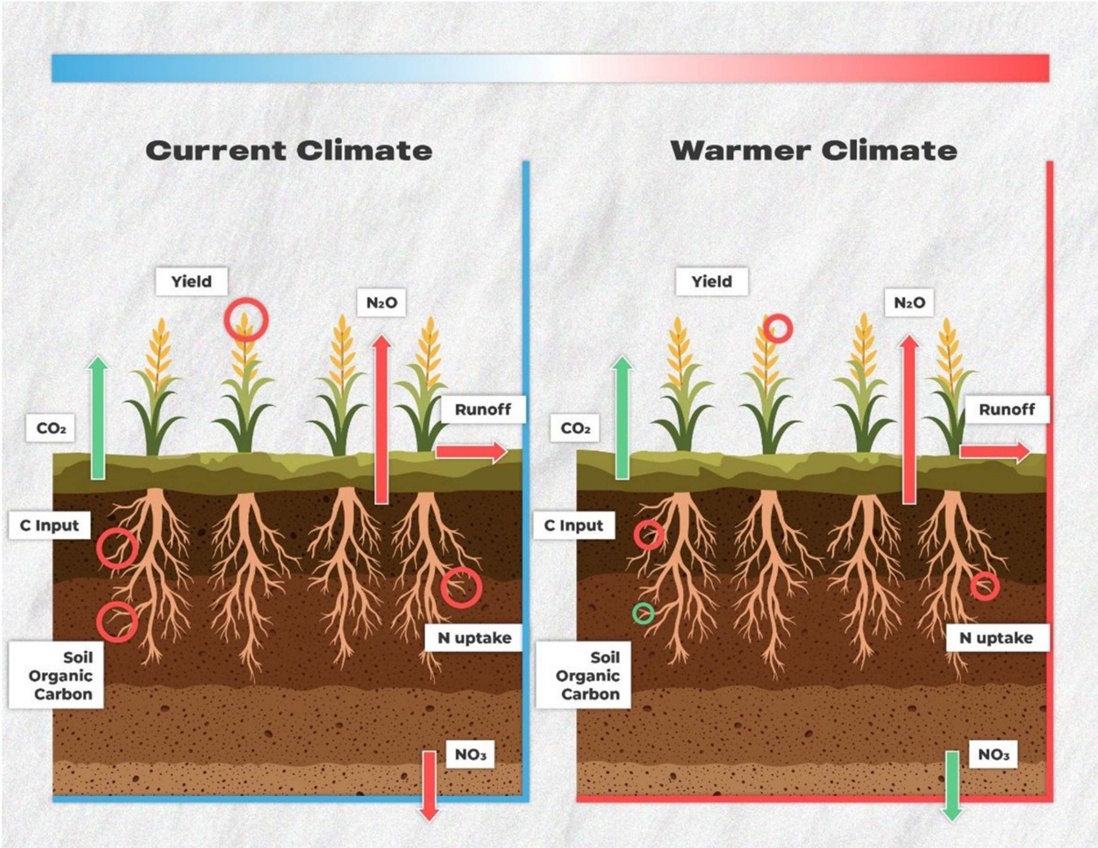

Figure 1. Graphical abstract. Schematic representation of changes in soil functioning by compaction in current (cooler) and future (warmer and with different precipitation patterns) climates. Under current climates, compaction results, on average, in losses in crop yield, increases in N_2O emissions, decreases in soil organic carbon stocks (negative balance between less inputs and less losses by CO_2), and enhanced NO_3 leaching. Under future warmer climates, compaction induces losses in crop yield and results in enhanced N_2O emissions. Yet compaction reduced losses of soil organic carbon stocks (positive balance between reduced inputs and reduced losses by CO_2) and reduced NO_3 leaching (positive balance between less uptake and less flushing). In the figure, losses are shown in red and reduced losses in green. The figure is based on the simulations conducted in this study (see section S1 in the supporting information SI).

Durner (1994) as:

$$S_e = \frac{\theta - \theta_r}{\phi_T - \theta_r} = w_{sm}\left[1 + (\alpha_{sm} h)^{n_{sm}}\right]^{1-\frac{1}{n_{sm}}} + w_{mac}\left[1 + (\alpha_{mac} h)^{n_{mac}}\right]^{1-\frac{1}{n_{mac}}} \quad (1)$$

and

$$K_{soil} = r_k K_{sm} \frac{(w_{sm} S_{e_{sm}} + w_{mac} S_{e_{mac}})^{0.5}}{(w_{sm}\alpha_{sm} + w_{mac}\alpha_{mac})^2} \times \left(w_{sm}\alpha_{sm}\left[1 - \left(1 - S_{e_{sm}}^{\frac{n_{sm}}{n_{sm}-1}}\right)^{1-\frac{1}{n_{sm}}}\right] + w_{mac}\alpha_{mac}\left[1 - \left(1 - S_{e_{mac}}^{\frac{n_{mac}}{n_{mac}-1}}\right)^{1-\frac{1}{n_{mac}}}\right]\right)^2, \quad (2)$$

where h is the pressure head, S_e is the effective saturation of the soil, θ_r is the residual water content, n_i is the van Genuchten (1980) exponent (related to soil texture) and α_i is related to the inverse of the air-entry pressure. In equation (4), K_{soil} is the pressure head (or water content)-dependent soil hydraulic conductivity (also known as relative permeability). The saturated hydraulic conductivity of the soil, $K_{sat} = r_k K_{sm}$, is defined as the product of the saturated hydraulic conductivity of the soil matrix, K_{sm}, and the ratio $r_k = K_{sat}/K_{sm}$. Hence, the modelled compaction induced changes in soil properties reflect in changes in (i) soil water dynamics controlling water availability for root water uptake, (ii) water filled pore space that is used—in addition to total porosity, which is also modified by compaction—to calculate nitrous oxide emissions by nitrification and denitrification, (iii) relative permeability of soils, ultimately determining daily water flow relevant for nitrate leaching, and (iv) daily carbon decomposition rates. The full description of the model development, implementation and calibration of the soil compaction model, and the interacting impacts of compaction on water flow, crop growth, nutrient and carbon dynamics is provided by Romero-Ruiz *et al* (2026) and summarized in section S3 of the SI.

2.2. Modelling setup

2.2.1. Climate scenarios, time horizons, and environmental zones

We conducted simulations using SSP585, which represents the highest greenhouse gas emissions and climate change trajectory. This scenario therefore serves as an extreme climate scenario to illustrate the potential risk of soil service loss due soil compaction under future climate conditions. SSP585 combines a 'fossil-fuel intensive' socioeconomic development pathway with a high level of radiative forcing (8.5 W m^{-2}) by the end of the century. We employed model outputs with standard (r1i1p1f1) initial conditions, daily temporal resolution, and 100 km (0.9°) nominal spatial resolution. Our ensemble consists of five climate projections and three compaction scenarios (see table S1 and next sections). We used raw (i.e. not bias corrected) native grid climate projections of the following coupled models: CMCC-CM2 (Cherchi *et al* 2019), CMCC-CM2-SR5 (Cherchi *et al* 2019), NorESM2-MM (Seland *et al* 2020), TaiESM1 (Lee *et al* 2020), and CESM2-WACCM (Danabasoglu *et al* 2020).

The climate variables, and hence agroecosystems modelling results, spanned from 2015 to 2100. The modelling results were analysed focusing on three temporal horizons: the NF (2020–2040), representing the current and near-future climate; the MT period (2040–2060); and the EOC period (2080–2100), both representing future climate conditions; and geographically according to environmental zones as defined by Metzger *et al* (2005) (see section S5 in SI for spatial extension and climatic variables for each zone).

2.2.2. Soil texture maps and water retention properties

Maps of soil texture (clay, silt and sand content) from six soil depths (0–1 m) across Europe were obtained from SoilGrids (Poggio *et al* 2021) at 0.11° spatial resolution. To better understand the primary influence of regional variations in soil texture and simplify interpretation, we considered all soil profiles to have a uniform texture across the entire depth range. For each location, the clay and sand content were computed as the averaged clay and sand content across all depths. Vertical averaging resulted in a mean continental standard deviation of 1.8% clay content (section S4 in the SI). This averaging leads to soil profiles representative of each location enabling interpretation of regional variations of soil texture at a continental scale. In addition, to increase the spatial resolution, avoid upscaling-related averaging from SoilGrids, reduce the number of individual simulations and optimise computing times, a *k*-means clustering algorithm was used to classify the soil texture maps (Lloyd 1982). We selected 20 different soil textural classes, providing a reasonable trade-off between accurately representing variations in soil texture across Europe (mean continental distance to cluster centroid of 2.7%) and reducing computation time (∼1/7 of the total number of individual simulations; section S4 in the SI). The water retention and transport properties of each soil textural classes were calculated based on the study and database of Carsel and Parrish (1988), using the pedotransfer functions described in Romero-Ruiz *et al* (2026).

2.2.3. Crop type and fertilization

We used winter wheat, the most important crop in Europe (harvested area ∼62.7 Mha[8]), in all simulations. The sowing date was set to October 1st at all locations. The harvesting date was based on the calculations by Heller *et al* (2024) and ranges for different locations from July 4th to September 20th (figure S5). Sowing and harvest dates were kept constant throughout simulations, and a fertilization rate of 150 kg Nha^{-1} yr^{-1} was added to all. The fertilization date across the continent was implemented as a function of the latitude ranging from 8th of February (38° N) to 18th of April (65° N; figure S5). Simulations were conducted at locations where cropland area was higher than 10% of total land area (according to the Copernicus Land Cover Land Use community; CLMS), leading to an approximate cropland of 188 Mha for Europe (FAOSTAT estimated 160 Mha cropland in Europe; FAO 2023) distributed across 28 426 pixels.

2.2.4. Soil compaction scenarios

The soil compaction scenarios were simulated using the soil compaction model by Romero-Ruiz *et al* (2023), calibrated by Romero-Ruiz *et al* (2026). To account for variability in farm machinery, we created an ensemble of simulations using three different wheel loads of 4, 6 and 8 Mg, representing typical wheel loads of agricultural machinery across Europe (Keller and Or 2022), and resulting on realistic predictions of changes in soil bulk density and saturated hydraulic conductivity (section S6).

In the compaction modelling scenarios, we aimed at representing the variation of soil compaction as a function of time in a simplified manner. Soil compaction was introduced on the 2nd year of the simulation (i.e. during year 2016) in all simulations and soil compaction recovery was not considered. Once induced, simulations used compacted soil properties from 2016 to 2100. This simplification was intentionally chosen as an approximation to represent realistic agricultural scenarios where the frequency of mechanical loading of soil caused by agricultural field traffic overshadows the slow recovery of soil structure as shown by Keller *et al* (2025).

[8] https://data.europa.eu/doi/10.2762/722428.

2.2.5. Results convention, modelling ensembles, and uncertainty quantification

Within the defined time horizons, the soil compaction induced mean annual changes (averaging over the 20 year periods) per hectare were defined as: mean annual change in crop yield (in Mg ha^{-1} yr^{-1}), mean annual change in organic carbon stocks of the upper soil layer (0–25 cm, Mg ha^{-1} yr^{-1}), mean annual change in N_2O emissions (kg ha^{-1} yr^{-1}), mean annual change in NO_3 leaching (kg ha^{-1} yr^{-1}), and mean annual change in surface water runoff (mm yr^{-1}). The soil organic carbon stocks are presented as yearly changes (i.e. differences between the change in carbon stocks in two consecutive years) and not accumulated losses. Across latitudes, we calculated both mean annual losses per hectare (g ha^{-1} yr^{-1}) and annual cumulative losses (g yr^{-1}) considering 3°-wide latitude windows (latitude uncertainty) from the 35–70° range. Reductions by soil compaction in crop yields and soil organic carbon stocks, and increases in N_2O emissions, NO_3 leaching and surface water runoff are expressed in this work as positive values (i.e. indicating increased losses).

For all variables and all years, we first averaged soil compaction induced losses of all compaction level sub-ensemble ($N = 3$; compaction level uncertainty) within each climate model, then averaged the results within each time horizon ($N = 20$; time horizon uncertainty), and then averaged the losses predicted for the ensemble of climate models ($N = 5$; climate model uncertainty) (table S1). Unless stated otherwise, the reported losses and standard deviations in this study were the results of the later averaging.

2.3. Estimation of compaction costs

To estimate the costs of soil compaction for the NF, MT and EOC scenarios, we used literature data of current market values and societal costs in combination with model simulations in this study (table S2). We report cost due to losses in yield, carbon and nitrogen as ecosystem service costs (E_{YCN}), and cost due to increased runoff as potential flooding costs (E_F). This is done because, although we acknowledge that flooding protection is an ecosystem service linked to water regulation, the actual economic impacts of flooding are expected to be highly variable and heavily depend on proximity to population/infrastructure and their calculation beyond the scope of this work. All estimations of total continental and country-specific costs are calculating considering 35% of compacted cropland in all grid cells.

2.3.1. Cost due to yield, carbon and nitrogen losses

Loss of winter wheat yield was valued at the average (from 2018 to 2025) European market price of €227 Mg^{-1}. This reflects only farm sales revenue and excludes input costs (OECD-FAO 2021). Loss of soil organic carbon was valued based on the cost of CO_2 (estimated for 2020 at a 2% discount average) resulting in a cost of carbon of €695 per Mg C, capturing climate-related damages but omitting factors such as soil fertility and biodiversity (EPA 2023). Nitrogen lost as N_2O was converted to CO_2 equivalents using the IPCC 100 year global warming potential of 273 and valued as for CO_2, resulting in €81 per kg N. Nitrogen lost as NO_3 via leaching was valued at €3.4 per kg N, considering costs for drinking-water treatment, undesired odour and taste, and increase in colon cancer risk (Preza-Fontes *et al* 2023). We used the same cost factors for each variable for all periods, i.e. we did not project the future costs of wheat, CO_2 and N losses. The annual economic cost linked to yield, carbon and nitrogen losses (E_{YCN}) was calculated as:

$$\begin{aligned} E_{YCN} = {} & \alpha_{yield}\left[€Mg^{-1}\right]\Delta\text{yield}\left[\text{Mg yr}^{-1}\right] \\ & + \alpha_{SOC}\left[€\ \text{Mg}^{-1}\right]\Delta\text{SOC}\left[\text{Mg yr}^{-1}\right] \\ & + \alpha_{N2O}\left[€\ \text{kgN}^{-1}\right]\Delta\text{N2O}\left[\text{kgN yr}^{-1}\right] \\ & + \alpha_{NO3}\left[€\ \text{kgN}^{-1}\right]\Delta\text{NO3}\left[\text{kgN yr}^{-1}\right], \end{aligned} \quad (3)$$

where α_x and Δx are the cost per unit and simulated annual losses for each variable, respectively.

2.3.2. Cost due to increase in water runoff and flooding risk

Flooding cost associated with agriculture were estimated using the annual cost from the UK ($E_{FTEC-UK}$) reported by EFTEC (2004) and the total runoff simulated in the NF for uncompacted soils in the UK (RO_{NF-UK}). This leads to an average annual flooding cost (α_F) of €2.3 mm^{-1}. Flooding costs are hence estimated as:

$$\begin{aligned} E_F &= \frac{E_{FTEC\text{ - }UK}\left[€\right]}{RO_{NF\text{ - }UK}\left[\text{mm yr}^{-1}\right]}\Delta\text{run}\left[\text{mm yr}^{-1}\right] \\ &= \alpha_F\left[€\ \text{mm}^{-1}\right]\Delta\text{run}\left[\text{mm yr}^{-1}\right]. \end{aligned} \quad (4)$$

As the real economic impacts of increased runoff associated with reduced groundwater recharge due to compaction are highly dependent on spatial proximity to infrastructure and population, we note that this formulation leads to a rough approximation of the potential cost of flooding.

3. Results

3.1. Spatial patterns within time horizons

3.1.1. Changes to soil services due to soil compaction in the near future

In the NF time horizon, the relative changes predicted for all variables were within the ranges observed in the literature (figure S8). We predicted a mean annual compaction induced crop yield decline of 0.08 ± 0.1 Mg ha^{-1} yr^{-1}, corresponding to an average crop yield decline of 2.3% (figure 2(a)). Yield losses were maximum (around 0.13 ± 0.10 Mg ha^{-1} yr^{-1})

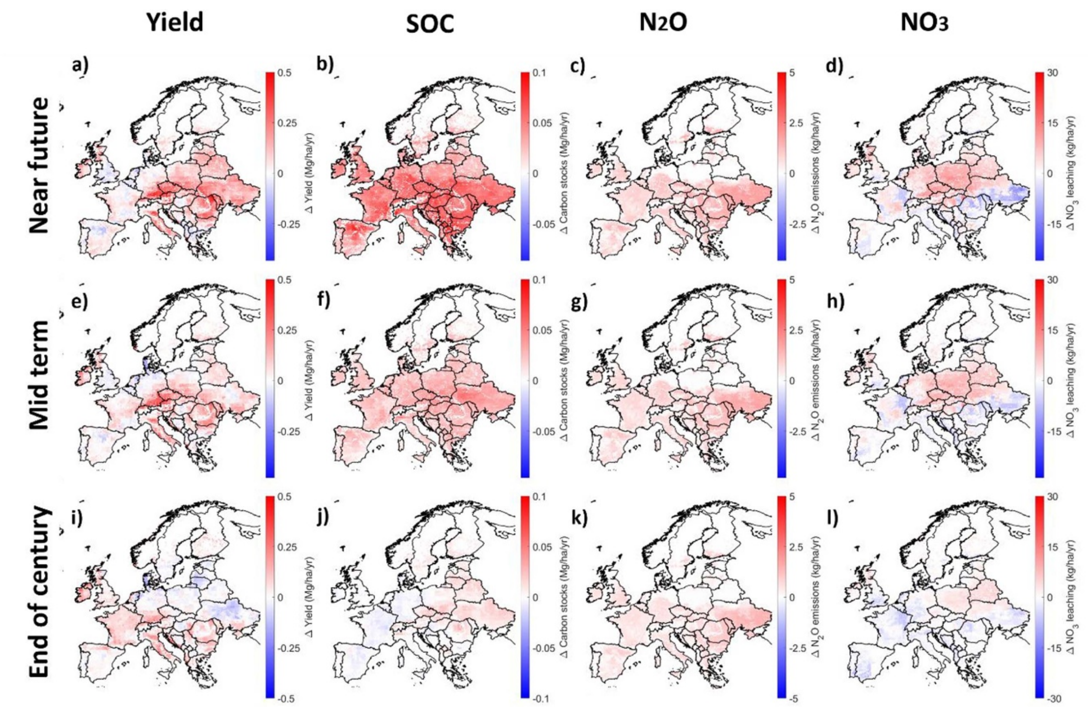

Figure 2. Simulated soil compaction induced losses in crop yields, soil organic carbon (SOC) stocks, N_2O emissions and NO3 leaching across Europe in the NF (a)–(d), Mid-term (e)–(h) and End of Century (i)–(l) time horizons for the SPP585 climate scenario. Standard deviation for these values are presented in figure S12 and in table S4.

in the Continental zone (zones shown in figure S6). Soil organic carbon stocks reduced due to compaction in all locations (figure 2(b)). Annual compaction induced reductions ranged from 0.00 to 0.09 Mg ha^{-1} yr^{-1} (average decrease of 0.07%) with highest values estimated in the Alpine South and Pannonian zones.

In all locations, the annual yearly N_2O emissions were predicted to increase with compaction (figure 2(c)). The mean increase in annual N_2O emissions was 0.7 ± 0.5 kg ha^{-1} yr^{-1}, corresponding to an increase in 14%. The highest losses occur in the Pannonian zone (1.2 ± 0.4 kg ha^{-1} yr^{-1}). Compaction induced changes in NO_3 leaching largely vary across Europe, and spatial patterns were also highly dependent on the latitude (figure 2(d)). In the NF, changes in NO_3 losses due to leaching spanned from increased losses of 4.4 ± 2.8 kg ha^{-1} yr^{-1} in the Atlantic North to reduced losses (compared with uncompacted soil) of up to −1.3 ± 1.7 kg ha^{-1} yr^{-1} in the Mediterranean South zone.

3.1.2. Temporal trends from near future to end of century

The mean annual crop yield losses were 0.08 ± 0.1 Mg ha^{-1} yr^{-1} (NF), 0.05 ± 0.08 Mg ha^{-1} yr^{-1} (MT) and 0.02 ± 0.07 Mg ha^{-1} yr^{-1} (EOC) (table S5). At the EOC, compaction induced yield losses were small in the Continental, Atlantic North and Boreal zones (less than 0.01 Mg ha^{-1} yr^{-1}, figure 2(i)). The annual changes in soil organic carbon stocks decreased from 0.04 ± 0.01 Mg ha^{-1} yr^{-1} in the NF (figure 2(b),) to 0.02 ± 0.01 Mg ha^{-1} yr^{-1} in the MT, while losses in annual soil organic carbon stocks were estimated for the EOC to be 0.002 ± 0.01 Mg ha^{-1} yr^{-1}. A compaction induced reduction of carbon stock losses were predicted in the EOC for the Atlantic central, Lusitanian, Atlantic North Mediterranean Mountains, Mediterranean North, and Mediterranean South.

Annual compaction induced changes in N_2O emissions were predicted to decrease from 0.7 ± 0.5 kg ha^{-1} yr^{-1} in the NF to 0.6 ± 0.5 kg ha^{-1} yr^{-1} in the MT and 0.5 ± 0.4 kg ha^{-1} yr^{-1} the EOC. In all time horizons, compaction induced emissions were lowest in the Alpine North and Nemoral ranging from 0.02 to 0.14 kg ha^{-1} yr^{-1}, and highest in the Pannonian zone with ranges from 0.7 to 1.23 kg ha^{-1} yr^{-1}. In the NF, the mean continental compaction induced annual loss by NO_3 leaching was 1.2 ± 5.3 kg $ha^{-1}yr^{-1}$, whereas compaction induced leaching losses of 0.9 ± 4.2 and −0.5 ± 2.5 kg ha^{-1} yr^{-1} were predicted for the MT and EOC, respectively. In the EOC, increased losses by NO_3 leaching remained for the Alpine North (4.3 ± 4.4 kg ha^{-1} yr^{-1}), Nemoral (1.9 ± 2.4 kg ha^{-1} yr^{-1}), Continental (0.3 ± 0.6 kg ha^{-1} yr^{-1}), and Boreal (0.7 ± 1.2 kg ha^{-1} yr^{-1}) (see supplementary table S5).

3.1.3. Soil compaction impacts along the north-south gradient

Crop yield losses due to compaction presented a bell-shaped curve as a function of latitude, with

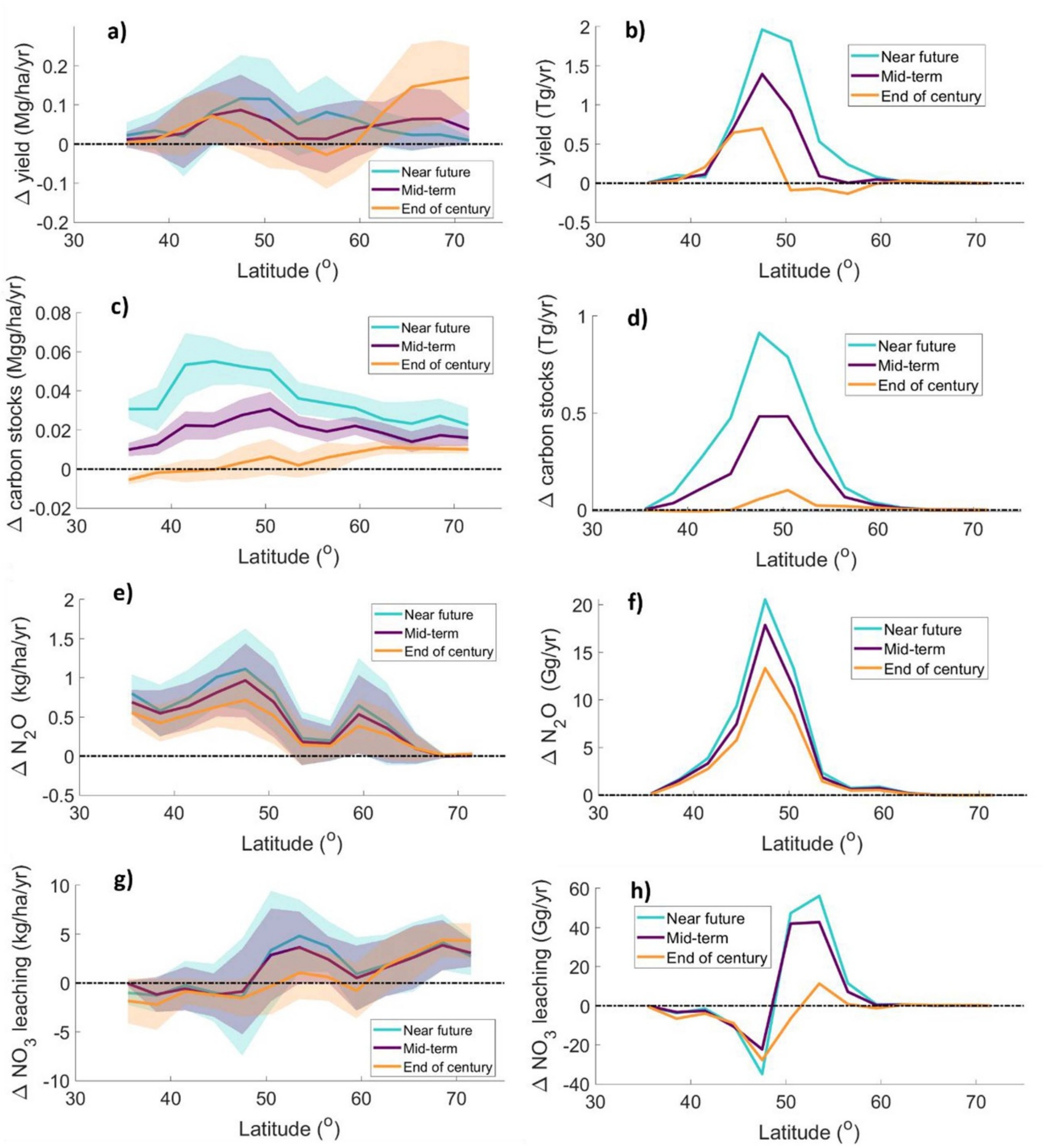

Figure 3. Simulated annual mean and accumulated (averaged and summed over a 3° latitude windows) compaction induced annual changes as a function of latitude for crop yield (a), (b), soil organic carbon stocks (c), (d), N_2O emissions (e), (f), and NO_3 leaching (g), (h). The shaded area envelops in the lefthand side panels correspond to the standard deviations of model simulations within the corresponding 3° latitude windows.

a peak in crop yield losses around 50° N latitude (figures 3(a) and (b)). Mean and cumulative crop yield losses were the highest for the NF for all latitudes lower than 60° N. The mean losses in carbon stocks were relatively constant across latitudes for all time horizons (figure 3(c)). In the NF, cumulative losses peaked at 45° N (figures 3(c) and (d)).

The compaction induced mean N_2O emissions showed a decreasing trend with increasing latitude (figure 3(e)). The trend and magnitudes for mean and accumulated losses in N_2O emissions were similar for all time horizons. In the NF, both the mean and accumulated compaction induced losses in N_2O emissions increased in latitudes between 50° and 60°, and were low beyond these values. Mean compaction induced changes in NO_3 leaching followed a similar dependence on latitude, yet they shifted to lower values for the MT and EOC, transitioning from absolute increases in leaching to reductions in leaching in latitudes up to 60° N.

3.2. Temporal patterns within environmental zones

We analysed the impact of compaction in three zones with contrasting climates (figure 4, table S5): Mediterranean North (MDN, Aridity Index of 0.35 in the NF), Continental (Aridity Index of 0.69 in the NF) and Boreal (Aridity Index of 1.72). Crop yield losses presented a decreasing trend as a function of time for the Continental zone, an increasing trend

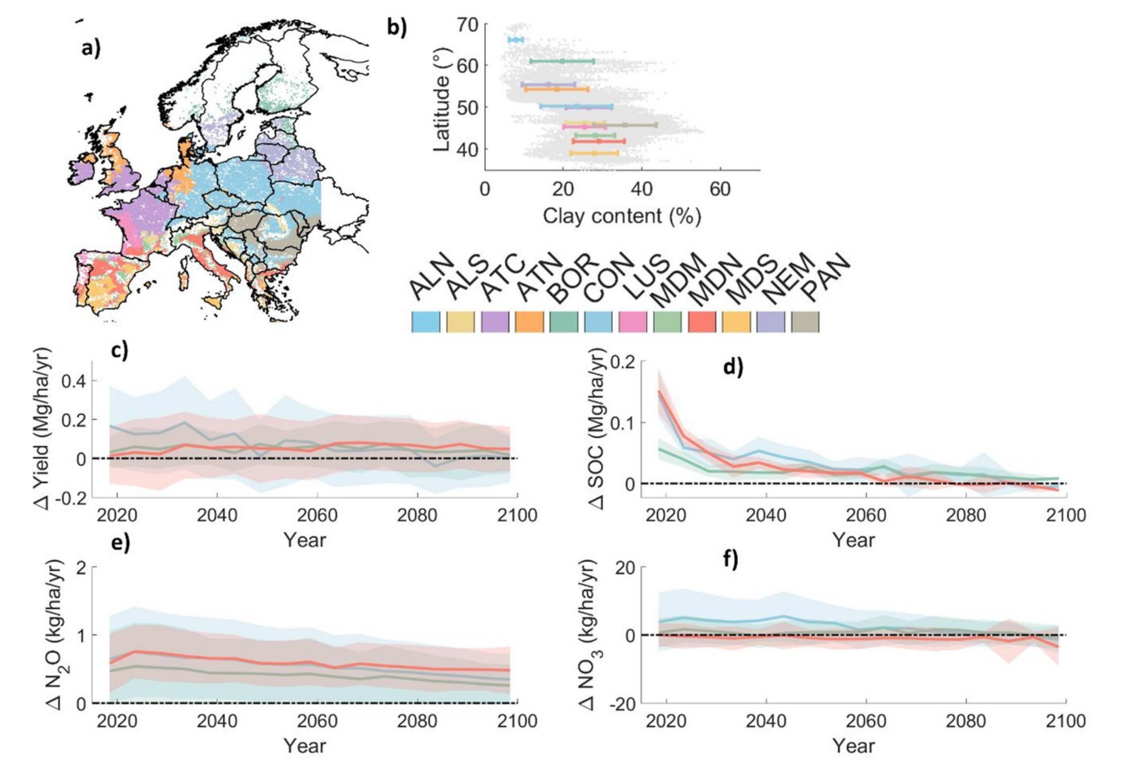

Figure 4. (a) Map of environmental zones and (b) clay content as a function of latitude. Simulated differences (compacted—non-compacted) in crop yield (c), soil organic carbon stocks (d), N_2O emissions (e), and NO_3 leaching (f). The relative values are presented for the three environmental zones (MND: Mediterranean North, CON: Continental, and BOR: Boreal). The zones are Alpine North (ALN), Nemoral (NEM), Atlantic North (ATN), Alpine South (ALS), Atlantic Central (ATC), Pannonian (PAN), Lusitanian (LUS), Anatolian (ANA), Mediterranean Mountains (MDM), and Mediterranean South (MDS). The shaded area envelopes correspond to the standard deviation within environmental zones and considering five-year time windows from 2015 to 2100.

for Mediterranean North, and no clear trend over time for the Boreal zone (figure 4(c)). The trends in changes in soil organic carbon stocks were similar for the three zones (figure 4(d)): losses in the first years after compaction were the largest, decreased over time and finally fluctuated around zero, between reductions and increases of soil organic carbon. Increases in N_2O emissions were highest for the Continental and Mediterranean North zones. The changes remained relatively constant for the three zones, with a slight decreasing trend for all zones (figure 4(e)). All zones showed a decreasing trend of the increased NO_3 as a function of time towards negative values (i.e. reduction of leaching losses). The year in which NO_3 leaching transitioned from compaction induced increases to compaction induced reductions vary depending on the climate zone, with the fastest transition occurring in the driest climate (MDN; figure 4(f)).

3.3. Estimated costs of soil compaction

We estimated a decreasing trend in the mean continental annual loss of 100 $\pm$ 47, 72 $\pm$ 40 and 38 $\pm$ 30 € ha^{-1} yr^{-1} for the NF, MT and EOC, respectively (figure 5, country-based predictions found in table S6). This corresponds to annual economic losses in Europe due to soil compaction of 7 $\pm$0.3, 5 $\pm$0.5 and 2.7 $\pm$0.3 B€ yr^{-1}, respectively. In the NF, crop yield losses and enhanced N_2O emissions accounted for 19% and 54% of the total costs, respectively. Soil organic carbon losses and increased NO_3 leaching contributed with 25% and 2% of the total costs, respectively. In the EOC, crop yield losses and increased N_2O emissions remained the main contributors to the total economic losses, with values corresponding to 18 and 82%, respectively. We predicted economic saves from reduction on NO_3 leaching compared with uncompacted soil to balance out losses corresponding to soil organic carbon loss (about 4% of the total losses). The continental annual costs of flooding due to compaction had small fluctuations across the century and were estimated to be 3, 3.1 and 3.2 B€ for the NF, MT and EOC, respectively (figure 5).

4. Discussion

4.1. Continental losses of crop yield, SOC and nitrogen

We predicted soil compaction induced changes in crop yields, carbon stocks, N_2O emissions and NO_3 leaching under changing climate, offering an avenue to understand unexplored spatial patterns of compaction damage. The ranges in simulated compaction

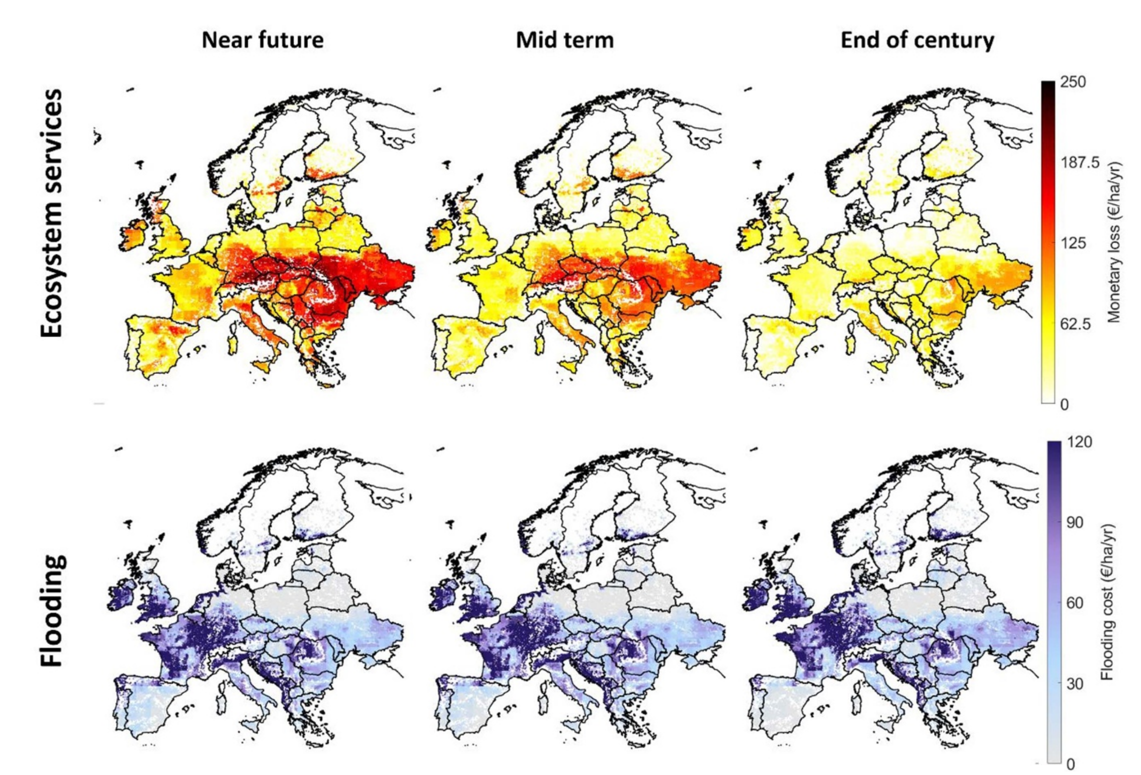

Figure 5. Estimated annual monetary costs from soil ecosystem services losses, involving losses in yield, carbon and nitrogen, due to soil compaction for the NF, MT and EOC (top panel). Estimated potential annual monetary costs from flooding due to soil compaction for the NF, MT and EOC (bottom panel). Country-based estimations and standard deviations can be found in table S6 of the supporting information.

induced changes in the modelled variables (see figure S8) demonstrate how the same compaction can lead to differences depending on yearly and long-term variations of weather and spatial variations in soil texture (figure S13). This highlights the challenge of quantifying negative impacts of compaction at a given field, which responds strongly to yearly weather variations and small-scale variations of soil texture within a field.

On average across Europe, crop yield losses due to compaction were predicted to be 2.3% for the NF and 1.4% for the EOC. The reduction in compaction induced yield loss is partly explained by a predicted ∼8% general decline in crop yields from the NF to the EOC, driven primarily by increased temperatures (Asseng *et al* 2015). Soil organic carbon stocks were predicted to decline relatively fast in the NF, with a relative loss of about 2% corresponding to a total loss of about 79 Gg C in Europe by 2040. By the end of the century, total soil organic carbon losses due to compaction were estimated to approximately 5% from today, which amounts to a total loss of about 143 Gg C in Europe. The changes in soil organic carbon resulted from two competing mechanisms: (i) reduced soil carbon inputs by roots and crop residues (figures S15 and S16), and (ii) reductions in mineralization-related soil carbon losses by CO_2 emissions (Beare *et al* 2009). Compaction led to net soil organic carbon losses in the NF. Over time and depending on the climatic zone within Europe, this balance between compaction induced reduced inputs and reduced emissions changed from negative values (i.e. increased soil organic carbon losses due to compaction) to positive values (i.e. reduced soil organic carbon losses due to compaction) by the EOC (figure S16).

Levels of N_2O emissions simulated across Europe were less sensitive than the other simulated variables to climate change induced increases in temperatures (Li *et al* 2024). The trends predicted for NO_3 leaching were sensitive to climate change-induced increasing temperature. Compaction increased continental NO_3 leaching in the NF but reduced leaching at the EOC. The transition year depends on the environmental zone (figure 4) and was linked with the efficiency for root water and nutrient uptake across the soil profile, and the amount of water available for drainage. In the NF, root water and nutrient uptake were higher (228 ± 69 mm yr^{-1} and 205 ± 53 kg $ha^{-1} yr^{-1}$, respectively) in the non-compacted than in compacted soil (figure S17), which reflects on higher yields losses due to compaction, and higher losses of NO_3 by leaching in compacted soils with respect to uncompacted soils. Rising temperature limit biomass accumulation (Asseng *et al* 2015), making root water and nutrient uptake more even between compacted and non-compacted soils, which results in overall decreases in NO_3 leaching losses in compacted soils due to reduced soil hydraulic conductivity. The predicted ranges in NO_3 leaching were consistent with literature reports of amounts of NO_3 leaching globally under current climate (Wang *et al* 2019).

4.2. Assumptions and uncertainties of the modelling framework

This works offers a systematic approach that situates the focus on soil structure and soil health to obtain continental scale and mechanistic estimations on the extent, spatial patterns and temporal trends of the impacts of soil compaction on variables that are key for soil-based ecosystem services. The study involves modelling choices and assumptions that may lead to several limitations as discussed below.

4.2.1. Process-based modelling limitations

Simplifying the description and interactions between system processes is an inherent limitation of mechanistic modelling, resulting from balancing trade-offs between robustly representing processes while avoiding overparameterisation and reducing computing times (Vereecken *et al* 2016). The simplified approach to model impacts of compaction on soil properties within the RLM-SCC, as discussed by Romero-Ruiz *et al* (2026), offered a novel systematic way to predict soil compaction impacts on soil properties within ranges observed in the literature (figure S9). In combination with the utilization of an ensemble of compaction scenarios, this ensures that, although the model calibration was conducted using data from a soil compaction experiment in a loamy soil experiment (section S6.1), the modelled changes in soil properties fall within the ranges of compaction-induced variations reported in the literature (Obour and Ugarte 2021, figure S9). Additional limitations of our approach relate to the reliance on calibrated empirical models to represent certain soil physical, chemical and biological processes, and the uncertainty of pedotransfer functions for water retention and transport properties estimations (Turek *et al* 2025). To explore model-biases, future work may address the implementation of compaction within other agroecosystem models, complementing results of this study and quantifying uncertainties related to model structure (Müller *et al* 2021).

4.2.2. Representing continental pedoclimatic conditions

Gridded continental simulations of agroecosystems processes and functions strongly rely on how pedoclimatic conditions are incorporated spatially and temporally. Although clustering soil texture variations across the continents introduced simplification of their spatial representation, it provided a reasonable trade-off between computational cost and the ability to capture continental variability of soil texture at a $0.11'$ resolution (figure S3(b)). We opted for considering homogeneous soil profiles, which enables direct interpretation of modelling results with regional variations of soil texture across the continent. Since such implementation equally impacts the compacted and uncompacted simulations, the simulated compaction induced losses resulting from layered and homogeneous soil profiles are similar (figure S4). Moreover, although continental country-based predictions of yields reasonably agreed with FAOSTAT yields (RMSE = 1.7 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$, figure S10), applying raw climate projections (i.e. non-bias corrected) underpredicted crop yield for high rain regimes where precipitation may be overpredicted (figure S10), likely due to the presence of unresolved local terrain effects such as coastlines or mountainous regions. In this work, the effect of bias correction is expected to be limited as the analysis is based on differences rather than absolute values, and spatial aggregation at ~100 km scale may also affect precipitation interpretation. Despite these simplifications, predictions of compaction induced losses were highly correlated between all climate models (ranging from 0.4 to 0.96).

4.2.3. Compaction and agricultural practices in a changing climate

We considered no recovery of soil compaction in our simulations to represent, in a simplified way, slow recovery and recompaction from agricultural practices that involve repeated wheeling (Duttmann *et al* 2022, Calleja-Huerta *et al* 2026). Because soil compaction recovery is very slow (years, decades or even longer in subsoils; Arvidsson 1996, Schjnning *et al* 2015, Keller *et al* 2021), it is likely that the duration between compaction events is shorter than recovery times, leading to a net gradual increase of compaction levels over time (Keller *et al* 2025). The development of strategies towards the usage of smaller vehicles may help to prevent compaction. Yet, these were not considered in this study, as current trends are still towards increasing vehicle size and weights (Keller and Or 2022). In addition, representing continental variations of agricultural management practices and how they could change as a function of time is a major challenge that was outside the scope of this manuscript. This includes the lack of consideration of diverse management practices such as crop rotations, adapting fertilization applications rates and times, etc. This limitation particularly impacts predictions of losses towards later parts of the century.

4.3. Estimation of economic losses due to compaction

4.3.1. Complementing currently scarce estimations

By considering various soil ecosystem services in cropland and simulating key variables linked to them, it was possible to estimate the economic costs of compaction across Europe. Based on an estimated 35% of compacted agricultural land in Europe (see in Keller *et al* 2019) and assuming this proportion remains constant throughout the century, soil compaction was projected to cause economic losses in Europe of 7, 5 and 2.7 B€yr^{-1} in the NF, MT and EOC, respectively; and flooding cost were estimated as 3, 3.1 and 3.2 B€ for the NF, MT and EOC, respectively. This complements the currently scarce large scale estimations of economic impacts of soil compaction, such as the study by Graves *et al* (2015), that estimated equivalent annual costs to be 70 € ha^{-1} yr^{-1} and 280 M€yr^{-1} for England and Wales (67 ± 22 € ha^{-1} yr^{-1} and 191 M€yr^{-1} were estimated in this study for the NF), and an increase of flooding cost of 193.2 M €yr^{-1} (197 M €yr^{-1} in this study for the NF).

4.3.2. Uncertainties and limitations of economic cost estimations

The economic costs were calculated using current market prices and estimated societal cost values, without considering future cost trajectories that may tend to increase (Costanza *et al* 2014), and other cost-increasing factors such as soil erosion, increase of fertilizer and diesel use and eutrophication, and did not consider escalation of soil compaction extent which can be expected considering the ongoing trend to heavier machinery. Moreover, environmental regulations are likely to become more stringent in response to these impacts, increasing the costs of compliance for agricultural systems. This suggests that the estimated soil compaction costs for yield, carbon and nitrogen losses are conservative estimates in both current and future climates.

The flooding costs were calculated using rough country-wide estimations for the UK (EFTEC 2004, Graves *et al* 2015). Our estimations imply that economic damage is the same across the continent, i.e. they do not explicitly consider other relevant regional elements such as topography or proximity to infrastructure, hence may not directly apply to other regions and present a higher uncertainty compared with costs related to yield, carbon and nitrogen losses.

4.4. Soil health maintenance and policy making

The projected economic and environmental losses were substantial for all European countries and across the century ranging from at least 2 M€ yr^{-1} in Montenegro to around 600 M€ yr^{-1} in France (see table S6). The growing recognition of soil health as a cornerstone of sustainable agriculture is increasingly reflected in emerging policy and management strategies (Shokri *et al* 2025). These approaches promote practices that reduce soil compaction risk, including regulating machinery loads and field traffic intensity, adopting controlled traffic farming, and developing low-impact or autonomous technologies such as lightweight machinery and unmanned aerial vehicles (Keller *et al* 2019, European Commission 2021). The systematic estimation of soil compaction costs presented in this study provides quantitative evidence to support the design of policies and management schemes aimed at protecting soil health while maintaining agricultural productivity.

5. Conclusions

The intensification of agricultural operations and increasing use of heavy machinery, combined with the low recovery times of compacted soils, are expected to exacerbate soil compaction across European agricultural and further contribute to soil function loss. In this context, we have simulated continental compaction induced of about 7 B€yr^{-1} and 3 B€yr^{-1} in the Near Future and End of Century, respectively; resulting from losses in crop yield, carbon and nutrient; and costs of flooding of about 3 B€yr^{-1}, and 3.2 B€yr^{-1} for the Near Future, and End of Century, respectively. This significant impact on soil services and economic output under current and future climate underscores the need for adaptive strategies to minimize soil compaction and promote soil health for improved sustainability of European cropland.

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Data availability statement

The summary of the simulations results presented in this study are presented in the supplementary files tables S4–S6.

Supporting information file available at https://doi.org/10.1088/1748-9326/ae7c8d/data1.

Supplementary Table S4 available at https://doi.org/10.1088/1748-9326/ae7c8d/data2.

Supplementary Table S5 available at https://doi.org/10.1088/1748-9326/ae7c8d/data3.

Supplementary Table S6 available at https://doi.org/10.1088/1748-9326/ae7c8d/data4.

Conflict of interest

The authors declare no competing interests.

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