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Policy implications of multiple concurrent soil erosion processes in European farmland

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Soil erosion is a serious threat to soil functions leading to land productivity decline and multiple off-site effects. Here we show, using a multi-model approach, the spatial risk of soil erosion by water, wind, tillage and harvesting and where the co-occurrence of these different processes is observed. Moreover, we analysed where these locations of multiple erosion co-occurrence are likely to intersect with the projected increase of dry/wet climate conditions. Of the ~110 million hectares (M ha) of arable land in the European Union, our estimates show that 43 M ha are vulnerable to a single driver of erosion, 15.6 M ha to two drivers and 0.81 M ha to three or more drivers. About 3.2 M ha of arable land are vulnerable to the possible interaction of increased flood, drought, water and wind erosion. We contend that this set of predictions serves as a basis for developing an efficient stratified monitoring network and informing targeted mitigation strategies under the Common Agricultural Policy 2023–2027. The road to the sustainable, carbon-neutral and biodiversity-friendly system of agriculture advocated for in the EU Green Deal goes through a thematic strategy for soil protection from multiple concurrent erosion processes.

Healthy soil is the foundation of agriculture and ecosystem functioning. Changes in soil quality affect the delivery of important ecosystem services, including the provision of food, water supply and regulation; carbon sequestration; and maintenance of a major microbial gene pool from which we extract biomedical resources, for example[1,2]. Erosion is notoriously ephemeral as it depends on the nexus of susceptible soil, antecedent moisture conditions and weather, especially the occurrence of climate extremes, large intense rainfall events or droughts with wind. However, when the right combination of events occur, positive feedbacks can lead to erosion striking with devastating socio-economic effect, for example, the dust bowl of 1930s North America. Soil erosion reduces soil stability, alters soil structures, impedes soil biology, reduces water holding capacity, leads to a loss of soil nutrients and potentially reduces soil organic carbon pools, therefore impairing all major functions of soil, not only its productivity. The ephemeral nature of erosion makes prediction and monitoring to allow for a proper risk assessment and policy mitigation quite challenging. Worldwide, very few national survey programmes of soil erosion exist (for example, US National Resources Inventory and Chinese National General Survey Program on Soil and Water Conservation). No coordinated monitoring exists across the European Union, and while recent modelling has been transformative in informing policy, it has been restricted to single

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processes[3] whereas often several natural and anthropogenic erosion processes operate in the same area[4] simultaneously or subsequently. In addition, single erosion processes may mutually reinforce or trigger each other and may thus require different mitigation measures. Using a combination of models, we present, for the first time, a novel assessment of the spatial distribution of the combined (additive) threat of four soil erosion processes across arable land in Europe. We are able to identify areas where a single process is dominant or areas with a combined effect where two, three or more processes are operating and interacting. This provides an unprecedented challenge to empirical science to continue to verify these predictions but acts as an early warning for policymakers to implement efficient monitoring to aid the direction and development of mitigation strategies on the ground. In addition, we are able to cross compare our model outputs with the locations of projected areas at risk from increased extreme weather events. This is critical as an increase in water surplus or deficit may mitigate the threat from erosion in some areas or, more importantly, exacerbate it in others, especially where wetter winters and drier summers are likely to intersect with areas vulnerable to water and wind erosion, exacerbating the total threat.

Geography and co-occurrence of soil erosion in Europe

Our multi-model approach provides estimates of gross soil displacement by water, wind, tillage and (root or tuber) crop harvesting on a 100 × 100 m grid cell basis for the arable land of the 27 EU member states and United Kingdom (~110 million hectares (M ha)). Gross soil-displacement rates here refer to the amount of soil moved annually from their original location, without considering sediment deposition within fields, expressed as a mass of soil per unit area and time (Mg ha^{-1} yr^{-1}; 1 Mg = 1 tonne). An estimated total of 575^{+108}_{-56} Tg (million tonnes) of soil is annually displaced by these four erosion processes over the simulated area, corresponding to an average area-specific soil displacement of $5.2^{+1.0}_{-0.5}$ Mg ha^{-1} yr^{-1}. This value is 95% greater than the average soil displacement due to sheet and interrill processes alone, which are typically the most commonly considered processes[3]. Figure 1a illustrates the spatial pattern of estimated soil displacement across the European Union's arable land. Large portions of this arable land area are projected to experience moderate (class 3) to severe (class 5) soil-displacement rates (Fig. 1). Co-occurrence analyses of different processes indicated that 43 M ha were vulnerable to a single driver of erosion (an area roughly equivalent to twice the land area of the United Kingdom), 15.6 M ha to two drivers and 0.81 M ha to three or more drivers (Supplementary Fig. 1). The latter is an important result of this study as two or multiple co-occurring processes might not only enhance the severity of soil degradation but may also trigger each other or lead to self-reinforcing feedback loops. There are various conceivable scenarios how erosion processes, simultaneously or subsequently, may enhance each other. One of them, for instance, could be water erosion in spring during snowmelt or heavy rain events that may deplete soil organic matter, impede its aggregate formation and reduce the development of the vegetation cover. This, in turn, may increase the risk for wind erosion during subsequent dry and windy periods. Similarly, the occurrence of tillage erosion, especially on wind-exposed hilltops or upslopes, may lead to a decrease in soil organic matter and deterioration of soil structure, thereby enhancing the impact of subsequent wind and water-erosion events. Erosion process combinations depend on topography, climate and management of respective sites. Therefore, site management has to consider individual mitigation practices to identify the underlying trigger process(es) to break self-reinforcing feedback loops and mutually reinforcing processes.

If we consider the commonly accepted long-term tolerable soil-displacement rate of 2 Mg ha^{-1} yr^{-1}, indicated by Verheijen et al.[5] as a suitable baseline rate for Europe given potential soil-formation rates ranging between a lower (0.3 Mg ha^{-1} yr^{-1}) and upper (1.4 Mg ha^{-1} yr^{-1}) limit, our results show unsustainable soil erosion rates occurring over half of the EU arable land (that is, 53.7% or ~55 M ha). With regard to the individual processes, soil displacement by water erosion is dominant both quantitatively (51% of the total displacement) and spatially (57% of the total area). Soil displacement due to water erosion in the European Union is estimated to be equal to a 1 cm displacement of soil annually from an area twice the size of Belgium. Tillage erosion is the second-largest driver of soil displacement with an estimated 36%, followed by wind erosion and crop harvesting with 10% and 2.7%, respectively. These numbers alone demonstrate the importance of adopting a multi-process modelling approach for estimating the soil erosion risk for Europe or any other global location. Although spatially and quantitatively dominant, there is still about 40% of soil displacement in the EU member states and United Kingdom that cannot be spatially attributed to water erosion but to erosion by tillage, wind or crop harvesting in arable landscapes. However, the ephemeral nature of all these processes means they often occur almost unnoticed without leaving substantial geomorphic evidence. Accordingly, our results suggest that countries such as Denmark and the Netherlands, generally considered to be little affected by soil erosion, are very prone to wind erosion risk resulting in about 79% and 73% of the area above the considered long-term tolerable soil erosion rate of 2 Mg ha^{-1} yr^{-1}, respectively.

This may be important where there is a high occurrence of organic soils, such as in Denmark, where soil may simply volatilize and disappear unnoticed. Likewise, the imperceptible creep of soil slowly downhill due to tillage operations is predicted to be highly diffuse in the EU member states and United Kingdom, resulting in $1.88^{+0.7}_{-0.2}$ Mg ha^{-1} yr^{-1} of soil displacement (Table 1). The geography of each individual process is illustrated in Supplementary Fig. 2, while Supplementary Fig. 3 reports the dominant process estimates in each individual cell.

The spatial prediction allows for an analysis of the data by climatic zones. Figure 1b reports the average soil-displacement rates, which mirror climate domains (that is, Mediterranean, continental, Atlantic, boreal, Pannonian and alpine—illustrated in Supplementary Fig. 4). Most soil erosion is projected to occur in the continental and Mediterranean zones (Fig. 1b) with respectively ~41% and ~29% of the total soil displacement. Respectively, 43% (47.3 M ha) and 18% (20.3 M ha) of the total arable land is located in these zones, while the average total area-specific soil-displacement values are 4.9 Mg ha^{-1} yr^{-1} and 8.2 Mg ha^{-1} yr^{-1}, respectively. About 17% of the total soil displacement occurs in the Atlantic zone (average rate: 4.2 Mg ha^{-1} yr^{-1}), which includes ~19 M ha of the arable land. The other zones account for ~10% of the soil-displacement estimation. Figure 1b also provides, as complementary information, the fractions of arable land per country above and below the tolerable rate (the spatial patterns are illustrated in the Supplementary Fig. 5). Countries with over 75% of their arable land above the tolerable rate include Italy, Bulgaria, Spain, Denmark, Austria, Czech Republic and Romania (Supplementary Table 1 provides the full country list). Country-wide differences in soil displacement due to the different processes are illustrated in Supplementary Fig. 6.

Given that most soil erosion processes, and especially water and wind erosion, are driven by weather conditions, it is highly relevant to also compare the spatial patterns of our multi-process soil erosion estimates with those of projected changes in weather. We anticipate that soil erosion by water will be reinforced in areas that get persistently wetter, while areas getting drier may become more vulnerable to wind erosion. We propose that areas vulnerable to water and wind erosion processes intersecting with areas where the wettest quarter becomes wetter and driest quarter drier will be the most vulnerable and will have the highest risk. Our analysis (Fig. 2 and Table 2) identifies the Atlantic and the continental climate zones as being the locations most vulnerable to water erosion with increasing weather extremes during the wettest quarter. The countries more vulnerable to water erosion during the wettest quarter are France (1.5 M ha), Germany (1 M ha), the United Kingdom (0.8 M ha), Italy (0.2 M ha) and Belgium (0.1 M ha).

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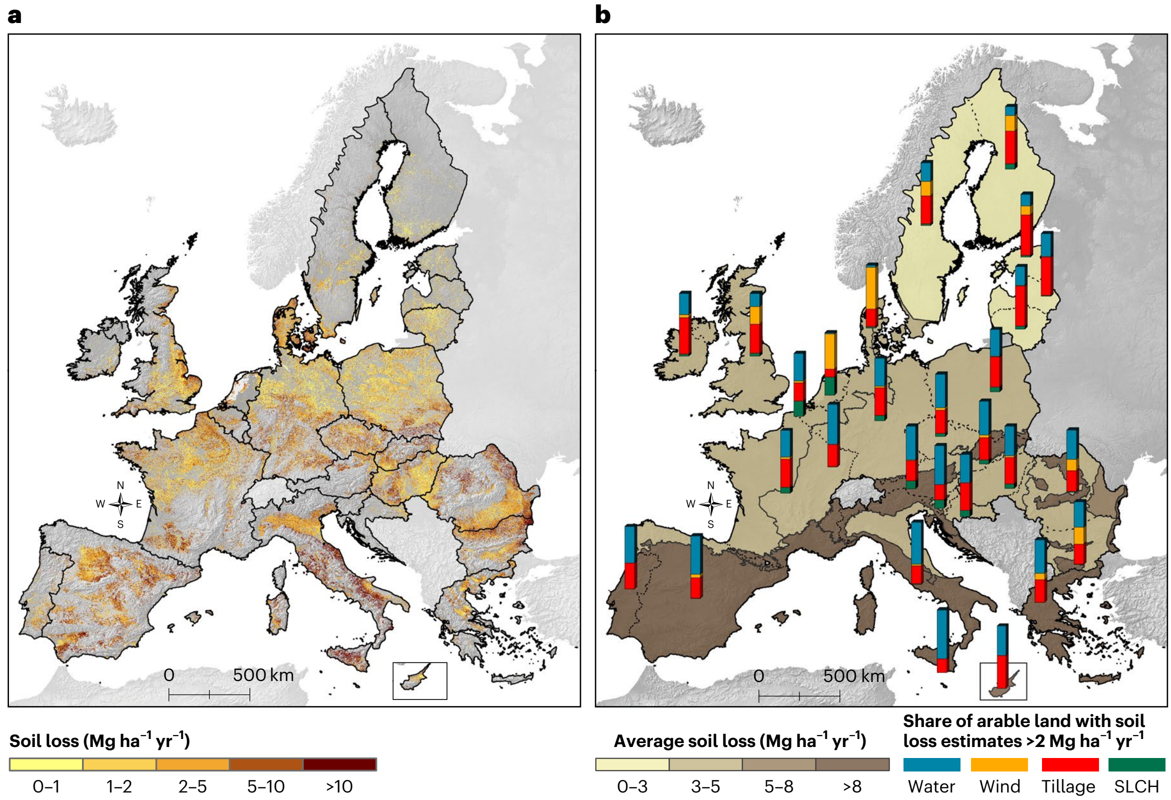

Fig. 1 | Potential multi-process soil displacement modelled for the EU member states and UK arable land. a, The soil erosion rates divided into five classes (very low–class 1; low–class 2; moderate–class 3; high–class 4; and severe–class 5). The colour gradation from yellow to brown indicates the intensity of the predicted erosion rates. The grey colour indicates the topography (hill shade derived from the National Aeronautics and Space Administration (NASA) Shuttle Radar Topography Mission[50] version 3.0) of the areas that were excluded from the modelling (that is, no arable land). **b**, The total annual soil rate (based on all four processes), averaged for the dominant climate (Supplementary Fig. 4) zones of Europe. The colour gradation from light tan to dark tan indicates the intensity of the predicted erosion rates. The vertical bars show each process' share of the arable land per country above long-term tolerable soil erosion rate of 2 Mg ha^{-1} yr^{-1}. SLCH is the acronym of soil loss by crop harvesting.

Table 1 | Descriptive statistics of the multi-process soil-displacement estimates

Erosion process	Soil displacement (Mg $ha^{-1}yr^{-1}$)	Total soil displacement (Tg)	Dominant cell process (Mha)	Land (%) with soil displacement (above 2 Mg $ha^{-1}yr^{-1}$)
Water	$2.67^{+0.15}_{-0.15}$	$295^{+17}_{-16.8}$	62.9	32.6
Tillage	$1.88^{+0.7}_{-0.2}$	$208^{+78.2}_{-26}$	31.4	26.6
Wind	$0.52^{+0.1}_{-0.1}$	$57^{+9.1}_{-9.1}$	13.1	6.8
SLCH*	$0.14^{+0.4}_{-0.4}$	$15^{+3.8}_{-3.8}$	3.1	3.2
Total	$5.21^{+1.0}_{-0.5}$	575^{+108}_{-56}	-	**69.2**

*Soil loss by (root) crop harvesting

During the driest quarter, vulnerability to water erosion is predicted to increase in a diffuse region covering most of central Eastern Europe. By contrast, noteworthy decreases in water erosion are predicted in Portugal, Spain, western France, southern Italy, Greece and Bulgaria. Concerning wind erosion, the Mediterranean climate domain possesses the most vulnerable areas due to increased drought during the driest quarter. Specifically, regions showing higher vulnerability to wind erosion are central eastern Spain (0.4 M ha), South Italy (0.3 M ha), Bulgaria (0.3 M ha), eastern Greece (0.2 M ha) and the Mediterranean coast in Provence (0.1 M ha). A few areas in the Mediterranean climate zones are considered to experience the highest risk, where wind and water erosion are both reinforced by more extreme rainfall surplus and summer drought.

Overall, these projections provide the basis for both: (1) designing a more targeted and efficient stratified monitoring scheme and (2) targeting policy for coping and mitigation actions. Monitoring design is most effective when a stratified random approach can be used. Understanding and identifying areas that are more susceptible to specific erosion processes can help in the delineation of strata for such an approach. In light of our findings, we also suggest that monitoring programmes need to be adopted not only to address water erosion[6,7], but also in finding strategies to mitigate tillage and wind erosion. For example, areas affected by both wind and water erosion may benefit from monitoring activities that aim to detect dust emission from fields/landscapes, especially when glyphosate-like herbicides[8] are used for terminating cover crops or weed control. This would help to identify areas with upwind pollution-emission sources that otherwise negatively impact the air quality of some EU cities. Concerning the opportunities for new policies, on the eve of entry into force of the new EU Common Agricultural Policy (CAP)[7], and while a new EU Soil Strategy for 2030, capable of addressing soil- and land-related issues in a comprehensive manner is under discussion[9], this work is timely, providing a first multi-process pan-European assessment of the primary threat to EU soil degradation. This study provides information that will help to set up the new EU strategies for monitoring, deploying soil-conservation measures and soil erosion mitigation actions (for example, Good Agricultural and Environmental Conditions (GAECs) and Farm to Fork Strategy)[10].

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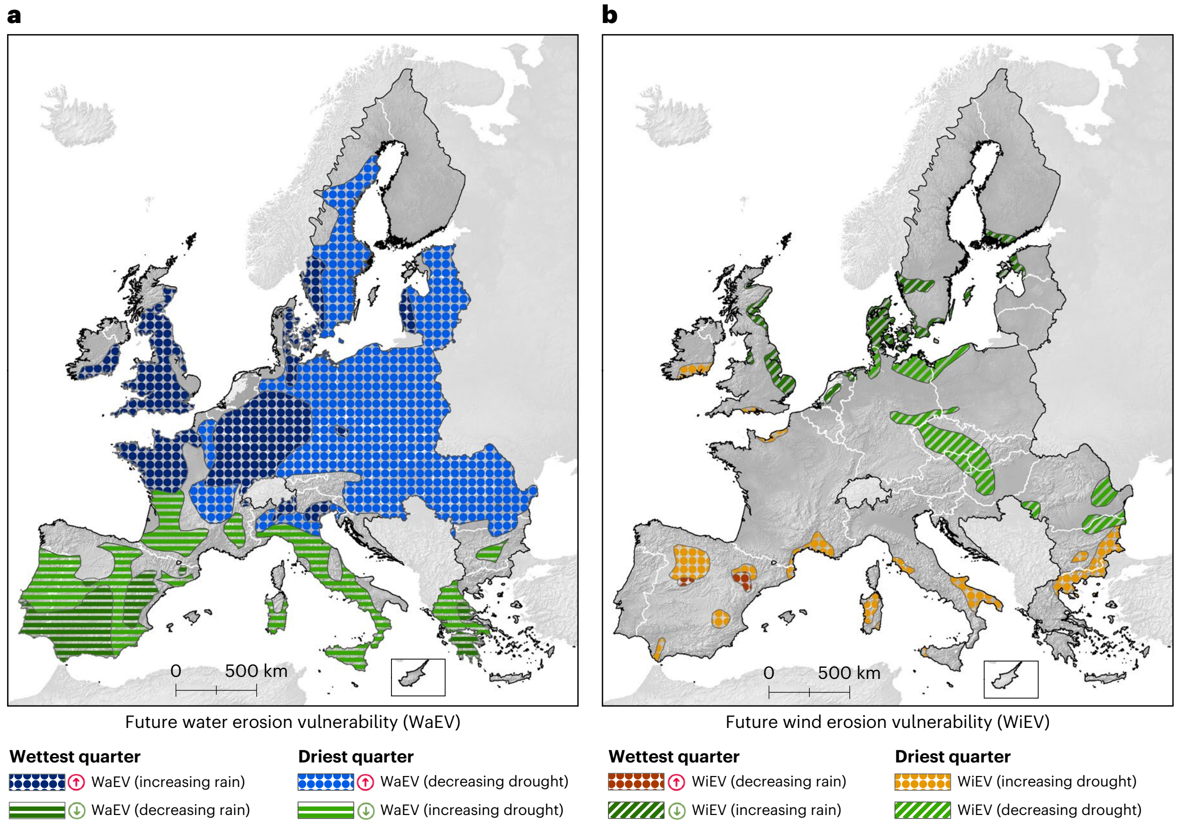

Fig. 2 | Changes in future water and wind erosion vulnerability in the European Union and United Kingdom. a,**b**, Changes in future water (**a**) and wind (**b**) erosion vulnerability in the European Union and United Kingdom based on the comparison of the long-term rainfall dynamics between the 1970–2000 period and the 2061–2080 period, according to the 'middle-of-the-road' scenario SSP2–4.5 (WorldClim[17]). The analysis assumes that soil erosion by water may be reinforced in areas that persistently receive more precipitation, whereas the areas getting drier may be more vulnerable to wind erosion. Dotted areas indicate estimated future increases in water or wind erosion. By contrast, the striped areas highlight estimated future decreases in water or wind erosion. Grey areas indicate areas with changes below the considered threshold (that is, ±5%). The grey colour indicating the topographic relief (hill shade) was derived from the NASA Shuttle Radar Topography Mission[50] version 3.0.

Table 2 | Descriptive statistics of future water and wind erosion vulnerability based on the comparison of the long-term rainfall dynamics between the 1970–2000 period and the 2061–2080 period, according to the 'middle-of-the-road' scenario SSP2–4.5

Process	Increasing rain	Increasing drought	Increasing rain and drought	Decreasing drought	Decreasing rain
	(Mha)				
Water erosion	4.1	14.4	0.01	15.4	3.1
Wind erosion	0.1	1.3		2.6	2.6
Total	4.2	15.7	0.01	18	5.7

Soil-conservation efforts and solutions in Europe

Writing the framework of the CAP scheme, soil-conservation standards are integrated in the cross compliance mechanism to promote resilient and sustainable agriculture. GAEC includes a set of standards identified by the European Union and member states concerning (1) minimum level of maintenance, (2) protection and management of water, (3) soil erosion, (4) soil organic matter and (5) soil structure. In the 2020 version of the GAEC, two standards directly address soil erosion mitigation (that is, GAEC–4: minimum soil cover and GAEC–5: minimum land management reflecting site-specific conditions to limit erosion), while a third one aims to reduce the transfer of soil pollutants to the riverine system (that is, GAEC–1: establishment of buffer strips along water courses). It is worth noting that GAEC standards are not applied homogeneously across the European Union but are rather country-based strategies, differing across the EU member states.

The standards adopted by most EU countries to reduce soil erosion can be summarized under two main actions: (1) increasing vegetation cover on arable land throughout the year and (2) reducing tillage intensity. These actions are desirable for increasing the functional agrobiodiversity[11] of the farming system. Cover crops increase carbon fluxes into soils aiding structural stability and nutrient retention, while minimum tillage maintains soil structure and allows fauna such as earthworms to structure the soil and bind soil minerals into aggregates, stabilizing the soil. According to the EU Farm Structure Survey, in 2016, conservation tillage was applied to 26.6% of EU arable land, with a marginal increase (0.8 percentage points) compared with the previous

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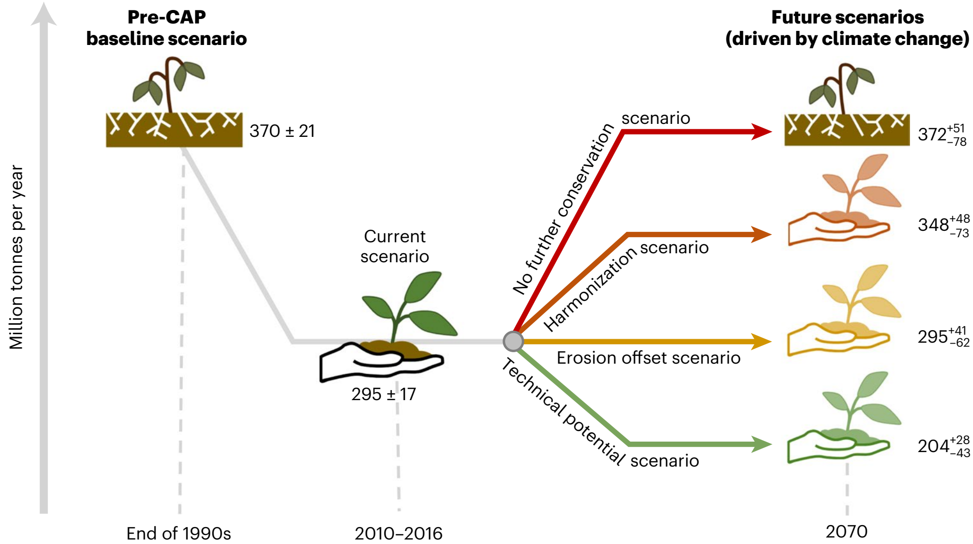

Fig. 3 | Flow diagram of the conservation scenarios and their effects on the soil displacement by water-erosion estimates. The pre-CAP baseline scenario assumes no implementation of soil-conservation measures (assumed year = 1990). The current scenario considers a set of management practices related to the GAEC (period = 2010–2016). The future scenarios consider four possible future land-management scenarios from the least (no further conservation) to the most conservative one (technical potential) (year = 2070). The confidence intervals in all scenarios are related to error propagation, accounting for the climate and probability distribution using Bayesian modelling. For the 2070 scenarios, the wider confidence intervals are related to the error propagation, which also accounts for the variability of future climate projections of the eight General Circulation Models.

EU Farm Structure Survey of 2010. No-till cover in the European Union showed both a low extent (4.2% of the total arable land) and a limited increase (0.2 percentage points compared with 2010). Both values are far from the ones recently observed in the United States, where no-till, for instance, is adopted on 40% of wheat and 30% of corn plantings with greater annual increase rates[12]. Concerning cover crops, an appreciable increase of 2.4 percentage points could be observed between 2010 and 2016 under the influence of the GAEC standard (GAEC−4), increasing the EU arable land under cover crops from 6.5% to 8.9% of the total area.

Our modelling approach demonstrates that compared to a pre-CAP baseline scenario and assuming no implementation of soil-conservation measures, GAEC soil-conservation standards reported for the EU member states and United Kingdom in the 2016 EU Farm Structure Survey could reduce soil displacement by a computed 20% (−75.5 g yr^{-1}; 1 Tg = 1 million tonnes) for water erosion, 27% (−55.3 Tg yr^{-1}) for tillage erosion and 9% for wind erosion (−5.3 Tg yr^{-1}). This results in a potential overall reduction of ~136 Tg^{-1} yr^{-1} (about −24% of the total annual soil displacement of 575.9 Tg yr^{-1}). Soil-displacement reductions associated with (root) crop harvesting were not estimated as mitigating strategies for this phenomenon and are completely lacking. Recent global-scale climate projections suggest that we are moving towards a more vigorous hydrological cycle[13], which may substantially affect future water-erosion dynamics. In a context where detailed wind projections are not yet mature enough for pan-European future erosion assessments, simple, physically plausible projections of rainfall erosivity can provide a reasonably accurate understanding of the mitigation strategies needed to mitigate future, more vigorous climatic conditions. Figure 3 illustrates the modelling insights obtained by simulating multiple future scenarios of water erosion by 2070 (using the middle-of-the-road rainfall-erosivity Shared Socioeconomic Pathway 2–Representative Concentration Pathway 4.5 (SSP2–RCP4.5) provided by Borrelli et al.[13]). Climate projections suggest that potential future net increases of rainfall erosivity in Europe are capable of offsetting the effect of current soil-conservation efforts, leading to a possible annual soil displacement in 2070 of 372^{+51}_{-78} Tg yr^{-1} (+1.6 Tg yr^{-1} compared with the pre-CAP baseline scenario). We also simulated three further scenarios, considering multiple policy actions aimed at soil conservation (Supplementary Tables 2 and 3). The *harmonization scenario* assumed the application of the current European average soil-conservation efforts (22.4% of conservation tillage, 4.2% no tillage, 18% of winter cover crops and contour farming for the arable land on slopes greater than 10%) to all arable lands. This yields an estimated reduction of ~20 Tg yr^{-1}. The *offset scenario* assumed an increase in the application of soil-conservation measures to offset the expected increases in water erosion due to climate change. This would correspond to 30% of conservation tillage, 15% no tillage, 35% of winter cover crops and contour farming for the arable land on slopes greater than 10%. Finally, the *technical potential scenario* assumed a very advanced conservative approach where contour farming is introduced on all arable land with slopes greater than 10%, 50% of conservation tillage, 20% no tillage and 30% of winter cover crops applied to the entire modelled arable land. In this last scenario, the annual soil displacement was estimated at $1.85^{+0.3}_{-0.4}$ Mg ha^{-1} yr^{-1}, with an overall soil-displacement reduction compared with the baseline scenario equal to 45% (total displacement 204^{+28}_{-43} Tg yr^{-1}).

Acknowledging some degree of uncertainty, our multi-process modelling approach presents novel insights into the various risks of soil erosion across Europe and where the co-occurrence of different processes may occur. Our analysis indicates that soil erosion rates often continue to exceed soil-formation rates. Although the CAP and regional programmes have been narrowing the gap over the past decades, both future geography and rates of erosion may be substantially affected by climate change. In a similar context, the proposed multi-model approach allows insights into the co-occurrence of soil erosion processes, performs ex ante and ex post policy evaluations and considers alternative conservation strategies. Depending on the spatial co-occurrence of different soil erosion processes, ad hoc management and mitigation measures should be defined accordingly. For instance, in areas prone to water and tillage erosion, with the latter acting as igniting process of self-reinforcing feedback loops and self-enhancing processes of soil degradation, mitigation measures such as contour farming, no-till or low-till and terracing may be highly effective management strategies. However, some of these mitigation measures, especially terracing, will be less effective if wind erosion is the main erosion agent. In this case, it is recommended to introduce hedges, lines of trees or temporary installation of landscape fences combined with high crop residue and strip cropping, especially, throughout the dry and windy season. Mitigation measures, when combined with prolonged vegetation cover during the wet season, may also be effective when both wind and water erosion co-occur in an area. As such, spatially explicit modelling of process distribution is an important step forward for region- and season-specific mitigation measures. Different types of mitigation have to be applied, given different types of erosion. Different types of erosion, however, may also require the involvement of different actors and spatial scales. For instance, addressing tillage erosion may involve more direct interaction with farmers, whereas wind erosion may require involvement of policymakers at a more regional scale. In this regard, knowing the likely co-occurrence of erosion processes can help decisionmakers providing an additional tool to move towards a climate-smart and integrated approach to manage agriculture landscapes in relation to soil erosion processes. Last but not least, the thorough comparison of multiple soil erosion processes provided in this study will help overcoming the dominant idea in policymaking that soil erosion by water is a synonym for soil erosion. Soil erosion by water certainly constitutes a major threat to soils. Multiple processes, however, contribute to soil degradation due to erosion, and, as our results suggest, tillage erosion is potentially just as big a threat as water-driven erosion for the European Union. Accordingly, solely considering soil erosion by water in the EU GAEC standards may be the result of an insufficient perception of the phenomenon by policymakers. Depending on the location one investigates, other processes of soil erosion may be more important. Scientists and decisionmakers should give adequate attention to this and develop appropriate solutions accounting for the processes co-occurrence. Scientifically, the multi-process modelling approach provides the basis for a more realistic, strategic and efficient approach to directing local modelling and field observations. Future proofing of the agricultural system requires a combination of mitigating the impact of extreme weather and adopting more sustainable practices, especially in vulnerable locations that have been identified in this study.

We recognize that the modelling based on data-driven assumptions has its limitations, among other factors due to the large-scale[14], the lack of unison multi-process modelling and site conditions that leave room for potential overestimation[15] of the overall soil erosion vulnerability. We see the need for field monitoring, including other processes such as land sliding and gully erosion[6,16]. However, in light of the insights gained from this multi-process soil-displacement assessment, we argue that large-scale modelling constitutes a powerful assessment tool for identifying erosion hotspots and areas of concern in Europe. It provides the basis for more targeted monitoring efforts, which could corroborate or contest the results presented here and help the scientific community to refine strategies for large-scale assessments of soil erosion.

Methods

Study area

The geographical extent of the study area includes the arable land of the 27 member states of the European Union plus the United Kingdom. The agricultural area under analysis consists of the three main agricultural units of the 2006 Coordination of Information on the Environment (CORINE) land cover inventory, covering a total area of 110.5 M ha: (1) 2.1.1 non-irrigated arable land (106.8 M ha, 96.7%), (2) 2.1.2 permanently irrigated arable land (3.1 M ha, 2.8%) and (3) 2.1.3 rice fields (0.6 M ha, 0.5%). This simulated area covers approximately 25% of the total land area of the European Union and the United Kingdom.

Overview

The overall objective of this study is to gain a broader understanding of the geography and co-occurrence of multiple soil erosion processes under arable land in the European Union and the United Kingdom. This information is essential for paving the way towards future integrated modelling and soil-conservation strategies. Here we provide quantitative soil-displacement estimates for four different processes: (1) water erosion, that is, top soil erosion due to interrill and rill processes (based on Panagos et al.[18]), (2) tillage erosion (based on Van Oost et al.[19]), (3) wind erosion (based on Borrelli et al.[20]) and (4) soil displacement due to (root or tuber) crop harvesting (Panagos et al.[21]). Hereafter and in the main text, we refer to these processes as water, tillage, wind and SLCH (soil loss by crop harvesting) erosion, respectively. All estimates of soil displacement are given as a mass of soil displaced per unit area and time (Mg ha^{-1} yr^{-1}). The four considered modelling approaches were run separate from each other. This means that each process was assumed to be independent from the others and that the proposed approach would not account for the possibility that one process (for example, water erosion) modifies or affects a factor (for example, soil properties) that could ultimately affect other considered erosion processes (that is, wind, tillage or SLCH). Supplementary Table 4 reports the main characteristics of the considered soil erosion assessments. The main methodological operations with respect to the harmonization of these model runs include (1) the harmonization of the spatial resolutions so the four assessments match a mutual 100 m cell grid (which exactly fits the spatial extent of the CORINE Land Cover inventory); (2) the definition of the modelled area, assuring that each soil-displacement assessment spatially matches the 110.5 million 100 m cell grid into which the arable land was subdivided, (3) geostatistical operations to compute the cumulative erosion rates and dominant erosion process in each cell and (4) the calculation of total and average soil displacement at multiple spatial scales, that is, climate zones, countries (EU Nomenclature of Territorial Units for Statistics (NUTS) level zero), regional scales (EU NUTS level two) and provincial scales (EU NUTS level three). A test was performed to compare the spatial agreement of EU arable land (CORINE 2006; used in this study) and CORINE 2018 data. The results from this analysis show that, in absolute terms, arable land in the European Union decreased only very marginally (about 0.05%) between 2006 (133.78 million ha) and 2018 (133.23 million ha). An additional analysis indicated that 126.8 million ha of the arable land did not experience any spatial change in use between the two time periods. Accordingly, the arable lands reported in this study, based on CORINE 2006, are about 95% spatially consistent with the ones reported in the latest CORINE 2018 version.

Modelling water erosion

Processes of water erosion may include splash erosion, sheetwash, rill erosion, piping erosion (or tunnel erosion) and (ephemeral or permanent) gully erosion. A combination of these processes may simultaneously occur on hillslopes, but they can also occur in isolation depending on the rainstorm and hillslope characteristics[22]. Piping and gully erosion currently remain notoriously difficult to predict, especially at continental scales, but are generally also restricted to specific areas with a relatively limited spatial extent. Conversely, interrill and rill erosion commonly occur in most landscapes. Interrill processes are the consequence of the rain-splash kinetic energy (that is, the primary cause of soil particle detachment and entrainment). Rill processes are the consequence of the interaction between concentrated overland flow and hillslope characteristics (for example, slope length and steepness, soil characteristics, vegetation cover), resulting in the formation of small channels (generally narrow and shallow).

Consistent with the predictive capacity of available large-scale models, soil displacement due to processes such as gullying and piping erosion were not estimated. Spatial patterns of long-term annual gross soil displacement (or gross soil loss[23] as it does not account for sediment deposition within the fields) due to interrill and rill erosion processes were estimated using a large-scale Geographic Information System (GIS) version of the Revised Universal Soil Loss

Equation (RUSLE), named RUSLE2015 (ref. [18]). RUSLE2015 belongs to the so-called detachment-limited model types, where the soil erosion (E, expressed in Mg ha^{-1} yr^{-1}) is estimated by the multiplication of six contributing factors (equation (1)). Conceptually, these factors represent the forces that physically govern interrill and rill erosion processes. R represents the driving force, that is, the rainfall-runoff erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}). The soil erodibility (K, Mg ha h ha^{-1} MJ^{-1} mm^{-1}) reflects the resistance of the soil against erosion. The other factors modulate this balance and are largely influenced by farming choices, that is, the topographical characteristics of the field (LS, dimensionless), cropping system (C factor, dimensionless) and soil-conservation practices (P factor, dimensionless):

$$E = R \times K \times C \times \mathrm{LS} \times P \quad (1)$$

The construction and properties of the data layers used to quantify these factors in the context of this study are described in detail in various sources. The spatial resolution of these layers was 25 m for LS[24], 100 m for C[25], 500 m for R[26] and K[27] and 1,000 m for P[28]. The native spatial resolution of RUSLE2015 is 25 m (defined by the topographical factor LS). Model output was then resampled to a 100 m cell grid using the Raster Resample Tool available in ArcGIS 10.6 (performing a nearest neighbour assignment interpolation method). Land cover (C) and conservation practice (P) conditions are representative for the year 2010. R values are representative for the period 2000–2010.

Modelling tillage erosion

Tillage erosion occurs in cultivated fields through the net downhill movement of soil due to tillage operations[29]. Govers et al.[30] suggested that tillage is a soil degradation process per se, rather than a process that simply makes the soil more sensitive to other forms of erosion. In hilly arable lands, the erosion and deposition rates associated with tillage can be as high as 100–400 kg m^{-1} yr^{-1} and locally easily exceed rates of water erosion[30]. Yet the variation in soil-displacement rates may be rather large, depending primarily on topographic characteristics, tillage depth and tillage direction and to a lesser extent to tillage velocity and implement characteristics[31]. Estimates on tillage erosion used in this study are derived from the pan-European assessment of soil displacement due to tillage erosion on European agricultural land as proposed by Van Oost et al.[19]. The authors applied a modified version of the tillage erosion model proposed by Lobb et al.[32].

This is a diffusion-type model that, contrary to recent directional models[33], does not account for tillage direction and the interaction between complex topography and soil translocation and operational settings (for example, tillage speed, depth and direction). This approach was adopted because more complex, directional models would require detailed information (for example, on tillage practices) that currently remain unavailable at the scale of Europe. The model is based on a minimal parameterization, where the downhill movement of soil due to tillage operations (E_t) (equation (2)) is a function of the erosivity of tillage operations (T_e) and the erodibility (L_e) of the cultivated landscape:

$$E_t \approx f(T_e, L_e) \quad (2)$$

A simplified version of the model applied by Van Oost et al.[19] for large-scale applications is organized as follows:

$$E_t = K_{til}\left(\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2}\right) \quad (3)$$

where E_t is the tillage soil-displacement rate (in kg m^{-2} per unit time), h is the elevation (in m), x and y are distances (in m) and K_{til} is the tillage (soil) transport coefficient (in kg m^{-1} per unit time).

Here we report an application of the Van Oost et al.[19] model obtained using the Water and Tillage Erosion Model and Sediment Delivery Model (WaTEM/SEDEM) tool provided by Van Oost et al.[34]. A diffusion-type model where T_e was defined using the proportionality factor K_{til} (set constant to 500 kg m^{-1} yr^{-1} for the whole of Europe, as also done by Van Oost et al.[19]), and L_e was spatially defined using the topography total curvature (rate of change in slope gradient) obtained by the 25 m cell size European digital surface model. More details about the modelling procedure are provided in Van Oost et al.[19,31]. The native spatial resolution of the European map of tillage erosion was 25 m, and it was resampled to a 100 m cell grid using the Raster Resample Tool available in ArcGIS 10.6 (performing a nearest neighbour assignment interpolation method).

Modelling wind erosion

For the quantitative estimate of soil displacement by wind erosion, we used the Revised Wind Erosion Equation (RWEQ). RWEQ is a combination of empirical and process modelling and has being extensively tested under field conditions[35]. It provides field-scale estimates of soil gross displacement due to wind[36]. Accordingly, in this case, sediment deposition within the fields was not considered. Technically, in RWEQ, the average soil erosion from a (complete) field is given by dividing the computed transport mass by the field length. The transport mass in RWEQ "is the mass of soil being transported by wind in a band of unit width that extends from the soil surface to a specific height of 2 meters"[35]. Here we used the soil-displacement (SL) estimates obtained by the application of GIS version of the RWEQ (named GIS-RWEQ), presented by Borrelli et al.[20] for large-scale applications. GIS-RWEQ is a simplified version of RWEQ with a driving force (that is, the wind factor, WF), resistance terms (that is, the soil erodible fraction, EF; soil crust factor, SCF; and soil roughness, K) and other factors representing the farming characteristics and practices, that is, the field size and orientation (Field) and crops on the ground (COG). More specifically:

$$\mathrm{SL} = \frac{2_x}{s^2}\, Q_{\max}\, e^{-\left(\frac{x}{s}\right)^2} \quad (4)$$

where S is the critical field length (m) and Q_{max} (kg m^{-1}) expresses the maximum transport capacity:

$$Q_{\max} = 109.8 \times (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times K \times \mathrm{COG}) \quad (5)$$

$$S = 150.71 \times (\mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times K \times \mathrm{COG})^{-0.3711} \quad (6)$$

The native spatial resolution of the GIS-RWEQ map is 1 km (ref. [20]). Here the estimates were resampled to a 100 m cell grid. The portion of arable land within the original 1 km GIS-RWEQ estimates (equal to 81%) was resampled through a nearest neighbour assignment interpolation method (using the Raster Resample Tool available in ArcGIS 10.6). For the remaining areas (equal to 19%), the resampled information was obtained through interpolation (using the Inverse Distance Weighting interpolation method in ArcGIS 10.6).

Modelling crop harvesting erosion

The estimates of soil displacement due to (root and tuber) crop harvesting rest on the work performed by Panagos et al.[21], with some further operations of data spatialization. The method proposed by Panagos et al.[21] combines crop statistics of the European Union and United Kingdom (aggregate at regional EU level NUTS2) with soil-displacement rates due to crop harvesting reported in literature[37–41]. The crops considered were sugar beets and potatoes, which according to the European Commission Statistical Office, in the period 2000–2016, covered 1.1% (1.92 M ha) and 1.3% (2.27 M ha) of the EU-utilized agricultural area (reference year 2018), respectively. The average regional SLCH was estimated as follows:

$$\mathrm{SLCH} = \mathrm{NUTS2}_{ha} \times \mathrm{Textural\ Index} \times \mathrm{SLCH}_{rate} \quad (7)$$

where $NUTS2_{ha}$ represents the hectares cultivated with sugar beets and potatoes in each EU NUTS2 region, $SLCH_{rate}$ represents an estimate of the potential average soil-displacement rate per country based on available data from the literature. For sugar beets, this ranges from 4.7 Mg ha^{-1} per harvest in the United Kingdom to 10 Mg ha^{-1} per harvest in Denmark and France[39,42]. For potatoes, SLCH is assumed to be 3 Mg ha^{-1} per harvest in all considered countries[40,43]. The textural index is a correction factor that adjusts the SLCH to describe the impact of the soil physical properties on $SLCH_{rate}$. It was computed as follows:

$$\text{Textural index} = \frac{1}{\text{ha}}\,(\text{total})\sum_{k=1}^{12}\text{USDA}_k \times \text{ha}_k \qquad (8)$$

where k refers to each of the 12 United States Department of Agriculture (USDA) soil texture classes in which the EU and UK soils were classified[44], $USDA_k$ is a texture correction factor with possible values: 0.25 (sandy soils), 0.5 (sandy clay, sandy clay–loamy, sandy loam and silt), 0.75 (loamy sand, silt–loam, silty clay, silty clay–loam) and 1 (clay, clay loam, loam)[38,42]. The term ha_k refers to the area of arable land in the specific region which has a given $USDA_k$ value[44].

Here the approach of Panagos et al.[21] was applied in a spatially explicit pixel-based fashion, overcoming the original limitation related to the regional aggregation to the EU NUTS2 level. To do so, we used the pan-European crop-type map (reference year 2018) of d'Andrimont et al.[45], which provides gridded information on potato (code 221) and sugar beet (code 222) locations. The map was obtained combining Sentinel-1 radar imagery and the Copernicus Land Use-Land Cover Area Frame Survey (LUCAS) in situ observations. Buffering operations were applied to fill some no-data gaps. Moreover, further pixel allocation operations were also applied to ensure a very good match between the remote sensing data and the statistics[46].

Uncertainty of the soil-displacement estimates

The modelling approaches used were purely deterministic in their outcomes in relation to their input data and did not inherently provide an assessment of the associated uncertainties. Therefore, the uncertainties associated with each simulated erosion process were computed as follows. For water erosion, the uncertainty associated with RUSLE-based estimates was computed following the scheme already presented in Borrelli et al.[47,13]. Overall, the uncertainty was represented as a probability distribution using a Bayesian modelling technique for each factor implemented in the modelling structure. Combining a large number of simulations (in a Markov Chain Monte Carlo approach), allows estimation of how the uncertainty propagates in the model output (soil displacement). Yet, as deriving spatially continuous simulations for each of the layers is impractical at such a scale, a simulation approach based on Gibbs sampling and an additive model was used:

$$z(S_0) = z(R) + z(\text{LS}) + z(K) + z(C) + e(s) \qquad (9)$$

where the $z()$ values are a realization of each of the log-transformed model input layers and $e(s)$ is the spatial component of the model. R, LS, K and C are the inputs of the RUSLE equation.

To account for the rainfall intensity–kinetic energy (I–KE) relationships for different regions, we used coefficients of the exponential relationships fitted through collected field data as described in Borrelli et al.[13]. We then used different regional I–KE relationships and their standard deviations to quantify I–KE uncertainty in present and future rainfall-erosivity estimates. In the case of the 2070 scenarios, the wider confidence intervals are related to the error propagation accounting also for the variability of future climate projections of the eight General Circulation Models (GCMs) used to assess future rainfall erosivity and the set of uncertainties already considered in the current scenario (2010–2016). These large confidence intervals associated with future climate projections reflect the higher uncertainty of these estimates. The *wind erosion* estimates rest on daily simulations covering a ten-year period (about 3,600 individual simulations). Uncertainty values for wind erosion were estimated by accounting for the ten-year time series variability plus the spatial distribution of soil erodibility. To assess the predictability of a given year, a regression model based on the data of the remaining years in the series was fitted using all the simulated pixels. Then, prediction confidence intervals were calculated by using a Markov Chain Monte Carlo approach to estimate regression parameters and their empirical variance. The process was repeated for each one of the years in the time series and the respective confidence intervals were pooled to derive an interval for the whole series. In the case of *tillage erosion*, the uncertainty was computed based on the possible spatial variability across Europe of the transport coefficient K_{til}, which is the main unknown variable if we do not consider the errors associated with the digital terrain model (DTM). Consistently with Van Oost et al.[19], we applied a K_{til} value of 500 kg m^{-1} yr^{-1} over the entire study area. Afterwards, we repeated the simulation applying K_{til} values representing a lower (400 kg m^{-1} yr^{-1}) and an upper (800 kg m^{-1} yr^{-1}) boundary. These values, according to Van Oost et al.[19], are typical for mechanized agriculture in Europe under primary tillage with a mouldboard or chisel plough (depth about 0.2 m) and two secondary operations with a harrow or disc. SLCH, our average rates of soil displacement due to (root and tuber) crop harvesting were very close to the median values reported by field measurements in Europe[21,48] (modelled–sugar beets: 5 Mg ha^{-1} yr^{-1}, potatoes: 2.25 Mg ha^{-1} yr^{-1}; field measurements–sugar beets: 5.66 Mg ha^{-1} yr^{-1} ($n = 13$), potatoes 2.25 Mg ha^{-1} yr^{-1} ($n = 7$). The upper and lower bounds were obtained by adding and subtracting possible maximum margins of error derived from the statistical analysis of field measurements reported in the literature[21,48] to our values.

Error propagation

A summary of error was calculated considering the uncertainty of (1) the spatial estimated water-erosion predictions using the proposed Bayesian modelling approach, (2) the uncertainty associated with the interannual variability of the wind erosion estimates, (3) the uncertainty related to the range of the K_{til} factor (tillage erosion) and (4) the uncertainty of the soil-displacement estimates associated with crop harvesting. The error propagation is the square root of the sum of squares of the different uncertainties.

Future water and wind erosion vulnerability

Here we propose an analysis to gain insights on change in future patterns of water and wind erosion vulnerability in the European Union and the United Kingdom based of the comparison of measured (1970–2000) and projected (2061–2080) long-term rainfall data. In both cases, we used WorldClim[17] data. More precisely, we used the WorldClim bioclimatic variable BIO16 (precipitation of wettest quarter) and BIO17 (precipitation of driest quarter). For the future projections, we used the average values obtained combining the bioclimatic variables of eight GCMs (Supplementary Table 5). The selected future climate scenario was the one derived from the SSP–RCP4.5, known as the 'middle-of-the-road' scenario. In the analysis, we assumed that soil erosion by water will be reinforced in areas that get persistently wetter while areas getting drier may become more vulnerable to wind erosion. Potential increases or decreases of future erosion are reported where changes between the two considered periods were greater than the considered threshold of ± 5%.

Soil-conservation scenarios

The estimates of soil displacement by water erosion for the 2070 scenarios rest on the future climate projections of Borrelli et al.[13], which according to our tests, were free from errors described by

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McGehee et al.[49] for some Rainfall Intensity Summarization Tool (RIST) versions. Future rainfall erosivity was constituted by the average value obtained using 14 GCMs and the 'middle-of-the-road' scenario SSP2–RCP4.5 (more detail in Borrelli et al.[13]). The amount of arable land was kept constant to ~110 M ha in all the simulated scenarios (pre-CAP baseline scenario, current scenario and 2070 future scenarios). The adopted modelling assumptions with respect to conservation practices are reported in Supplementary Table 4. All soil displacement by water-erosion scenarios presented were computed using a spatially explicit approach (pixel-by-pixel). Conversely, soil-displacement reductions for tillage and wind erosion were approximated assuming soil displacement totally (tillage) or partially (wind, −60% in reduced tillage and −30% in no tillage) offset in correspondence of arable lands under reduced or no tillage management.

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

All data supporting the findings of this study are available within the article text and Supplementary Information or are freely available at the European Soil Data Centre (ESDAC), the institutional soil data repository of the European Commission Joint Research Centre (https://esdac.jrc.ec.europa.eu/). Additional higher-resolution maps (GeoTIFF format) will be made available via ESDAC.

Code availability

Code and programmes can be retrieved from the European Soil Data Centre (ESDAC) (https://esdac.jrc.ec.europa.eu/) and from the corresponding author upon reasonable request.

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Author contributions

P.B., D.A.R. and P.P. led the work and designed the study. P.B., C.B., P.P. and E.L. performed the computational steps and analysis. D.A.R and P.B. wrote the initial draft of the manuscript; all other remaining authors made substantial contributions to the study design and methodology, provided data and helped improve the manuscript. P.B. was the research leading author, and D.A.R. and P.P. were the supervising authors. All other contributing authors are listed in alphabetical order.

Competing interests

The authors declare no competing interests.

Additional information

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Software and code

Policy information about availability of computer code

Data collection	Data were mostly collected from the European Soil Data Centre (ESDAC), the institutional soil data repository of the European Commission Joint Research Centre (https://esdac.jrc.ec.europa.eu/). Satellite imagery were collected from ESA (Sentinel programme) and NASA (MODIS programme). The digital terrain model was provided by Copernicus (EU DEM 25m). Future climate variable were provided by the WorldCLIM database. Information about crops and agricultural statistics were provided by Eurostat. Point soil data were provided by the LUCS project of the European Commission.
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Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The data used and the data generated by the current study are all open source. The data generated in this study are available in the paper and supplementary materials. The citations to the external data sources used by the study are given in the references and supplementary materials.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	n/a
Population characteristics	n/a
Recruitment	n/a
Ethics oversight	n/a

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	It was assessed the spatial risk of soil erosion by water, wind, tillage and harvesting in the European Union arable land using a multi-model approach, with the goal to highlight where the co-occurrence of these different processes was modelled.
Research sample	n/a
Sampling strategy	n/a
Data collection	n/a
Timing and spatial scale	The modeled period ranges between 2010 and 2070. The spatial scale is pan-European involving the EU27 Member States.
Data exclusions	n/a
Reproducibility	The analysis was documented in the text, supplementary information and is fully reproduce using open source data.
Randomization	n/a
Blinding	n/a

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging