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The State of SOILS in Europe

Fully evidenced, spatially organised assessment of the pressures driving soil degradation.

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04 Regional status and trend of soil degradation

Assessing soil condition involves evaluating a range of physical, chemical and biological indicators. Soil degradation is defined as a change in soil health resulting in the diminished capacity of the ecosystem to provide goods and services for its beneficiaries (FAO, 2024). Drawing from existing and recent evidence, including research findings, case studies and soil monitoring data, our assessment focuses on various soil degradation indicators. These include:

- soil acidification
- soil carbon change
- soil erosion
- soil compaction
- soil pollution
- soil salinisation and sodification
- soil biodiversity change
- soil sealing and land take.

4.1 Excess and deficiencies in soil nutrients

Soil nutrients are essential for plant biomass production and quality, and other ecosystem services (Li *et al.*, 2016; Ros *et al.*, 2022). These other services includes the major biogeochemical cycles and related soil functions, notably carbon sequestration (Van Groenigen *et al.*, 2017).

Nutrient management is therefore essential to maintain soils in good chemical, biological and physical conditions. Nutrients are managed to achieve agronomic and economic objectives (i.e. yields and yields versus costs) while minimising environmental impacts (avoiding losses to air and water and the introduction of contaminants) (Beegle *et al.*, 2000; Hou *et al.*, 2023).

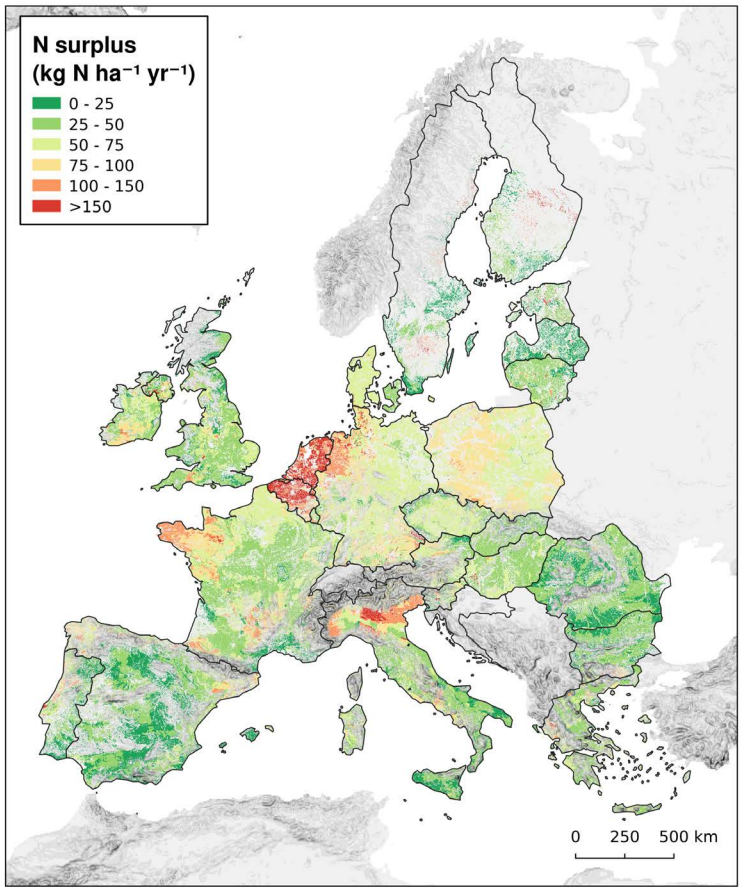
Soil nutrient status in Europe, particularly regarding nitrogen (N) and phosphorus (P), exhibits significant spatial variations, influenced by factors such as agricultural practices, climate, and soil properties. Despite efforts to manage nutrient inputs, high N and P surpluses persist in many regions, posing risks to soil and water quality. Addressing the drivers of nutrient excesses and deficiencies, including fertilizer application, land use practices, soil erosion, and climate patterns, is crucial for mitigating environmental pollution, soil acidification, and economic costs, while safeguarding human health and agricultural productivity. Effective soil management strategies are essential to balance nutrient inputs and outputs, ensuring sustainable land use and ecosystem resilience in the face of ongoing environmental challenges.

4.1.1 Status and trends

Soil N content ranges mostly from 1 g and 2 g kg^{-1} in EU topsoils (Ballabio *et al.*, 2019). Due to the high mobility of nitrate, N losses from the soil are highly correlated with N surpluses (input minus crop uptake). There is a large variation in N surpluses across the EU and the United Kingdom (Figure 2), from nearly 0 kgN ha^{-1} yr^{-1} to more than 150 kgN ha^{-1} yr^{-1}.

A high N surplus mostly occurs in areas with high N inputs, especially in intensive livestock areas, except for some regions with low (Poland) or high (Massif Central in France, Ireland and the United Kingdom) N use efficiency (De Vries *et al.*, 2021).

Figure 2. The N surpluses (inputs minus offtake by crops) for agricultural land across the EU and the United Kingdom.



Source: *De Vries et al. (2021)*

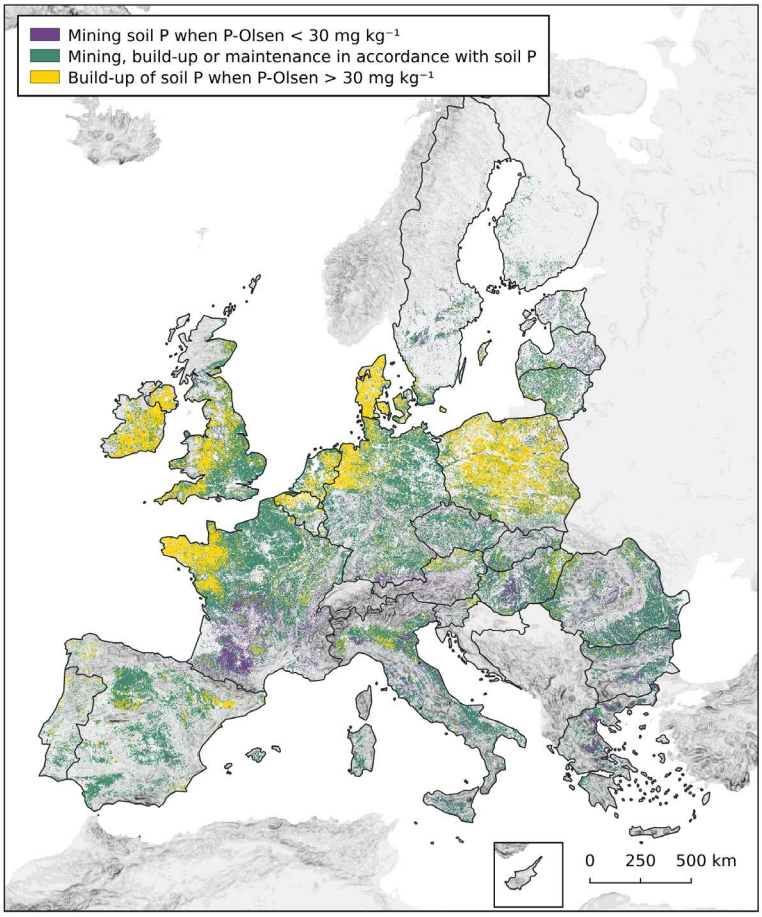
About 74 %, 66 % and 18 % of all agricultural land in the EU and the United Kingdom has excessively high N inputs when considering the regional variation in ecosystem sensitivity for N loss by run-off to surface water, ammonia (NH3) emissions and N loss through leaching to groundwater, respectively (De Vries *et al.*, 2021).

Between 1930 and 1990, N surplus increased by a factor of 2–3 (Batool *et al.,* 2022), reaching its highest value around 1990 because of a peak in N inputs. The surplus declined in subsequent years. Since 1990, total N inputs in cropland have been relatively stable, with a slight increase from 138 kgN ha^{-1} yr^{-1} to 145 kgN ha^{-1} yr^{-1} in 2021 (Einarsson *et al.,* 2021).

Available phosphorus (P) concentrations in topsoils vary considerably across the EU and the United Kingdom, with most areas having concentrations around 20–25 mg kg^{-1} (based on P-Olsen). Higher levels occur in northern Germany, northern France and northern Italy, and in Belgium, Denmark, Ireland, the Netherlands, Poland and the United Kingdom. Despite these high soil P levels, balance calculations have shown an average surplus of P in the EU and United Kingdom of 0.11–0.80 kg P ha^{-1} yr^{-1} (Panagos *et al.*, 2022b; Muntwyler *et al.*, 2024) or higher (De Vries *et al.,* 2014; Einarsson *et al.,* 2020). However, there is considerable variation among countries, and extensive areas in the EU and the United Kingdom are currently experiencing surpluses of more than 10 kg P ha^{-1} yr^{-1}, despite the generally high soil P concentrations in these regions.

The current P management practices were evaluated by comparing the P balance with the available concentration of P in the soil (P-Olsen) (Ballabio *et al.*, 2019). The P balance is defined as organic and mineral fertilizer inputs minus outputs due to removal by crops and loss by erosion (Muntwyler *et al.*, 2024). When the P-Olsen concentration is less than 30 mg kg^{-1}, negative P balances increase the potential risk of P deficiency for agricultural production (Jordan-Meille *et al.*, 2012; Steinfurth *et al.*, 2022). This occurs in 13 % of EU and UK agricultural land. When P-Olsen concentrations are greater than 30 mg kg^{-1} (Jordan-Meille *et al.*, 2012; Steinfurth *et al.*, 2022), positive P balances increase the

Figure 3. Current P inputs for a P-Olsen threshold of 30 mg kg^{-1}.



Source: EUSO, based on Ballabio et al., (2019) and Muntwyler et al., (2024).

risk of P environmental losses which is the case in 33 % of EU and UK agricultural land (Figure 3). Many Member States have experienced much more imbalanced P management in recent decades: P inputs peaked above 30 kg ha^{-1} in around 1980 (Sattari *et al.*, 2012), while P inputs are nowadays, on average, 16 kg ha^{-1} in the EU and the United Kingdom (Panagos *et al.*, 2022b). Due to the low mobility and high retention of P in soils, the positive P balance of the past have resulted in high soil P legacy (Sattari *et al.*, 2012). When 30 mg kg^{-1} of P-Olsen is used as threshold values for excess (Jordan- Meille *et al.*, 2012; Steinfurth *et al.*, 2022), about 60 % of agricultural soils in the EU and the UK can be defined as P-rich soils, with possible adverse impacts on water quality. The threshold of 30 mg kg^{-1} is the lowest value of the range proposed by the European Commission in the proposed Soil Monitoring Law to define P excess in soils (European Commission, 2023b). When taking the upper range value of 50 mg kg^{-1}, 10 % of agricultural soils in the EU and UK has excess of P.

In non-EU countries such as Norway, P surpluses reduced from 1985 to 1990, and have remained relatively stable since (OECD, 2024). The P surpluses in Norway are similar to those in the United Kingdom, contributing to the eutrophication of water bodies in the region (Ulén *et al.*, 2007). P surpluses reduced in Switzerland between 1990 and 2000, and have since fluctuated between 2 kg ha^{-1} and 5 kg ha^{-1} (OECD, 2024).

The N and P budgets in Iceland are generally low and have been stable over the years (OECD, 2024). Ukraine has seen the largest decrease in N and P budgets since 1990 of all non-EU countries considered (OECD, 2024), with a P budget of – 2.4 kg ha^{-1} yr^{-1} in 2020. This drastic reduction in fertiliser input after the 1990s can be attributed to the political transformations in post-Soviet countries. Political changes have also affected the nutrient balances in the western Balkans (Zdruli *et al.*, 2022). In this region, about 5.2 % of total agricultural land could have relatively large N surpluses, as this area consists of greenhouses and open

field horticulture crops, which receive the largest N fertiliser doses. However, generally fertiliser application in these countries happens to be far below the average EU level; they therefore have a higher chance of having negative N and P budgets (as found in Ukraine (OECD, 2024)), contributing to nutrient mining and a decrease in soil fertility (Zdruli *et al.*, 2022).

In Türkiye, both the N balance and the P balance have increased in the last 5 years (OECD, 2024). N fertiliser use on crops fluctuated between approximately 46 kg N ha^{-1} yr^{-1} and 89 kgN ha^{-1} yr^{-1} from 2004 to 2022; the application of P fertiliserfluctuated between 6 kg P ha^{-1} yr^{-1} and 15 kg P ha^{-1} yr^{-1}; and the application of potassium (K) in agricultural production varied from approximately 2 kg ha^{-1} to 6 kg ha^{-1} from 2004 to 2022 (MoAF, 2022).

Available K concentrations, determined using ammonium acetate, vary across the EU and the United Kingdom depending on parent material, soil clay content and manuring history, with higher concentrations in clay-rich soils (Ballabio *et al.*, 2019). K inputs are usually higher in countries or regions with intensive animal husbandry. For example, in France, the exchangeable K thresholds (ARVALIS, 2020) defining the risk of K deficiency vary from 49 mg kg^{-1} to 247 mg kg^{-1} (with an average of 123 mg kg^{-1}) depending on soil type (Comifer, 2019). Using these threshold values, 16 % and 68 % of EU and UK agricultural soils have exchangeable K concentrations of below 123 mg kg^{-1} and 247 mg kg^{-1}, respectively. They can therefore be considered soils with low K levels for biomass production.

Secondary macronutrients (e.g. sulphur (S), calcium and magnesium) and micronutrients (e.g. iron, zinc (Zn), copper (Cu), manganese (Mn), molybdenum, boron and cobalt) have a fundamental role in sustaining terrestrial ecosystems, which is partly related to their contribution to sustaining biomass development. In addition, these elements are divalent cations, which control aggregate stability, soil water retention and supply, resistance to wind erosion, topsoil sealing, subsoil compaction, and drought and wetness stresses (Ros *et al.*, 2022). However, at the EU level, there is limited information on the levels of these nutrients in soil and their input to correct deficiencies. In the EU, there is information on the total amounts of some micronutrients in soils (Ballabio *et al.*, 2018; Van Eynde *et al.*, 2023), but these have low agro-environmental relevance (Alloway, 2009). Micronutrients are typically applied in the form of salts and chelates, but there is no spatial information regarding the quantity of micronutrient fertilisers used in the EU to correct deficiencies. Soils at risk of micronutrient deficiencies are generally those characterised by a high pH and low organic matter content (Moreno- Jiménez *et al.*, 2022), while intense cropping can exacerbate micronutrient depletion in specific soils (Jones *et al.*, 2013). Budget calculations underscore the significance of manure as a source of Cu and Zn for agricultural soils in the EU (De Vries *et al.*, 2014), alongside sewage sludge (Yunta *et al.*, 2024) and fungicides (El Hadri *et al.*, 2012).

4.1.2 Drivers

The main drivers of soil nutrient excesses and deficiencies are multifaceted and can vary depending on the specific context. However, some common drivers include the following.

- Fertiliser and manure application. Since the 1950s, the increased use of fertilisers has boosted crop and forest production, but their excessive and inefficient use has led to nutrient excesses and losses (Townsend *et al.*, 2003). Gaseous emissions from industry and agriculture, as well as natural processes, also lead to the deposition of nutrients in terrestrial ecosystems.

- Land use and management practices. Agricultural systems have become specialised, resulting in the decoupling of crop and livestock production. On the one hand, there are systems relying on both internally and externally produced feed, resulting in significant amounts of nutrient-rich waste such as manure. Applying this nutrient source inappropriately often leads to substantial losses. On the other hand, some arable fields depend on external fertiliser inputs to manage their nutrient needs. In addition, agricultural practices such as tillage, irrigation and pesticide use can impact soil nutrient levels (Edlinger *et al.*, 2022).

- Soil erosion and leaching. Erosion results in the loss of nutrients such as P to lower areas and to surface water (Alewell *et al.*, 2020), while leach-

ing can result in the loss of nutrients such as N and S to groundwater (De Vries *et al.*, 2021). The loss of nutrients leads to a decline in soil fertility, while sedimentation and leaching can result in an excess of nutrients elsewhere.

- Soil properties. Soil types and related characteristics, such as mineralogy (e.g. clays, carbonates, oxides) control the release and retention of carbon and nutrients such as K and P in soils (e.g. van Doorn *et al.*, 2023). Furthermore, soil pH influences the solubility, concentration in soil solution, ionic form, and adsorption and mobility of many elements (Moreno-Jiménez *et al.*, 2022; Hartemink and Barrow, 2023). Organic matter affects nutrient content, retention and release in soils (Moreno-Jiménez *et al.*, 2022).

- Climate and weather patterns. Weather events such as heavy rainfall can accelerate nutrient leaching and nitrous oxide (N_2O) emission to the atmosphere, while drought conditions can concentrate salts in the soil, potentially leading to nutrient imbalances. In addition, climatic conditions control crop yield and nutrient use efficiencies (Young *et al.,* 2021).

4.1.3 Impacts

Soil nutrient excesses and deficiencies can greatly influence agricultural productivity, and environmental, ecosystem and human health. Some of the key consequences are as follows.

- Environmental pollution. Excess nutrients, particularly N and P, can leach into groundwater or move to surface water bodies in run-off and by erosion. This results in eutrophication, with the loss of biodiversity, the depletion of subaquatic vegetation, a decline in coral reef health, the occurrence of algal blooms and the creation of oxygen-depleted or hypoxic waters (Carpenter *et al.*, 1998; Smith, 2003; Smith and Schindler, 2009; Lundin and Nilsson, 2021). An excess of N can also result in increased N losses into the atmosphere. The subsequent deposition of N is a major driver of plant biodiversity loss through N enrichment and soil acidification in natural areas (Bobbink *et al.*, 2010).

- Climate change. Excess N in soil can lead to the increased emission of N_2O, a potent greenhouse gas (GHG). N_2O is released from soils through denitrification, whose rate increases with N input (Butterbach-Bahl *et al.*, 2013; Arias-Navarro *et al.*, 2017; McDonald *et al.*, 2022; Pan *et al.*, 2022).

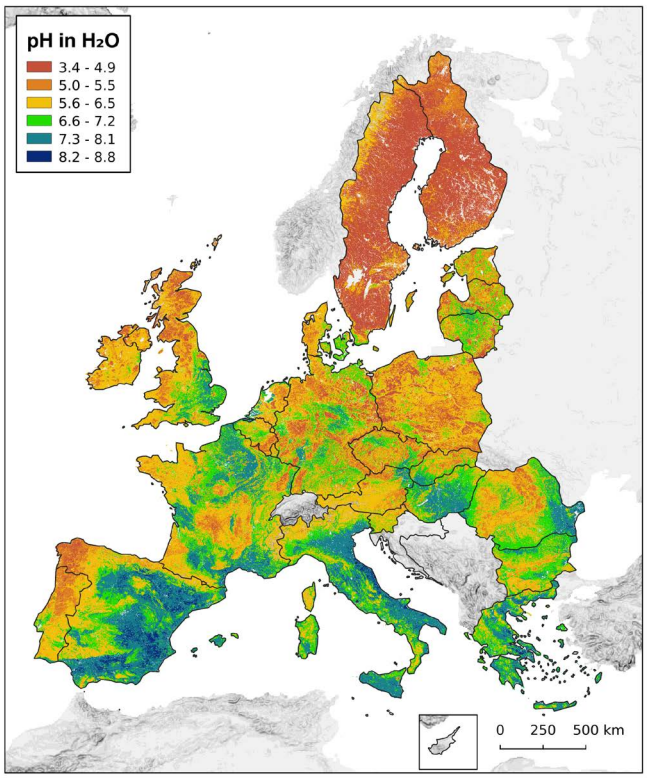
- Soil acidification and salinisation. Excessive nitrate in soils due to N fertilisation causes acidification due to the release of hydrogen ions during the process of nitrification, affecting the availability of other nutrients, and contaminants (Zhang *et al.*, 2023). Finally, excess N fertilisation in dry and sub-dry regions can lead to soil salinisation (Han *et al.*, 2015).

- Soil pollution. The excessive use of P fertilisers (Nziguheba and Smolders, 2008), as well as organic fertilisers and amendments, may introduce heavy metals and other soil pollutants (Mantovi *et al.*, 2003; Pan and Chu, 2017). The application of synthetic chelates to correct micronutrient deficiencies in Mediterranean soils may also lead to the introduction of recalcitrant products, with negative environmental impacts (Yunta *et al.*, 2013).

- Economic costs. Soil nutrient deficiencies can lead to reduced crop yields (Schils *et al.*, 2018) and crop nutritional quality (Dimkpa and Bindraban, 2016), and increase the susceptibility of plants to disease (Dordas *et al.*, 2000). These impacts reduce farmers' incomes, and increase the costs of inputs. Excess nutrients can also lead to serious losses to the environment, requiring environmental mitigation measures, with associated costs.

- Human health risks. Gaseous N emission contributes to the formation of aerosol and particulate matter air pollutants, affecting human health (Pozzer *et al.*, 2017). Nutrient losses to aquatic ecosystems also affect human health, as they can compromise the safety of drinking water (Lundin and Nilsson, 2021). Finally, nutrient deficiencies or imbalances reduce crop nutritional quality, compromising livestock production, as well as food security and food quality for humans (Ishfaq *et al.*, 2023). For instance, a deficiency of Zn in semi-arid and arid regions is very common and is a growing concern, as this nutritional disorder causes almost 116 000 deaths per year worldwide (Galetti, 2018).

Figure 4. Soil pH, measured in H_2O, in EU and UK soils.



Source: EUSO, based on Ballabio et al. (2019).

4.2 Soil acidification

Soil acidification, a global concern, impacts soil quality, ecosystem integrity and human well-being. It predominantly affects non-calcareous soils, with low buffer capacity, leading to a decline in pH. This decline can impair nutrient availability and increase the mobility and availability of toxic elements. While some countries have seen improvements, acidification remains a significant issue in Ukraine and Türkiye, affecting agricultural productivity and environmental quality. Drivers of soil acidification include natural processes, industrial emissions and agricultural practices. The excessive use of ammonium-based fertilizers may lead to soil acidification.

Soil acidification, defined as a decrease in the acid neutralisation capacity of the soil (De Vries and Breeuwsma, 1987; Guo *et al.*, 2010) is a major issue all around the world. In calcareous soils with a high natural buffer capacity, there is little concern, as the pH remains stable and slightly alkaline until all carbonates are depleted. This depletion depends on their dissolution rate. However, in non-calcareous soils, with a low buffer capacity, especially sandy soils with low organic matter content, soil acidification may cause a relatively fast decline in soil pH and base saturation. Soil pH is an important indicator of soil health, as it affects the availability and mobility of nutrients and toxic elements (e.g. aluminium, cadmium and other heavy metals). As a consequence, it affects primary productivity (Bolan *et al.*, 2003; Pagani and Mallarino, 2012; Hartemink and Barrow, 2023), the quality of surrounding water bodies (Haynes and Swift, 1986; Dijkstra *et al.*, 2004), and the functioning of soil as a habitat for organisms and hence biodiversity (Siciliano *et al.*, 2014).

4.2.1 Status and trends

Soil pH differs across the EU (Figure 4). The differences mainly reflect the soil type, which is a result of climatic conditions (Ballabio *et al.*, 2019), parent material, vegetation and past management practices, such as liming.

Soils with a relative low pH (< 5.5) are present in 10 % of the agricultural land across Europe (Figure 4), with possible adverse effects on plants and soil microor-