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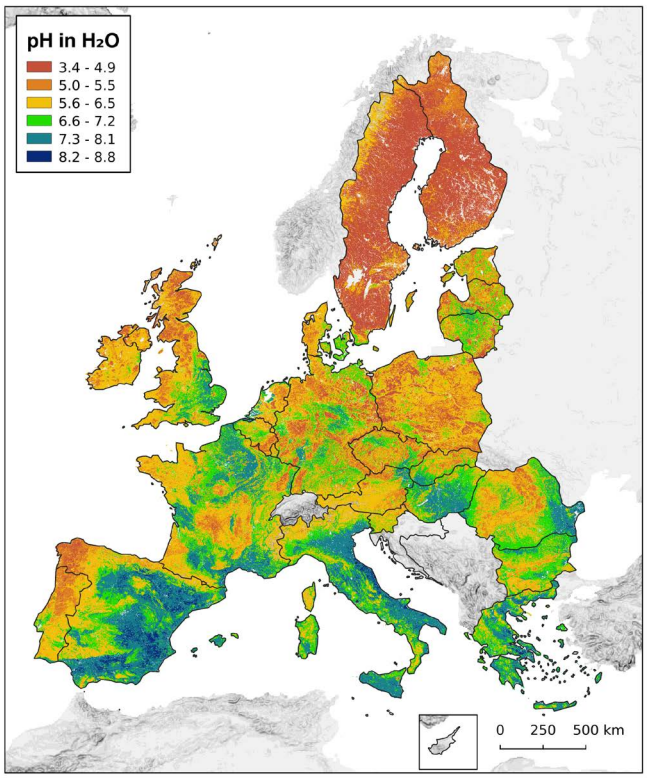
Figure 4. Soil pH, measured in H_2O, in EU and UK soils.



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.

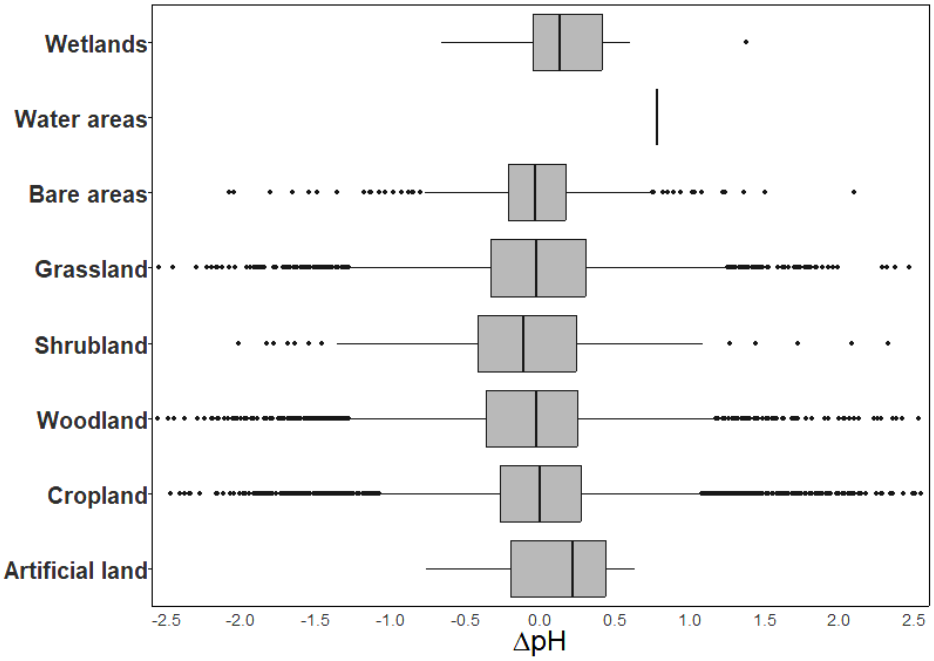
Soil acidification, defined as a decrease in the acid neutralisation capacity of the soil (De Vries and Breeuwsma, 1987; Guo *et al.*, 2010) is a major issue all around the world. In calcareous soils with a high natural buffer capacity, there is little concern, as the pH remains stable and slightly alkaline 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-

Figure 5. Difference in soil pH (ΔpH) measured in H2O for LUCAS topsoil samples collected in 2009 and 2018.



Source: EUSO, based on LUCAS 2009 and 2018 topsoil databases.

ganisms as toxic elements (e.g. aluminium) become increasingly available (Kunhikrishnan *et al.*, 2016).

A preliminary analysis of the Land Use / Cover Area Frame Survey (LUCAS) topsoil samples from 2009 and 2018 shows that pH both increased and decreased (Figure 5). Positive values reflect an increase in soil pH from 2009 to 2018, while negative values show a decrease in soil pH. In some land cover classes, the trend is an increase rather than a decrease. Further analysis should assess which factors explain the change in pH. Given the negative impact of soil acidification and low soil pH on primary productivity, as mentioned above, a typical management strategy is liming. However, there are currently no regulations on the application of lime to agricultural or forest soils at the EU level, nor are there any data about the application of lime to agricultural soils.

Historically, acidification has impacted various land uses, including forest, agricultural land and semi- natural ecosystems (Bolan *et al.*, 2003). In recent decades, a slight improvement in upper soil horizons has been observed, with pH values rising (Achilles *et al.*, 2021). However, recovery from past acidification appears to vary depending on soil depth. While some research indicates increasing pH values over time in forest floor soil and topsoil (Navrátil *et al.*, 2007; Schmitz *et al.*, 2019; Wellbrock and Andreas, 2019), deeper mineral soil remains acidified due to historical exposure to acidifying air pollutants (Berger *et al.*, 2006). In the United Kingdom, reduced sulphate deposition has facilitated the recovery of topsoil from acidification (Thomas *et al.*, 2020). Several monitoring schemes have reported an increase in soil pH across all UK habitats, with national-level data showing a mean increase in pH from 5.4 to 5.9 (Reynolds *et al.*, 2013). In Switzerland, soil acidification remains a significant concern in forests in terms of both extent and ongoing progression (Braun *et al.*, 2020). In Ukraine, approximately 24 % of soils are acidic. Acidic soils are predominantly found in the Polissya zone, while alkaline soils (18.4 %) are more prevalent in the steppe zone. Soil acidification, particularly in the natural areas of the Polissya zone, has been identified as a significant issue (Institute of Soil Protection of Ukraine, 2023).

Soil acidity is important for sustaining soil health, particularly in the East Black Sea Region of Türkiye. As a result of natural processes, the high annual rainfall results in leaching, which increases the presence of hydrogen and aluminium cations, ultimately leading to soil acidity.

4.2.2 Drivers

The drivers of soil acidification are diverse and can vary depending on regional and local factors. Some of the main drivers include the following.

- Natural processes. Soil acidification is a natural process. It is mainly caused by the dissociation of carbonic and organic acids, which leads to the leaching of bicarbonate and non-acidic cations (Zamanian *et al.*, 2024). The weathering of particular mineral rocks containing sulphide minerals (e.g. pyrite) can naturally generate acidic conditions in soils.

- Acid deposition and waste. Mining activities and industrial processes can release acidic substances into the environment, either directly through emissions or indirectly through the disposal of acidic waste materials. Ammonia (NH_3), nitrogen oxide (NOx) and sulphur oxide (SOx) emissions and air pollution have been major drivers of forest soil acidification in recent decades (through increasing the deposition of mainly N and S compounds), thereby hampering tree growth and affecting forest composition (EEA, 2014). However, regulatory controls have reduced emissions and consequently the deposition of compounds causing acidification (Engardt *et al.*, 2017), especially S compounds. This has resulted in the re-alkalinisation of several European forest soils in which acid deposition had decreased (Berger *et al.*, 2016; Prietzel *et al.*, 2020). N deposition is now identified as the main cause of acidification in many European regions (Michel *et al.*, 2022). Critical loads of acidity are currently rarely exceeded, except for in the Netherlands (De Vries *et al.*, 2024).

- Agricultural practices. In agricultural soils, acidification is caused by the application of acidifying fertilisers, nitrate leaching, nutrient uptake (affecting cation/anion balance) by plants, N fixation in legumes, plant root exudates and the mineralisation of soil organic matter (Debreczeni and Kismányoky, 2005; Goulding, 2016; Xu *et al.*, 2019). Agronomic measures such as the addition of manure and lime mitigate the impact of soil acidification, thereby preventing a decline in soil pH.

4.2.3 Impacts

Soil acidification can have various impacts on soil, ecosystem functioning and human health. Some of the main impacts are as follows.

- Reduced nutrient availability. Soil pH influences the solubility, concentration in soil solution, ionic form and adsorption of most nutrients, as well as their mobility (Hartemink and Barrow, 2023). The availability of some nutrients (calcium, P, magnesium and K) can be reduced in acidic soils, reducing primary productivity (Pagani and Mallarino, 2012).

- Contamination and human health. Soil acidification can increase the solubility and mobility of toxic elements such as aluminium, cadmium and other heavy metals (Bolan *et al.*, 2003), affecting primary productivity. Due to the increased mobility of pollutants upon acidification, the quality of surrounding surface water and groundwater is reduced (Haynes and Swift, 1986; Dijkstra *et al.*, 2004). This has negative consequences for aquatic biodiversity (Soveri, 1992) and human health (due to contamination of drinking water) (Steffan *et al.*, 2018).

- Altered soil biota activity. Soil acidification can influence the composition and activity of microbial communities in soil (De Vries *et al.*, 2006; Siciliano *et al.*, 2014). Studies have found that acidification results in a reduction in nematode and rotifer abundance and earthworm biomass, and a change in microbial composition, thereby affecting microbe-mediated processes such as SOC cycling (Tibbett *et al.*, 2019).

- Ecosystem disturbance. Soil acidification can disrupt ecosystem dynamics and alter the composition of plant communities. Acid-sensitive plant species may become less abundant, while acid- tolerant species may become more predominant, leading to shifts and reductions in biodiversity (Bobbink *et al.*, 2010).

Overall, soil acidification poses significant challenges to agriculture, forestry, ecosystem management and human health, reinforcing the importance of implementing strategies to mitigate its impacts and restore soil condition. Various practices can be employed to address soil acidification, such as the application of agricultural lime to neutralise acidity. On the other hand, soil alkalinisation, especially common in agricultural fields through liming activities, can enhance the volatilisation of ammonia, so the application of ammonium-based fertilisers at the same time as lime is not recommended (Adams, 1986).