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SOILS IN THE ANTHROPOCENE: HAZARDS, CHALLENGES AND OPPORTUNITIES

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Gleby w Antropocenie: Zagrożenia, wyzwania i szanse

Zarys treści: Gleby stanowią podstawę produkcji 95% żywnościoraz zapewniają kluczowe usługi ekosystemowe, takie jak regulacja zasobów wodnych i bioróżnorodności, a także są najbardziej efektywnym magazynem CO na powierzchni Ziemi. Degradacja gleb stanowi poważne zagrożenie, a znaczne zmiany w większości gleb na Ziemi przypisuje się działalności człowieka. Do typowych zagrożeń dla gleb w antropocenie należą: (i) zagęszczanie gleby, (ii) zasolenie, (iii) zanieczyszczenie gleby, (iv) osuwiska, (v) spadek zawartości materii organicznej oraz (vi) erozja gleby. Działalność człowieka znacząco wpływa na zawartość węgla organicznego w glebie (ang. *soil organic carbon*, SOC) poprzez zmiany w użytkowaniu i pokryciu terenu, praktyki rolnicze i zarządzanie gruntami. Wpływają na to również pośrednie czynniki, takie jak pożary. Większość badań wskazuje, że zmiany użytkowania ziemi oraz zarządzanie gruntami mają większy wpływ na SOC niż bezpośrednie skutki zmian klimatycznych. Erozja gleby, mimo że jest procesem naturalnym, została znacznie nasilona przez czynniki antropogeniczne, co prowadzi do drastycznego wzrostu globalnych wskaźników erozji w antropocenie. Zidentyfikowano liczne wyzwania, możliwości oraz luki w wiedzy. Konieczne jest jednak głębsze zrozumienie zarówno naturalnych, jak i wywołanych przez człowieka zagrożeń i wyzwań związanych z glebami. Niniejszy krótki przegląd podkreśla, że wciąż potrzeba znacznych nakładów pracy, aby w pełni zrozumieć wpływ działalności ludzkiej na gleby. Kontynuacja badań, odpowiadających na nowe pytania, jest kluczowa.

Słowa kluczowe: węgiel organiczny w glebie, erozja gleby, antropocen, zmiana globalna, gleby, degradacja gleby

Abstract: Soils provide the substrate for 95% of human food and essential ecosystem services, such as water regulation and biodiversity, while also serving as the most efficient CO_2 sink on the Earth's surface. However, soil degradation poses a major threat, with significant changes in most of the Earth's soil attributed to human activities. Common soil hazards in the Anthropocene include: (i) soil compaction, (ii) salinization, (iii) soil contamination, (iv) landslides, (v) decline in soil organic matter, and (vi) soil erosion. Anthropogenic activities greatly impact soil organic carbon (SOC) through land use and land cover changes, agricultural practices, and land management. Indirect effects, such as wildfires, also influence SOC dynamics. Most studies indicate that land use and land cover changes, along with land management, have a greater impact on SOC than the direct effects of climate change. Soil erosion, though a natural process, is significantly exacerbated by anthropogenic factors, leading to a drastic increase in global erosion rates in the Anthropocene. Numerous challenges, opportunities and knowledge gaps have been identified. However, a deeper understanding of both natural and human-induced soil hazards and challenges is necessary. This short review, highlights that a significant amount of work is still needed to fully comprehend the impacts of human activities on soil. Continued research, exploring new questions, is crucial.

Keywords: soil organic carbon (SOC), soil erosion, Anthropocene, global change, soils, soil degradation

Introduction

Soil is a critical and fragile natural resource. Soil formation is slow, and it is widely recognized that it takes approximately 1,000 years to form about 2.5 cm of soil. Despite this slow formation rate, soil is the largest terrestrial pool of carbon, hosts more than 25% of all biodiversity, and provides 95–99% of the food consumed by 8 billion people (Panagos et al. 2022). Soils deliver significant supporting, provisioning, regulating and cultural ecosystem services, including food production, water retention, nutrient cycling, carbon sequestration, and contributions to physical and cultural heritage. They provide the substrate for 95% of human food and constitute the most efficient CO_2 sink on the Earth's surface.

The term Anthropocene was first suggested by P.J. Crutzen and E. Stoermer (2000). The definition of the Anthropocene is controversial. While widely recognized by the scientific community, the International Union of Geological Sciences (IUGS) has not provided a formal and official definition. There is little doubt that the term Anthropocene is now well established in both public and research domains. However, it has faced criticisms, and in 2024, the IUGS once again rejected the proposal to define the Anthropocene as a new chronostratigraphic unit. Despite this, the Anthropocene is considered an informal, non-stratigraphical term, and it is generally accepted that human activity significantly impacts natural environmental conditions.

Five soil forming factors have been traditionally identified: (i) parent material, (ii) time, (iii) climate, (iv) topography, and (v) organisms. Recently, human activity has been identified as the sixth forming factor for some authors (Dror et al. 2022). Thus, human alterations of soils must be considered not only as soil disturbance but also as integral parts of soil genesis. Richter et al. (2011) argue that Anthropedology, should identify how humanity is a fully fledge soil-forming factor, while Shi et al. (2012) highlight the need to develop theories and methodologies for acquiring information on soil changes induced by anthropogenic factors and to investigate the major factors controlling these changes.

Various studies have been published related to soils in the Anthropocene (i.e., Ritcher et al. 2015; Poesen 2018; Novák et al. 2020; Dror et al. 2022; Beillouin et al. 2023). Despite the controversial definition and acceptance of the term Anthropocene, Hatermink (2023) has proposed a new term, Pedocene, suggesting that soil science has now entered a new era. The Pedocene is defined and characterized by the quantitative understanding and evaluation of the global soil system and the effects of human-induced changes on soil.

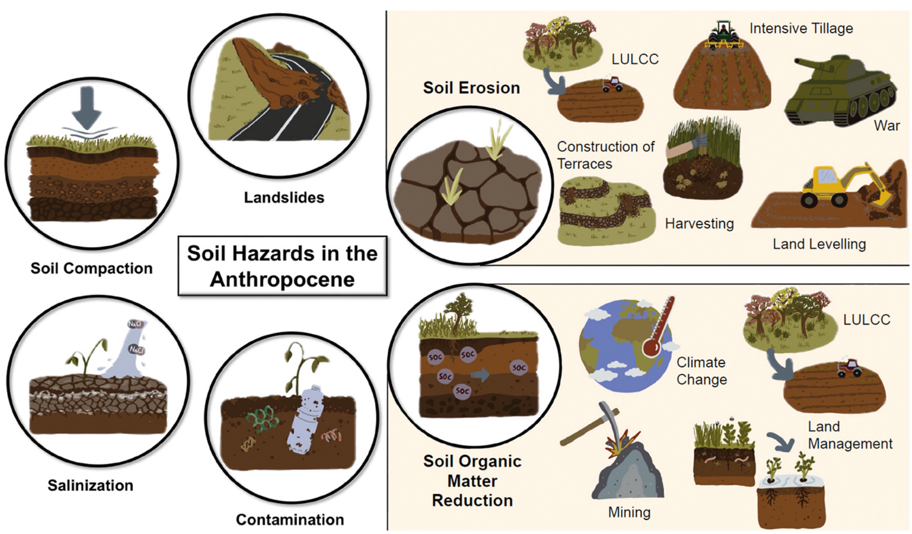
Soils have undergone extensive transformation and degradation due to human activities. While soils have always been under stress, in the Anthropocene, human influence has become the primary driving force. Humans began exerting significant control over soils, landscapes, and environments, once they started to deforest and cultivate land. The World Reference Base for Soil Resources (WRB) already recognizes two soils characterized by significant human influence: Anthrosols and Technosols. Montanarella et al. (2016) identified that global drivers of soil changes include population growth and economic development, particularly associated with agriculture intensification. They noted in the World's Soil Resources Report that a majority of the world's soil resources are in fair, poor, or very poor conditions. Presently, the European Commission (EC) reports that 60%–70% of European soils are degraded due to unsustainable agricultural practices, significantly reducing their capacity to provide ecosystem services (Veerman et al. 2020). Human activities have directly impacted soils, through practices such as land levelling, organic matter depletion or enrichment, and compaction from activities like overgrazing.

The definition, origins, and implications of anthropogenic activities on soil formation, properties, and processes have been extensively debated in numerous publications. For instance, Certini and Scalenghe (2011) propose defining the Anthropocene as the last approximately 2000 years of the late Holocene, characterized by anthropogenic soils, and discuss different time periods and definitions. Binkley (2019) concludes that human influences are becoming the dominant soil forming factor in forest soils. Geisen et al. (2019) highlight that human alterations also affect soil biodiversity. The main objective of this manuscript is to identify hazards, challenges and opportunities related to soil in the Anthropocene.

Soil Hazards in the Anthropocene

Soil hazards in the Anthropocene have been extensively studied by various authors. The most common hazards include (i) soil compaction, (ii) salinization, (iii) soil contamination, (iv) landslides, (v) decline in soil organic matter, and (vi) soil erosion (Figure 1).

Soil compaction is characterized by a reduction in soil porosity and an increase in bulk density, primarily caused by mechanical stress from human activities. This can modify soil properties and lead to the deterioration of one or more soil functions (Eckelmann et al. 2006). In most cases, this stress is related to the use of agricultural and forestry machinery (such as wheels, tracks, and rollers), intensive grazing (Pietola et al. 2005), and, in sensitive areas, activities such as walking, cycling, horseback



Explanations: Detailed human impacts for soil organic matter reduction and soil erosion are identified.
Objaśnienia: Zidentyfikowano w szczegółach wpływ człowieka na spadek materii organicznej w glebach i erozję gleby.

Fig. 1. Soil hazards in the Anthropocene: soil compaction, soil salinization, soil contamination, landslides, soil organic matter reduction and soil erosion
Ryc. 1. Zagrożenia dla gleb w antropocenie: zagęszczenie, zasolenie, zanieczyszczenie, osuwiska, spadek zawartości materii organicznej w glebie oraz erozja
Source: own elaboration.
Źródło: opracowanie własne.

riding, camping, tourism, and skiing (Ferreira et al. 2018). Soil compaction in agricultural areas is a worldwide problem resulting from mechanization and overgrazing, affecting about 33 million hectares of agricultural soils (Birkas 2008). Compaction is more evident in surface horizons but also affects subsoil, particularly in cultivated areas, and can hinder the soil's infiltration capacity.

Soil salinization, while sometimes occurring naturally (primary salinization) is also exacerbated by human activities (secondary salinization) (Shrivastava and Kumar 2015). Inappropriate irrigation practices, chemical additions, excessive use of fertilizers, and soil contamination contribute to secondary salinization, which adversely affects vegetation growth, biodiversity, and other environmental variables.

Soil contamination can arise from both natural processes and human activities involving toxic levels of chemical elements and substances. According to the Soil Science Society of America, any substance in soil that exceeds naturally occurring levels and poses risks to human health is considered a soil contaminant. Panagos et al. (2015) estimated that within the European Union, there are 2.5 million contaminated sites and approximately 11.7 million potentially contaminated sites. Urban areas, waste dumps, and former industrial sites pose the greatest risks for soil contamination. In urban settings, contamination is primarily attributed to industrial activities (37%), the industrial/commercial sector (33%) (Stolte et al. 2016), transportation, and inadequate waste disposal practices (Huber et al. 2008).

Agricultural soils also face significant contamination threats, in both conventional and conservation agriculture systems, largely due to management practices. The widespread use of pesticides (Silva et al. 2018) and the extensive plastics usage, leading to large amounts of waste generation (Sa'adu, Farsang 2023) contribute to this issue.

Human activities can also influence landslide activity by altering slope stability through practices such as excavation, construction, mining, irrigation, or land use and land cover changes (Cendrero et al. 2022). García-Ruiz and Valero (1998) observed an acceleration in landslide activity in the Central Pyrenees (Spain) (based on historical evidence), during the second half of the 19th century, coinciding with increased human population density and activities. Beguería (2006) analysed the effects of land use and land cover changes on shallow landslide activity in the same region, finding that abandoned arable slopes remained susceptible to landslides for many years after land abandonment, while revegetation efforts helped mitigate this risk over time.

Finally, both soil organic carbon (SOC) and soil erosion are profoundly influenced by anthropogenic activities and are recognized as major hazards to soil function on a global scale. While these processes are also shaped by natural factors such as climate variables (i.e., rainfall intensity, temperature variations), parent material, vegetation, and topography, human activities including land use and land cover changes, land management practices (such as tillage, irrigation, grazing, and fertilization), and land exploitation (such a sealing and mining) exacerbate the decline of soil organic matter and affect soil erosion rates (i.e., Poesen 2018). A detailed analysis will be conducted to examine these two threats comprehensively.

Soil organic carbon in the Anthropocene

Soil represents the largest terrestrial reservoir of carbon (i.e., Scharlemann et al. 2014), playing a crucial role in ecosystem services such as climate regulation. Anthropogenic activities profoundly impact SOC stocks and pools, with land use and land cover changes, land management and climate change identified as primary drivers significantly affecting SOC.

Global-scale studies highlight land use and land cover changes (LULCC) as a major driver influencing SOC (i.e.; Poeplau, Don 2017; Sanderman et al. 2017). According to Winkler et al. (2021), almost a third of the global land area has undergone LULCC in the last six decades (1960–2019). Agricultural areas often exhibit lower SOC content due to intensive tillage activities and soil erosion (Aguilera et al. 2018). Agriculture, therefore, emerges as a significant factor affecting SOC levels, and soil management practices in cultivated areas playing a critical role in influencing carbon fluxes between the biosphere and atmosphere. In general, agricultural activities lead to SOC depletion (Poeplau, Don 2013). However, certain land management practices in agriculture can enhance SOC levels (i.e., Niu et al. 2021). For instance, conservation practices like reduced or no tillage have been effective in increasing SOC stocks (e.g., Lal 2004).

Most studies indicate that the combined effects of LULCC and land management on SOC are more pronounced than the direct effects of climate change (Smith et al. 2005). The conversion of agricultural land to pasture or forest, particularly through afforestation practices, demonstrates the highest rates of SOC sequestration (Minasni et al. 2017). Enhanced management of overgrazed grasslands or shrub-clearing to establish new pasture also contributes to increased SOC stocks (Badgery et al. 2014; Cortijos-López et al. 2024).

In contrast, forest ecosystems experience significant SOC loss when forested areas are converted to cropland, and such management practices generally result in the depletion of SOC (Beillouin et al. 2023), highlighting limited solutions for enhancing SOC in forested lands.

While the direct impacts of climate change on SOC are relatively small, indirect effects, such as the increase in the frequency and magnitude of wildfires and the decline in snow cover, can substantially impact SOC stocks (i.e., Novara et al. 2011; Khedim et al. 2023).

Soils affected by mining activities are drastically influenced by human activities and are characterized by low SOC contents and poor fertility. However, implementing effective reclamation and management practices can potentially enhance SOC sequestration. Strategies such as increasing vegetation cover, improving soil fertility through amendments, and addressing physical, chemical and biological limitations have shown promise in restoring SOC levels (Usiri, Lal 2005).

In light of these challenges and opportunities, there is a critical need for enhanced efforts in both LULCC and land management practices aimed at transforming soils into effective carbon sinks. This approach is essential for achieving sustainable land management goals and mitigating the impacts of climate change.

Soil erosion in the Anthropocene

A major feature of the Anthropocene is the significant increase in global soil erosion rates. While soil erosion is considered a natural process, human activities such as land use and land cover changes (LULCC), intensive tillage, land levelling, and the construction of terraces can exacerbate this phenomenon. Consequently, the primary concern regarding soil erosion today is related to accelerated erosion rates, which surpass natural soil erosion rates due to anthropogenic influences (Poesen 2018).

Numerous studies have highlighted that climate factors alone do not account for the observed soil erosion processes and extreme erosion rates. Historical events, such as the development of pastoralism during the Bronze Age and the expansion of agriculture in the Middle Ages, were key factors in triggering substantial soil erosion in mountain environments like the Alps and the Pyrenees (Dotterweich 2008, 2013; Dreibrodt et al. 2010; Bajard et al. 2017; Vanwalleghem et al. 2017). Land use and land cover changes have frequently led to catastrophic episodes of soil erosion across many areas of the world (Bork, Lang 2003). Therefore, within the Anthropocene context, land use and land cover changes are recognized as the primary drivers increasing soil erosion rates worldwide (García-Ruiz et al. 2015).

Anthropogenic processes contributing to soil erosion encompass human-induced activities that directly detach and transport soil materials, such as tillage erosion, urban gully erosion, and land levelling. Globally, approximately 24 billion tons of topsoil are lost annually (Montanarella, Vargas 2012), with losses two to six times higher in Africa and Asia than in North America and Europe (UNEP 2012). Panagos et al. (2015) estimated that soil erosion by water is 1.6 times greater than soil formation rate. The widely cited acceptable soil loss rate is 1 t ha^{-1} y^{-1} (Verheijen et al. 2009), and soil erosion rates higher than this average annually may lead to irreversible soil degradation over 50 to 100 years (Jones et al. 2004).

The impacts of humans on soil erosion are profound and complex, especially in areas with frequent human activities. Soil erosion studies confirm that agricultural activities are associated with the highest erosion rates, despite high variability depending on agricultural uses (Verheijen et al. 2009; García-Ruiz et al. 2013, 2015). The greatest erosion rates have been measured in vineyards (i.e., Kosmas et al. 1997; Ramos, Martínez-Casasnovas 2006; Cerdan et al. 2010), mainly due to the low level of plant cover and the steepness of vineyard slopes (García-Ruiz et al. 2013), making vineyards particularly susceptible to heavy rainfall and soil erosion processes. High erosion rates with similar problems have been also recorded in rainfed almond and olive orchards (García-Ruiz 2010). Additionally, another major problem related to soil erosion arises from the expansion of irrigated agricultural in marginal areas (Cerdà et al. 2012). Recently, the expansion of new agricultural subtropical crops in marginal areas, such as mango and avocado in regions like the Mediterranean, along with the expansion of pistachio plantations and new vineyards, olive and almond orchards, has enhanced soil erosion processes and soil degradation with significant environmental consequences (i.e., Durán Zuazo et al. 2011; Atucha et al. 2013; Nadal-Romero, García-Ruiz under review). In relation to agricultural activities, high erosion rates are also recorded due to crop harvesting (Ruysschaert et al. 2007; Saggau et al. 2024). Additionally, soil piping erosion may have an anthropogenic origin, often linked to agricultural activities and can be either a cause or a consequence of agricultural land abandonment (Romero-Díaz et al. 2007, 2009).

Soil quarrying also represents a significant anthropogenic soil erosion process worldwide (i.e., Darwish et al. 2011). Building or infrastructure construction sites are often identified as hotspots for erosion rates. For example, activities such as the development of ski infrastructure can affect soil erosion processes, modifying hillslope and creating alternating patterns of erosion and accumulation (Piątek, Bernatek-Jakiel 2024).

In recent decades, new human impacts due to sport activities carried out in natural areas have also been identified. For example, Salesa and Cerdà (2019) analysed soil erosion rates during mountain running races and recorded erosion rates higher than 100 t ha^{-1} yr^{-1}. These authors suggested that conservation strategies are needed for these new trails to avoid unsustainable soil losses. Other less significant activities, such as archaeological excavations, also trigger the development of soil erosion processes (Rodrigo-Comino et al. 2023).

Finally, soil erosion caused by armed conflicts and wars, due to explosion cratering and trench digging, has been highlighted by several authors. Warfare not only accelerates soil degradation and erosion but also leads to soil contamination (Abdo 2018; Poesen 2018).

Knowledge gaps and research needs

To mitigate soil degradation due to human impacts, sustainable soil management practices are essential. These include conservation agriculture, reforestation, organic farming, and the use of green infrastructure in urban areas, among others. By adopting such practices, we can help preserve soil health, ensure food security, and maintain the balance of ecosystems in the Anthropocene era.

Related to SOC dynamics, Thorsøe et al. (2023) identified several knowledge gaps for four European regions (North, Central, West and South): (i) deep soil carbon (subsoil) and its dynamics; (ii) impacts of deep roots on SOC stocks; (iii) insufficient monitoring of SOC and the need for a common monitoring system; (iv) a better understanding of SOC modelling; and (v) SOC and its different fractions (considering a wide variety of physical and chemical fractionation methods). Additionally, more work is needed on the effects of soil erosion on SOC and SOC modelling. A wide variety of regional and global models have attempted to estimate SOC; however, the uncertainty in these models is very large.

Similarly, thousands of studies have investigated the effects of various drivers on SOC. However, a comprehensive global understanding of the effects of LULC changes, land management, and climate change on SOC is still lacking. Furthermore, most reviews have identified significant geographical research gaps, particularly in regions such as Africa and Asia, but also in other areas worldwide. Although soil data are available at the European level (see Cotrufo et al. 2019), and databases such as LUCAS (Orgiazzi et al. 2018) exist, substantial geographical gaps in European soil knowledge persist.

In relation to soil erosion, various authors have reviewed and identified the research gaps and questions needed to be answered in soil erosion studies (García-Ruiz et al. 2017; Poesen 2018). Some of the research gaps identified include: (i) the identification of dominant anthropogenic soil erosion processes; (ii) the need for long-term experiments at different scales and under various climate change scenarios (iii) achieving a consensus on the data that can be used to develop universal models; (iv) understanding the contribution of soil erosion to the carbon cycle (both organic and inorganic); and (v) determining the consequences of climate change on erosion processes. Additionally, more attention should be paid to a series of erosion processes that have not been studied in detail, such as gully erosion, piping erosion, erosion by tillage, and erosion processes linked to armed conflicts, such as trench digging. Furthermore, innovative techniques or strategies to prevent soil erosion and/or reduce soil erosion rates are needed.

Special research gaps are related to piping studies due to the difficulty in identifying and understanding subsurface soil erosion processes. Bernatek-Jakiel and Poesen (2018) highlighted that information related to the morphological characteristics of pipes is missing. Additionally, there is a limited availability of quantitative representative data on soil erosion rates due to piping, and as a result, most erosion models that do not include piping erosion may underestimate soil erosion rates.

One of the most critical issues in soil erosion studies is the scarcity of long-term datasets. García-Ruiz et al. (2015) identified that most soil erosion studies are short-term, typically around two years, with few extending beyond ten years. They suggested that an optimum study period is 20–25 years to reduce variability in erosion rates and incorporate the occurrence of extreme events.

Additionally, current soil erosion models do not adequately incorporate anthropogenic soil erosion processes. Improving these models requires a better understanding of both natural and anthropogenic soil hazards and challenges. This improvement is crucial for developing more accurate and comprehensive models that reflect the true complexity of soil erosion dynamics.

Final remarks

This short review, along with most studies on soil in the Anthropocene, underscores that there remains a substantial amount of work to be done to better understand the effects of human activities on soil. Further research, addressing new questions, is essential. Moreover, there is an insufficient transfer of knowledge from soil research to stakeholders, which is crucial for the adoption of sustainable practices. Enhancing this transfer of knowledge is essential to ensure that sustainable soil management practices are effectively implemented and widely adopted.

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