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Review

Handling the impacts of climate change on soil biodiversity

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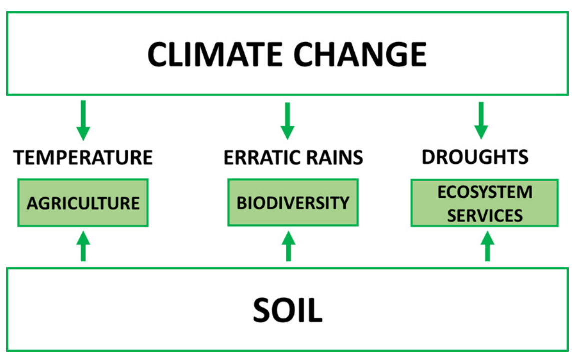
HIGHLIGHTS

- Climate change's impacts on soil and its biodiversity are underestimated.
- A healthy environment and soil biodiversity are milestones for food production.
- The synergy of the soil-plant-animal nexus may support combating climate change.
- Integrated agricultural production systems can reduce the effects of climate change.
- Agricultural zoning is a promising tool for minimising climate change effects.

GRAPHICAL ABSTRACT



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ABSTRACT

Land as a whole, and soil, in particular, plays a critical function in the climate system. The various types of land use, especially agriculture and forestry, account for nearly a quarter of the greenhouse gas emissions. On the other hand, the world's soil is under pressure from many factors, including climate change and land use change. Increases in temperature, prolonged drought and floods put pressure on the soil. In order to contribute to a better understanding of these interactions, we conducted a review combining a narrative-focused approach, selecting examples worldwide, and a bibliometric analysis (VosViewer software). This review reports on a study that analyses how climate change and land use change may negatively influence soil biodiversity and related services. It also outlines some of the actions needed to increase the resilience of soil biodiversity in the context of a changing climate. Some key findings are: 1) Well-managed soils are critical for resilient production systems. 2) Integrated agricultural production systems have gained prominence as climate-resilient production systems. 3) Agricultural zoning may be a valuable tool in integrated systems to minimise the effects of climate change. However, it is vital to continuously monitor environmental variations so producers can be more prepared for climate change and extreme events. Finally, adequate water management is essential for soil functioning under climate change aggravating water scarcity. An intersectoral approach between critical sectors facilitates comprehensive water management.

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Contents

1. Introduction

Soil biodiversity and sustainable soil management are preconditions for attaining Sustainable Development Goals (SDGs) (Keesstra et al., 2016), further highlighted by soil being mentioned in 5 of the 17 SDGs. Moreover, global estimates indicate that soil biodiversity contributes circa US$ 1.5 and 13 trillion yearly to the value of ecosystem services (Laban et al., 2018). However, despite its essential value to life on earth, soil biodiversity is overlooked mainly in global public policy dialogue. In addition, companies with implemented environmental management systems rarely associate their environmental impacts with soil contamination (Djekic et al., 2014). Soil biodiversity is gaining prominence as beneficial to human health because it can subdue disease-causing soil organisms and supply clean air, water and food. However, harmful land-use activities and climate change affect life forms underneath the surface soil worldwide. This situation also causes a reduction in soil biodiversity and erodes some of these benefits (Pascual et al., 2015). Studies buttress the notion that soil biodiversity can be preserved and, to some extent, restored when managed sustainably. Safeguarding the ecology and health of soil biodiversity through enhanced management approaches is an area that has received little attention but has the potential to improve human health (Wall et al., 2015).

Soil biodiversity denotes the complexity of life below the soil surface, e.g., bacteria, fungi, protozoa, insects, worms, and other invertebrates and vertebrates (Adhikari and Hartemink, 2016), which dynamic interaction with fauna and flora creates a web of biological activity. The soil biodiversity enhances the topsoil vegetation by decomposing plant residues and reinforcing soil resilience. In addition, the rich diversity of organisms promotes soil health and fertility; the soil system likely contains more than 25 % of overall biodiversity (Bach et al., 2020).

Besides, the complex interactions between the subsoil and topsoil systems facilitate life on earth through the following ecosystem services (Orgiazzi et al., 2016). For instance, soil biodiversity is critical for food production, maintaining a healthy environment, nutrient cycling, and mitigating climate change. Nevertheless, this vital ecosystem, one of the earth's main biodiversity reservoirs, is subjected to immense pressures due to poor land-use practices, erosion and compaction, and climate-induced factors. Moreover, soils are considered non-renewable resources as their degradation/loss is hardly recovered within a human life period (Dominguez et al., 2018).

The concepts mentioned above make it necessary to promote measures that safeguard soil biodiversity and protect the structure and function of soil ecosystems. Thus, soil stewardship has gained traction in recent times, given the realisation that the soil being a public good, requires socio-economic valuation and requisite institutional provisions to conserve it for the overall welfare of society (Laban et al., 2018). The United Nations designated the year 2015 as the International Year of Soils. The first-ever Status of the World's Soils Report was published towards the end of 2015, followed by the first-ever Global Soil Biodiversity publication in 2016 (Orgiazzi et al., 2015). These measures provide further insights and highlight soil biodiversity's intricate linkage and essence in the dynamic sustenance of all life forms on earth, including humanity. It is also a vital resource that underpins ecosystem processes critical to the performance of natural and global systems. The insights gained about the species, their mutual relations, and their impact on processes existing within the soil's food web in natural systems provide vital knowledge for effectively managing the land, especially regarding agriculture (Van der Putten, 2012). Strong connections exist between above-surface and below-surface diversity, even at diverse temporal scales for organisms. Moreover, changes that impact above-surface diversity and functioning also reflect in the below-surface ecosystems (Orgiazzi et al., 2015).

In general, soil biodiversity provides an avenue for advancing worldwide sustainability as it incorporates several challenges affecting contemporary society, such as climate change, water resources management, resources degradation, provision of food and fibre, and as well as habitat for organisms beneath the soil surface and underwater (Pascual et al., 2015).

Soil represents a crucial component of the climatic system. Apart from the oceans, the soil is considered an essential means of carbon (EEA, 2015). By definition, the soil is the "unconsolidated mineral or organic material on the immediate surface of the Earth" (NCRS, 2022).

Although this article emphasises SDG #13 (Climate action) and its relationship with other SDGs (e.g., #2: Zero Hunger, and #15: Life on Land), it has, actually, a global change approach, in the sense that global change refers to the changes of the Earth system, treated in its entirety with interacting physicochemical and biological components as well as the impact human societies have on the components and vice-versa (Steffen et al., 2005).

This review aims to highlight the climate change impacts on soil and its biodiversity, which affects the health of the environment and food production, and that the synergy of the soil-plant-animal nexus is crucial in addressing global change and combating climate change.

2. Materials and methods

To provide an overview of the impacts of global change (climate and land use changes) on soils at a planetary level, we conducted a literature review combining a narrative review and a bibliometric analysis of manuscripts published in the last ten years, focusing on the three research questions.

1. How does climate change affect soil biodiversity?
2. How does land use change affect soil biodiversity?
3. What are the main current climate change adaptation and mitigation activities?

From the literature review, we gathered examples from countries, regions, or global measures deployed to reduce the impact of climate change on soil biodiversity. A limitation of the study approach is that transcendent articles older than ten years in soil studies are essential to understand the importance of the process.

The co-occurrence analysis of terms provided an overview of the literature focused on the linkages between climate change and soil biodiversity. We used the VOSviewer freely available bibliometric analysis software for this purpose (Van Eck and Waltman, 2020). The data for term co-occurrence analysis were obtained from the Web of Science which is recognised for archiving quality peer-reviewed academic research. For this purpose, we used a broad-based search string that is composed of terms related to climate change ("climate* change*" OR "global warming") and soil biodiversity ("soil biodiversity" OR "soil health" OR "soil system*" OR "soil ecosystem*" OR "soil nutrient*" OR "soil salinity" OR "soil dry*" OR "soil erosion" OR "soil fertility" OR "soil erosion" OR "soil biolog*" OR "soil physicochemical" OR "soil's biolog*" OR "soil's physicochemical").

We searched in titles, abstracts, and author keywords of the database on October 29, 2022, and selected 3635 documents for inclusion in the term co-occurrence analysis. The analysis output is presented as a graph, where nodes represent primary keywords and links indicate how they are connected. Node size and link width are proportional to the frequency of co-occurrence and the strength of inter-term connections, respectively.

3. Results and discussion

3.1. Introducing some impacts of climate change on soil biodiversity

Increased temperatures and altered rainfall severely impact the quality and property of the soil (Venati et al., 2020); therefore, protecting soil from the harmful effects of climate change is of utmost importance. Notably, climate change led to a considerable decline in soil humidity in Mediterranean countries, requiring adequate irrigation.

Fig. 1 describes the current status of soil dryness in Europe using the Soil Water Index, which quantifies the moisture condition at various depths in the soil.

Nevertheless, a massive demand for irrigation, when combined with drops in precipitation and low levels of groundwater, can increase the risk of desertification, which entails far-reaching consequences for agricultural production (EEA, 2019).

3.2. Examples

Table 1 depicts selected examples (from the narrative-focused review) of the impact of climate change on soil diversity. It shows two main characteristics: (i) different models have been cascaded from a city level (Maoming, China) to regional (like Brandenburg, Germany, Amazonia), country (Sri Lanka, Slovakia), continental (European Union) and global level, and (ii) three dimension were studied: a) impact of various climatic conditions on soil biodiversity; b) impact of various agricultural practices on soil biodiversity, and c) assessment of the changes through different measurable soil-biodiversity indicators, including the legislative perspective.

The examples show that climate change and human behaviour, coupled with land use change, can negatively influence the ecosystem services soil provides, often in a feedback process.

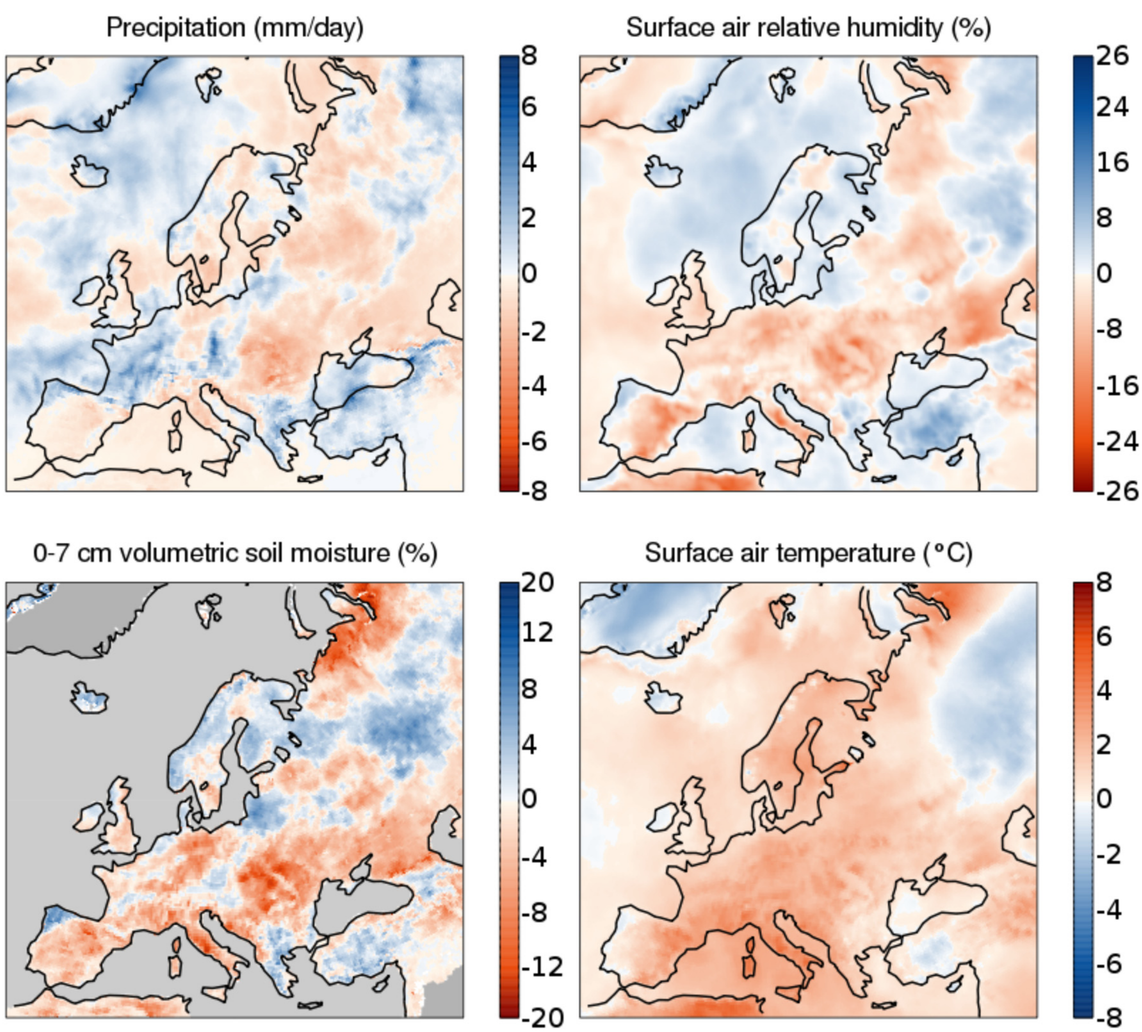

Fig. 1. Overview of soil dryness in Europe in June 2022.
Source: Modified from Copernicus Service Information (2022).

Table 1
Examples of the impact of climate change on soil diversity.

Region	Measure analysed/deployed	References
Global	• The authors identified and characterised existing environmental gaps in soil taxa and ecosystem functioning data across macroecological worldwide soil studies and 17,186 sampling sites.	• Guerra et al. (2020).
	• The authors examined the origin of popular ideas on the role of soil biology in sustainable soil management and their potential to address critical global challenges related to agriculture.	• Pulleman et al. (2022).
	• The authors tested ten drivers of global change as it affects soils individually and in combination at levels ranging from 2 to 10 factors.	• Rillig et al. (2019). • Zhou et al. (2020).
	• Synthesised 1235 Global change factors (GCF) observations worldwide showed that rare microbial species are more sensitive to GCFs than typical species. GCFs do not always lead to a reduction in microbial diversity.	• Guo et al. (2019).
	• The authors examined the species–time relationships STRs and phylogenetic–-time relationships (PTRs) of soil bacteria and fungi in a long-term multifactorial global change experiment with warming (+3 °C), half precipitation (−50 %), double precipitation (+100 %) and clipping (annual plant biomass removal) and confirmed that both the soil bacteria and the fungi demonstrated powerful STRs and PTRs throughout 12 different circumstances.	
• Global South	• A bioeconomic model that unpacks soil biodiversity's role in increasing and stabilising agricultural productivity in low-input rainfed farming systems was presented.	• Sidibé et al. (2018)
• Europe and the European Union	• An overview of the characterisation and assessment of soil biodiversity with examples of biological soil indicators and monitoring approaches was presented.	• Pulleman et al. (2012). • Aksoy et al. (2017). • Creamer et al. (2020).
	• The soil habitat potential for biodiversity was assessed and mapped throughout Europe by combining several soil features (pH, soil texture and soil organic matter) with environmental parameters (potential evapotranspiration, average temperature, soil biomass productivity and land use type).	• • Creamer et al. (2020). • Köninger et al. (2022).
	• The biodiversity and ecosystem function range was assessed across 76 sites across 11 European countries, and fourteen biological methods were applied as proxy indicators for these functions.	
	• The authors used network analysis to identify the critical connections between organisms under the different land use scenarios.	
	• Review the regulatory instruments and strategic policy documents at the EU and national levels to identify whether they adequately protect soil biodiversity.	
• Germany	• A gradient of soil biodiversity was created using the dilution-to-extinction approach and investigated the effects of soil biodiversity loss on plant communities during and following manipulations simulating global change disturbances in experimental grassland microcosms.	• Yang et al. (2020). • Yang et al. (2021). • Yin et al. (2020).
	• The authors investigated the effects of plant and soil biodiversity on the temporal stability of biomass production under varying simulated precipitation in grassland microcosms.	
Slovakia	• Assessment of Soil properties and biodiversity in different soil cultivation types: conventional, minimum till, mulch, no--till and organic farming based on two case study areas: organic farm Agrokruh and experimental farm Borovce.	• Houšková et al. (2021).
Wales, United Kingdom	• The effect of growing different forage crops on soil faunal diversity and abundance was compared.	• Crotty et al. (2015).
• China • Maoming City	• The authors investigated the diversity and composition of nematode communities in mainland China at the taxonomic, functional, and phylogenetic levels in 16 assemblage pairs (32 sites in total, with 16 in each habitat type).	• Li et al. (2019). • Jiao et al. (2022). • Wang et al. (2020).
Nanjing	• The authors reported relationships between soil biodiversity of multiple organism groups and ecosystem functions in 228 agricultural fields relating to crop yield, nutrient provisioning, element cycling, and pathogen control.	
	• Long-term grazing exclusion experiments were performed across eight sites along a precipitation gradient covering three major grassland types in northern China to compare the linkage between soil microbial diversity and N availability in overgrazed versus non-grazed conditions.	
	• The article mapped and analysed the biodiversity and functioning of multiple soil organism groups resulting from diverse afforestation methods in tropical coastal terraces.	• Wu et al. (2021).
	• Were evaluated seven factors expected to affect soil biodiversity (land-use change, organic carbon loss, agriculture/land-use intensity, soil erosion, soil compaction and sealing, soil pollution and soil acidification), and quantified and mapped the composite threats to soil biodiversity in Nanjing, China using a weighted sum method.	• Li et al. (2017).
Sri Lanka	• A review article on the impacts of climate change on biodiversity and ecosystems in Sri Lanka	• Kottawa-Arachchi and Wijeratne (2017).
• Sumatra, Indonesia	• The authors investigated the effects of herbicides' understory manipulation on soil fauna, litter decomposition rates, and soil abiotic variables: pH, soil organic carbon, soil water content, nitrogen, carbon/nitrogen ratio, potassium, and phosphorous.	• Ashton-Butt et al. (2018).
Amazonia	• A meta-analysis assessed the impact of deforestation and ecosystem conversion to arable land on Amazonian soil biodiversity.	• Franco et al. (2018).
Brazil	• The article combined two years of rainfall seasonality, leaf and wood litter production and decomposition with soil epigeic fauna abundance, taxa richness, Shannon's diversity and Pielou's evenness, and 16 soil biogeochemical variables measured in 12 plots of preserved savanna.	• Inkotte et al. (2022).

3.3. Term co-occurrence analysis

The result of the term co-occurrence analysis is shown in Fig. 2. The figure shows that existing research on the interactions between climate change and soil biodiversity can be divided into three broad clusters shown using different colours (blue, green and red) in Fig. 2.

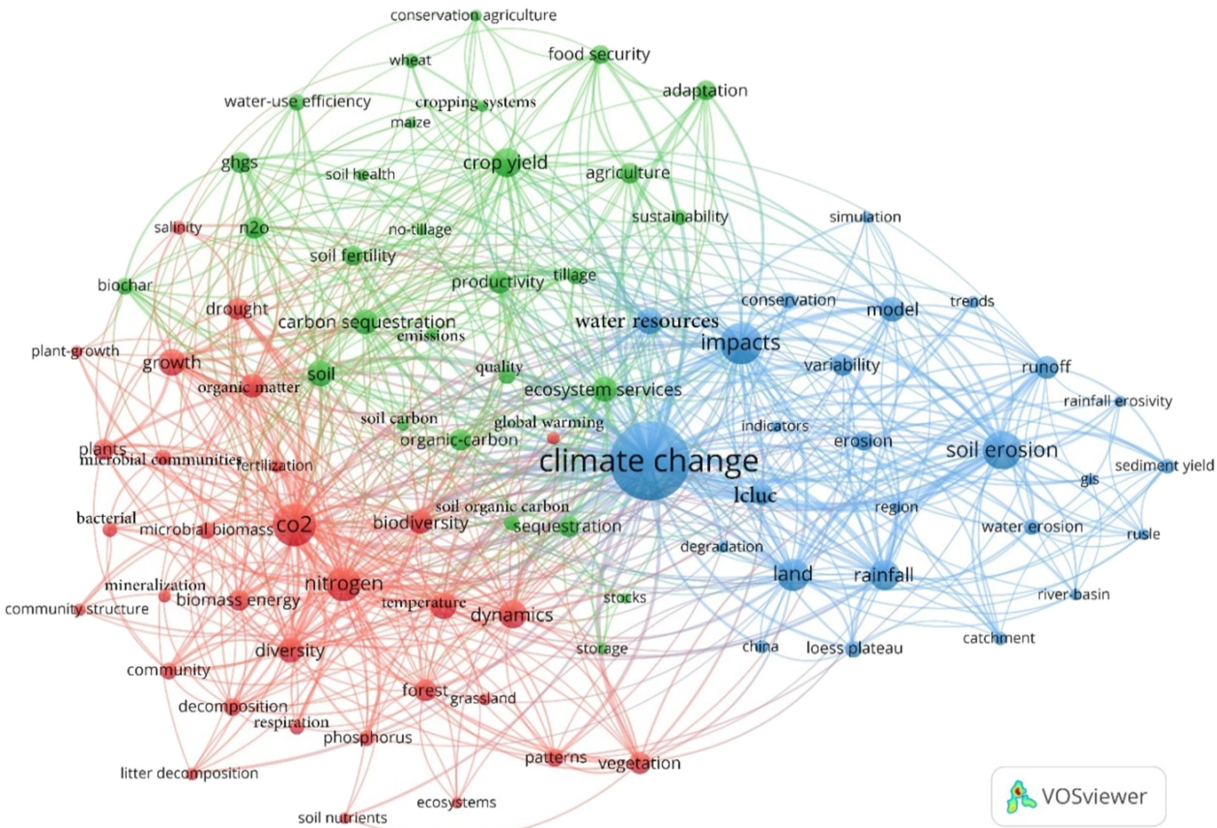

Fig. 2. Results of the term co-occurrence analysis.

The green cluster focuses on soil fertility, productivity, and crop yield. The blue cluster is dominated by terms related to soil degradation, loss, and erosion. Finally, the red cluster focuses on soil nutrients, sequestration capacity, and biodiversity issues.

The soil ecosystem comprises critical biodiversity indicators such as soil health, vulnerability, presence of plant pathogens, soil carbon stocks, nutrient cycle, soil fertility and conservation (Guerra et al., 2021) (Fig. 2, red cluster). In addition, these indicators aim to monitor changes over time due to environmental changes, including climate change (Martin et al., 2021).

The activities and interactions of soil organisms determine ecosystem functions which are vital for the sustained biomass productivity of land and the provision of various ecosystem services, including the supply of potable water or greenhouse gas (GHG) mitigation (Pulleman et al., 2022). Janzen et al. (2021) believe that soils are healthy when they sustain ecosystem functions like nutrient cycling, storage of carbon, suppressing diseases and pests, regulating water and stemming pollution. Moreover, functions are not restricted to services, which indicates direct human benefits (Fig. 2, green cluster). However, it also points to activities that safeguard the integrity of ecological systems and the biosphere (Janzen et al., 2021). The spotlight on living soils stresses the value of gaining further insights into ecological processes and approaches that ensure better management of soils (Janzen et al., 2021). The notion of enhanced soil management underpins measures towards soil biodiversity and health, for that matter. Moreover, safeguarding soil biodiversity is foregrounded in increasingly common farming methods, including agroecology, regenerative agriculture and conservation agriculture (Fig. 2, green cluster). A common denominator in all these approaches is an attempt to mimic or replicate natural ecosystem functions to attain sustainable food production (Giller et al., 2021).

The mimicry of nature, as reflected in the adoption of natural measures to enhance ecosystem functioning, is core to ecological intensification and nature-based agricultural systems (Bommarco et al., 2013; Pulleman et al., 2022). Furthermore, such approaches help limit modern agriculture's heavy reliance on the high usage of external inputs, which tends to reduce environmental externalities towards attaining food and water security coupled with climate ideals (Donkor et al., 2019; Dynarski et al., 2020) (Fig. 2, blue cluster).

Ultimately, safeguarding biodiversity continues to gain traction in crucial policy discourses to enhance soil health and simultaneously promote sustainability (Pulleman et al., 2022) (Fig. 2, red cluster).

Climate change has diverse impacts on the ecosystem (Donkor et al., 2019), like the intensification and acceleration of soil salinity issues, particularly in arid and semi-arid regions and coastal agricultural areas, with significant implications for global food security and could also increase CH_4 and N_2O emissions (Corwin, 2021; Mukhopadhyay et al., 2021) (Fig. 2, red cluster). However, different measures can be adopted to reduce the pace of soil salinity development and improve soil biodiversity, e.g., the use of amendments such as gypsum and biochar, cultivation of slat-tolerant genotypes, appropriate land use planning and agroforestry techniques, improved irrigation (drip system) and drainage (sub-surface), and other climate-smart solutions (Mukhopadhyay et al., 2021) (Fig. 2, green cluster).

Improving soil's physicochemical and biological characteristics can improve soil health and minimise negative impacts on agricultural productivity (Mukhopadhyay et al., 2021; Cavicchioli et al., 2019). Furthermore, they reduce CH_4 and N_2O emissions from salt-affected soils (Mukhopadhyay et al., 2021) (Fig. 2, red cluster). The soil microbiome plays an essential role in the ecosystem and affects eco-health through various mechanisms such as biogeochemical cycling, bioremediation, plant growth and primary production (Cavicchioli et al., 2019).

Climate change may affect microbial profiles in the soil through changes in soil carbon/nitrogen cycling (Naylor et al., 2020), leading to the emission of greenhouse gases to the atmosphere and carbon immobilisation into microbial or plant biomass, joined with additional side effects such as soil warming and elevated CO_2 (Sulman et al., 2014). In parallel, climate change impacts genetic alterations and some species' extinction, affecting underground species' biodiversity (Idris et al., 2022). Moreover, key aspects such as compaction, stability or structure of the soil can be significantly affected (Venati et al., 2020) (Fig. 2, blue cluster).

Primary food production is mainly associated with resource-based impacts (associated with depletion of various abiotic resources and soil use) and emission-based impacts (covering global warming, acidification, and eutrophication related to the use of chemicals, both organic and mineral) (Djekic et al., 2021).

Temperature increases and changes in precipitation regimes mainly result in more extensive pesticide use, increasing pesticide toxicity (Kaka et al., 2021). In parallel, other effects may occur, such as decreased soil pesticides' bioavailability and changes in growth patterns and reproduction of earthworm species, combined with increased acidification and eutrophication potential (Fig. 2, blue cluster).

However, if implemented, several measures could prevent soil erosion; specific sustainable management practices are integral to retaining nutrients and thus enhancing soil fertility and health (Venati et al., 2020) (Fig. 2, blue cluster). Furthermore, as climate change aggravates water scarcity, adequate water management is essential for soil functioning (Lal, 2012). For instance, newly introduced measures, such as mixing clay with sandy soils, retain more water (Unkovich et al., 2020). For comprehensive water management, an intersectoral approach between key sectors needs to be adopted (Karnib and Alameh, 2020).

Most importantly, crop residues are beneficial in reducing soil erosion if left on the surface (FAO, 2017). Moreover, soil tillage should be minimised in light of advancing climate change since this process is accompanied by a reduction in organic matter and increased erosion (Venati et al., 2020). Finally, crop rotation is vital in ensuring soil health because farming with cover crops retains the soil's essential nutrients and carbon (Corwin, 2021) (Fig. 2, green cluster).

As far as climate change mitigation and soil health improvement are concerned, other sustainable practices include comprehensive nutrient management and mulch cum manuring. In this context, conservation agriculture and water-saving technologies are also essential. Besides, intercropping and biochar application are additional practices for proper soil functioning (Venati et al., 2020) (Fig. 2, green cluster).

The integrated systems of agricultural production have gained prominence among the systems that promote sustainable intensification and, consequently, the improvement of soil biodiversity (Magalhães et al., 2019) (Fig. 2, red cluster). Within integrated systems, the soil remains covered throughout the year, and one activity can benefit the other in the replacement, incorporation, availability, and extraction of nutrients from the soil. For example, research showed that 60–70 % of the nitrogen taken up by plants could be recycled and taken up again, 77 % of the phosphorus can be available for the next crop, and the subsequent crop can use 100 % of the potassium (Mendonça et al., 2015). Thus, sustainable grain production in many areas can reduce the use of industrialised chemical elements and contribute to climate change adaptation and mitigation.

In summary, the current unsustainable use of the land and how it can aggravate and worsen due to climate change may negatively influence the biodiversity of soils. However, well-managed soils are the key to supporting production systems more resilient to climate change as they retain carbon, reduce CO_2 emissions, and promote nutrient cycling (FAO, 2017).

4. Conclusions

The narrative-focused review, the selected examples worldwide presented in Table 1 and the bibliometric co-occurrence analysis answer the research questions:

1) How does climate change affect soil biodiversity?
2) How does land use change affect soil biodiversity?
3) What are the main current climate change adaptation and mitigation activities?

This review shows that the current unsustainable use of the land, aggravated and worsened due to climate change and extreme weather, may negatively influence the biodiversity of soils. Therefore, well-managed soils that retain carbon, reduce CO_2 emissions and promote nutrient cycling are critical for resilient production systems.

Consequently, integrated systems of agricultural production have gained prominence among the systems that promote the improvement of the soil's chemical, physical, and biological characteristics, at the same time that they may make agriculture viable. These systems explore the synergistic effects of interactions in the soil-plant-animal-atmosphere compartments of areas that integrate agricultural and livestock activities and whether these activities may occur in parallel in the same area.

Therefore, in this context, it is necessary to consider the best ways to integrate the activities in each place of production (crop, livestock, forest, river and others) considering climatic specificities, the potential and the agricultural needs of the territory, as well as the accessibility of methods that seek to interfere less in the soil so that the impacts of climate change on soils and land use can be minimised.

In this context, agricultural zoning may be a valuable tool in integrated systems to minimise the effects of climate change. Agricultural zoning indicates the planting season for each crop throughout the agricultural year based on parameters such as rainfall, soil type, photoperiod, and temperature, allowing for the most appropriate development of each crop phase (germination, vegetative growth, flowering, physiological maturity, and harvest).

However, it is vital to continuously and closely monitor environmental variations so that producers can be more prepared for climate change, especially the influences of extreme events such as drought, excessive rain, sandstorms, hurricanes and cyclones. When the producer has this information, it becomes possible to plan the related activities better and sustainably explore each region's available resources.

There are other measures which, if duly implemented, could prevent soil erosion. For instance, specific sustainable management practices are integral to retaining nutrients and thus enhancing soil fertility and health. Furthermore, as climate change aggravates water scarcity, adequate water management is essential for the functioning of the soil. This may include newly introduced measures, such as mixing clay with sandy soils, which tend to retain more water. In addition, an intersectoral approach between critical sectors must be adopted for comprehensive water management.

Most importantly, crop residues reduce soil erosion if left on the surface, so a greater advantage of them may be taken. Moreover, soil tillage should be minimised, avoiding excess herbicides, in light of advancing climate change since this process is accompanied by a reduction in organic matter and increased erosion. Finally, crop rotation is vital in ensuring soil health because farming with cover crops retains the soil's essential nutrients and carbon.

As far as climate change mitigation and soil health improvements are concerned, other sustainable practices may include comprehensive nutrient management and mulch cum manuring. In this context, conservation agriculture and water-saving technologies are also essential. Moreover, intercropping and/or fallow biochar application may be additional practices for supporting proper soil functioning.

The fact that soils are widely exposed to global change as a whole, and climate change in particular, and bearing in mind that billions of people around the world rely on agriculture for their food supplies, suggests that measures aimed at soil conservation need to be regarded as a priority. Therefore, more research investments are needed, both in respect of soil conservation and protection and in optimising agriculture practices so that their impacts on soils may be minimised.

CRediT authorship contribution statement

All authors have contributed to the review research, writing and revision of the manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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