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Handling the Impacts of Climate Change on Soil Biodiversity

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Abstract

Land as a whole and soil in particular, plays an important 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. Increases in temperature, long drought and floods, all pose a pressure on soil. In order to contribute to a better understanding of these interactions, this paper reports on a study which has analysed how climate change impacts soil biodiversity and its related services. It also outlines some of the actions needed to increase the resilience of soil biodiversity in the context of a changing climate.

Keywords: Climate adaptation and mitigation; Sustainable Development Goals; Climate Change impacts; Food Production; Resilience; Ecosystem Services.

1. Introduction

Soil biodiversity and sustainable soil management are preconditions for attaining Sustainable Development Goals (SDGs) (Keesstra et al., (2016), which is 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 & Hartmik, 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[4]. Moreover, soils are considered non-renewable resources as their degradation/loss is hardly recovered within a human life period (Domínguez et al., 2017).

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 (Leban 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).

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). In addition, these indicators aim to monitor changes over time due to environmental changes, including climate change (Martin et al., 2021).

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).

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 indicate direct human benefits. 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. 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).

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. Plants and animals extract nutrients from the

soil (Absorption and Ingestion) and export them through products (grains, meat, energy, fibre and others).

However, plants and animals can return nutrients to the soil through excretion (urine and faeces), association with microorganisms, and residue deposition (crop residues, senescent material, and others). The atmosphere, in turn, can act as a receptor (volatilisation) and donor of nutrients (deposition).

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 can reduce the use of industrialised chemical elements and contribute to climate change adaptation and mitigation.

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

2. Materials and Methods

In order to provide an overview of the impacts of climate change on soils, we first gathered a set of case studies showing examples from countries, regions, or global, of measures deployed to reduce the impact of climate change on soil biodiversity. Then, we performed a bibliometric analysis illustrating the connections between climate change and soil biodiversity. To interpret the results of the bibliometric analysis, “we conducted a narrative literature review of manuscripts published in the last ten years focusing on two main research questions; how climate change affects soil biodiversity and the current climate change adaptation and mitigation activities”.

Term co-occurrence analysis was used to provide an overview of the literature focused on the linkages between climate change and soil biodiversity. We used the VOSviewer, a freely available bibliometric analysis software, for this purpose (Van Eck & Waltman, 2022).

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 3,635 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. Results from the case studies

Table 1 depicts selected case studies on 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, (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.

Table 1: Case studies on the impact of climate change on soil diversity.

Region	**Measure analysed/deployed**	**References**
Brandenburg, 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).
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).
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).
Europe	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).
Maoming City, China	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).
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).
Brandenburg, Germany	The authors investigated the effects of plant and soil biodiversity on the temporal stability of biomass production under varying simulated precipitation in grassland microcosms.	Yang (2021).
China	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).
Sri Lanka	A review article on the impacts of climate change on biodiversity and ecosystems in Sri Lanka	Kottawa-Arachchi & Wijeratne. (2017).
Europe	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).	Aksoy et al. (2017).

European Union	Review the regulatory instruments and strategic policy documents at the EU and national levels to identify whether they adequately protect soil biodiversity.	Köninger et al. (2022).
Amazonia	A meta-analysis assessed the impact of deforestation and ecosystem conversion to arable land on Amazonian soil biodiversity.	Franco et al. (2018).
Global	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).
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)
Nanjing, China	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).
Global	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).
China	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.	Jiao et al. (2021).
Germany	The authors investigated the functional responses of Collembola, one of the most abundant and ecologically important groups of soil invertebrates. They tested the effects of climate, land use, and their interactions on the functional diversity, community-weighted mean, traits (life-history, morphology), and functional composition of Collembola, as well as the Soil Biological Quality-Collembola (QBS-c) index.	Yin et al. (2020).
Wales, United Kingdom	The effect of growing different forage crops on soil faunal diversity and abundance was compared.	Crotty et al. (2015).
China	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.	Wang et al. (2020).
Global	The authors examined the 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).	Guo et al. (2019).
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).
Global	Synthesised 1235 GCF observations worldwide showed that rare microbial species are more sensitive to GCFs than typical species, while GCFs do not always lead to a reduction in microbial diversity.	Zhou et al. (2020).
Europe	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.	Creamer et al. (2016).

The case studies show that climate change, coupled with human behaviour, can negatively influence the ecosystems services provided by soil, often in a feedback process.

3.2 Impacts of climate change on soils

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).

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[12]. Nevertheless, a massive demand for irrigation can increase the risk of desertification, which entails far-reaching consequences for agricultural production (EEA, 2019). Figure 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.

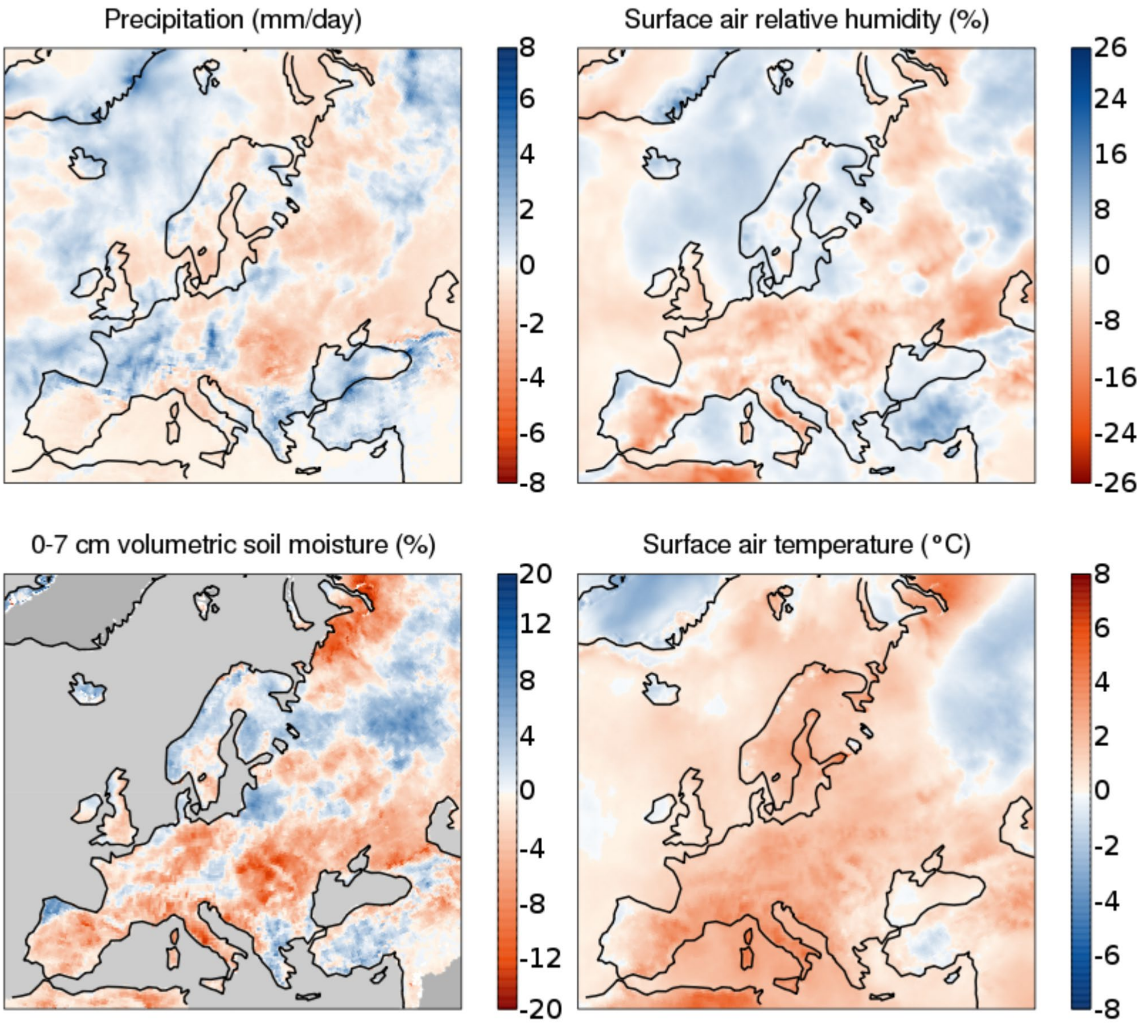

Figure 1. Overview of soil dryness in Europe in June 2022. Source: Modified from Copernicus Service Information (2022)[13]

Climate change has diverse impacts on the ecosystem (Donkor et al., 2019)[14], 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 CH4 and N2O emissions (Corwin, 2021; Mukhopadhiay et al., 2021). 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 (Mukhopadhiay et al., 2021). Improving soil's physicochemical and biological characteristics can improve soil health and minimise negative impacts on agricultural productivity (Mukhopadhiay et al., 2021; Cavicchioli et al., 2019). Furthermore, they reduce CH4 and N2O emissions from salt-affected soils (Mukhopadhiay et al., 2021). 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[18] 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).

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.

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). 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 & 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).

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).

3.3 Results of term co-occurrence analysis

The result of the term co-occurrence analysis is shown in Figure 3. The figure shows that existing research on the interactions between climate change and soil biodiversity can be divided into three broad clusters that are shown using different colours in the figure.

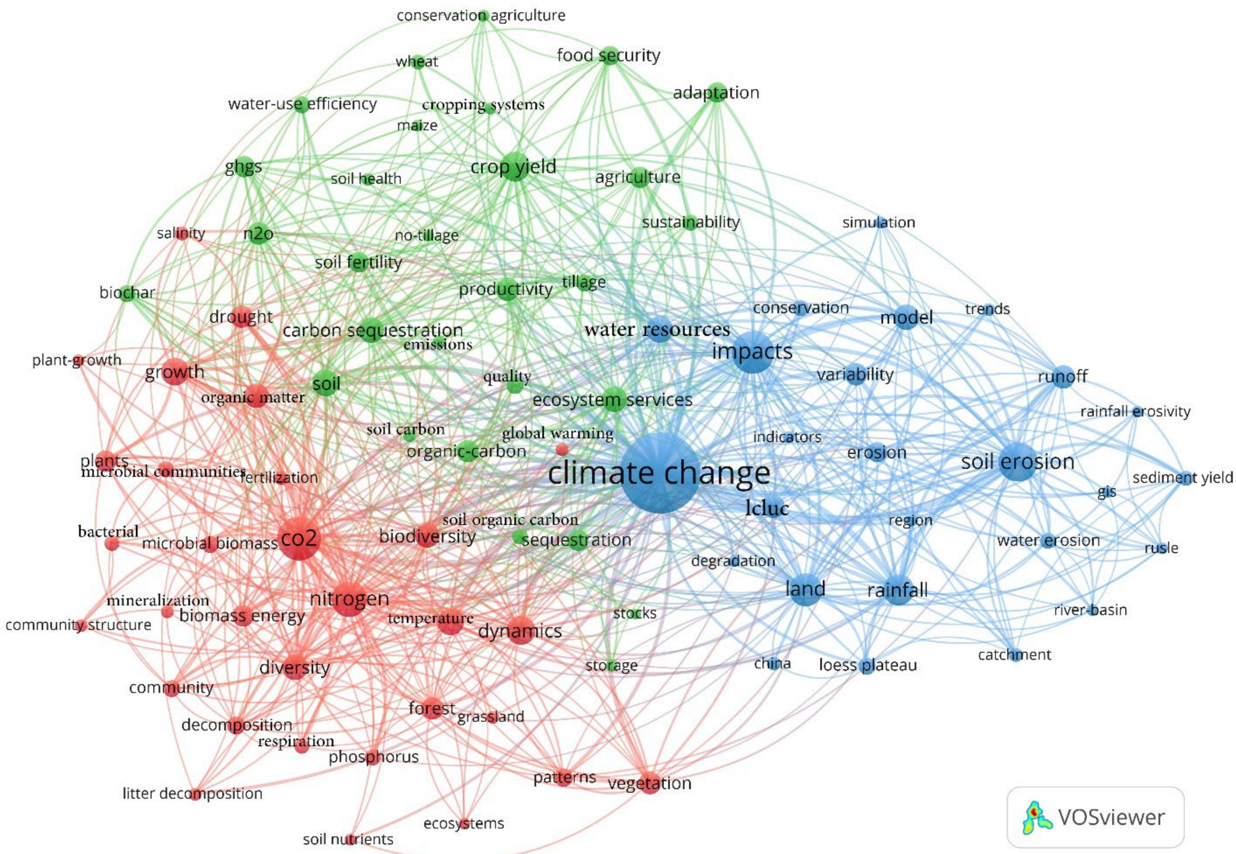

Figure 2. Results of the term co-occurrence analysis

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.

Conclusions

As this paper has shown, climate change may negatively influence the biodiversity of soils. 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). Consequently, the integrated systems of agricultural production have gained prominence among the systems that promote the improvement of the soil's chemical, physical, and biological characteristics. 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 be occurring in the same area.

Agricultural zoning may be an useful 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 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 monitor environmental variations so that producers can be more prepared for climate change, especially concerning extreme events such as drought, excessive rain, sandstorms, hurricanes and cyclones. When the producer has this information, he can better program his activities and sustainably explore each region's available resources.

Therefore, in this context, it is necessary to consider the best way 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 can be minimised.

There are, other measures which, if duly implemented, could prevent soil erosion; specific sustainable management practices are integral to retaining nutrients and thus enhancing soil fertility and health11. Furthermore, as climate change aggravates water scarcity, adequate water management is essential for the functioning of the soil22. For instance, newly introduced measures, such as mixing clay with sandy soils, retain more water23. For comprehensive water management, an intersectoral approach between key sectors needs to be adopted24.

Most importantly, crop residues are beneficial in reducing soil erosion if left on the surface25. 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 erosion11. Finally, crop rotation is vital in ensuring soil health because farming with cover crops retains the soil's essential nutrients and carbon14.

As far as climate change mitigation and soil health improvement 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 biochar application are additional practices for proper soil functioning11.

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