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The Effect of Global Change on the Soil Body.

Sophie Cornu¹, David Montagne², Antra Boca³

1- Aix Marseille Univ., CNRS, IRD, INRA, Coll France, CEREGE, Aix-en-Provence, France

2- Université Paris-Saclay, INRAE, AgroParisTech, UMR ECOSYS, , 78 850 Thiverval-Grignon, France

3- Latvia University of Life Sciences and Technologies, Jelgava, LV-3001, Latvia.

Sophie.Cornu@inrae.fr

david.montagne@agroparistech.fr⁷

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Abstract

Without soil, no life on land is possible because soil provides the means for plant growth and plays a crucial role in water and carbon cycling among others. Human-induced global changes related to climate, land use and management are altering soils. The concepts of ecosystem services and soil capital value them, their functions and prevent their degradation. A major challenge for soil science is to quantify the relationships better between global changes, and soil processes and properties. The aim is to predict soil changes and understand whether soils will continue to deliver the services required in the long-term and in what extent can soil management mitigate climate change.

Key points/objectives

- Soil is a dynamic system characterized by feedback loops, linking external forcing variables (or factors of pedogenesis), pedological processes, soil properties and ultimately soil functions and services.
- As a result of the complex interactions between climate, land-use and or management changes acting on various spatial and time scales, the direction, intensity and spatio-temporal pattern of future soil changes remain largely unknown.
- First indications of the effect of global change on a range of soil types, processes and properties have been observed already.
- In the future, effects of global change on soils will largely exceed well identified situations such as the reduction of Cryosols, soil degradation processes (e.g. erosion or desertification) or manageable soil properties (e.g. soil organic carbon stocks).
- With the irreversibility of numerous soil processes, a changed climate that can increasingly remove primary minerals, clay particles and base cations from soil threatens soil fertility, quality and health.
- If land-use or land management changes could be used theoretically to counteract climate change, their practical implementation at the pace and spatial scales of climate change is doubtful and could have counterproductive effects.
- Soil management must be planned and implemented to limit the risk of mutual reinforcement of climate and land-use changes that are already inducing cataclysmic soil degradation under extreme weather events.
- To face these arising and mostly inevitable challenges, there is an urgent need to develop tools and methodologies able to capture the new evolution of soil under global changes.
- The feedback loops between external forcing variables and soil properties are currently insufficiently considered in global modelling approaches, in which the soil compartment is generally poorly described.

Introduction

Soils are open systems produced by a complex combination of processes of input, transformation, transfer and export of materials and energy. Their occurrence and intensity are a function of external environmental conditions, otherwise called factors of pedogenesis. These factors include the parent material, the climate, the relief, living beings and time.

Under the control of these external environmental conditions (factors of pedogenesis), the physical, chemical or biological processes transform and structure the upper layers of the Earth's crust, i.e. the parent material of the soils, whose initial properties are gradually replaced by more stable constituents and organization. The emergence of these new properties is the basis for the ecosystem functions and services that soils provide to humanity. They also affect how the soil responds to external environmental conditions. For example, the physical fragmentation of a hard rock will gradually favour the infiltration of water into the soil and modify the pedoclimatic conditions; the redistribution of soil particles by erosion will modify the relief; the formation and deepening of the soil will allow its colonization by new plant or animal species which will, in turn, participate in the processes of alteration of the geological substrate. The soil is therefore a dynamic system characterized by feedback loops, linking external forcing variables (or factors of pedogenesis), pedological processes and soil properties. Thus, any modification of the external forcing variables is likely to modify some pedological processes and properties, which in turn will change how the external variables affect the soil depending on thresholds, positive or negative feedbacks or even hysteresis.

From the pedological factors, two - climate and vegetation – have constantly changed through time, notably over the most recent period, in which humans have strongly affected both and will continue to do so in the near future. These changes, also known as global change, have been shown to affect a range of soil properties with some changing rapidly and others gradually (Rounsevell et al., 1999). Agriculture, for example, affects soil rapidly, at a decadal to century time scale (Cornu et al., 2012; Guo et al., 2010; Montagne et al., 2016) and, in many cases, in an irreversible way (Sombroek et al., 1990; Rounsevell et al. 1999; Montagne et al., 2016). The effects of climate change on soils are more difficult to identify and quantify. However, its impacts may have serious consequences for soil productivity and sustainability of agriculture and forestry as well as the stability of our infrastructure. The changes induced in the soil may in turn act on land use through changes in fertility or on climate via the release of greenhouse gasses. These feedback loops are currently not considered sufficiently in global modelling approaches, in which the soil compartment is generally poorly described.

Therefore, quantifying the impact of global change on soils is a challenge that must be addressed. A major difficulty in addressing this is the large uncertainty about the kinetics of natural soil processes. Consequently, the direction, intensity and spatial distribution of change in the soil under global changes, and their consequences on the delivery of soil services and human well-being remain still largely unknown.

Global Change, the Dynamics and Impact on the Fluxes of Matter and Energy Responsible for Soil Evolution

Global Change and its Dynamics

The concept of global change, defined in the 1970s, considers human activities as part of the planetary system together with atmosphere, biosphere, hydrosphere and the geosphere. It can be divided in two main types of change: climate change and land use changes.

Climate change caused by anthropogenic emissions of greenhouse gases is widely recognised, and has resulted in a noticeable increase of the Earth surface temperature of 0.85°C since 1880 (Figure 1). This increase is responsible for the increasing temperature of permafrost areas since the 1980s and a decrease in ice mass and snow cover in most regions, with noticeable consequences for the hydrological regime. In addition, an increase in rainfall has been observed since the beginning of the 20th century in the Northern hemisphere, but with no clear change recorded elsewhere. A change in the frequency of extreme events has been recorded with a decrease in cold extreme events, and an increase in hot extreme events and strong rainfall events (Jia et al., 2019). Regardless of the climate scenario considered, these trends are predicted to continue over the 21st century together with a decrease of rainfall in the arid medium latitudes (Hartmann et al., 2013). An increase in the speed of such progressive changes or even abrupt changes in temperature or precipitation pattern, however, cannot be completely excluded, at least locally, as a result of the atmospheric CO₂ (carbon dioxide) accumulation or climatic break points such as the melting of polar ice caps or changes in ocean global circulations. Gradual changes in temperature and precipitation will induce slow, low amplitude and continuous modifications in soils, whereas extreme events will induce rapid, large amplitude and irregular changes, all of which will accumulate over time (Figure 2).

Land cover is the biophysical state of the Earth's surface and immediate subsurface. **Land use** involves both the manner in which the biophysical attributes of the land are manipulated and the purpose for which it is used. In other words, land use can be described by the terms 'forestry, parks, farmlands, etc.' as well as by biophysical manipulations such as the use of fertilizers, logging, change of forest species composition, etc. Purely natural disturbances of the land cover, e.g., wildfires have caused large-scale changes like the loss of tree canopy and gain in short vegetation in large patches of boreal Canada, eastern Alaska and central Siberia (Song et al., 2018). However, a much stronger force for change is from human impact. Land-use change is traditionally a local-scale human practice with an annual time step (e.g., deforestation of a plot), its evolution at the global scale has however a decadal to century time step (Figure 2).

Today, as much as 50 % of the Earth's ice-free land surface has been transformed, and virtually all land has been affected in some way by such processes as co-adapted landscapes, climate change, and tropospheric pollution (Turner et al., 2007). The Millenium Ecosystem Assessment (2005) states that, while these changes in land uses are not recent, they have been more rapid and extensive since the 1950s as illustrated by the exponential increase in surface area cultivated with soybean (*Glycine max* (L.) Merrill) and palm trees (Arecaceae) during that period (Figure 1). Nevertheless, a global increase in tree cover has also been observed from 1982 to 2016 together with a reduction in bare soil. The net gain in tree cover was mostly due to increases in the continental and polar regions, and across all climate domains for montane systems (Song et al., 2018). This increase counteracted losses of tree cover in the tropics and in many arid and semi-arid ecosystems where increasing conversion to intensive agriculture is occurring. In

northern temperate countries, the surface area dedicated to agriculture has tended to decline while the intensification of agriculture continues to produce more food on smaller land areas for an increasing human population, and a new challenge of biomass production to substitute fossil fuels emerges. On a positive note, new agricultural diversification practices are emerging worldwide (crop and non-crop rotation and diversification, various forms of conservation agriculture, organic farming, etc.), many of which show a win-win situation in the relationship between crop yields and multiple ecosystem services (Tamburini et al., 2020). The area under alternative farming systems is still small (~ 72.3 million hectares from ~ 5 billion hectares of agricultural land worldwide are under organic farming) but steadily increasing (FAOSTAT data). In Europe, for example, the area under organic farming currently constitutes around 9% of all agricultural land (Eurostat data).

Overall, land use and land cover changes are considered to be the major causes and consequences of global change on land. Song et al. (2018) estimated that from 1982 to 2016, of all land changes, 60% were associated with direct human activities and 40% with indirect factors such as climate change (e.g., woody vegetation growth in the Arctic). Land use and land cover changes are estimated to have contributed 25% of cumulative carbon emissions to the atmosphere since industrialization (Friedlingstein et al., 2020). Conversely, climate change affects cultivation in many regions of the world (Jia et al., 2019). Indeed, the continuing increase in global temperature, and the shifts in precipitation patterns affect in turn the net primary production and biome distribution. These complex interactions between climate and land-use changes lead to a complex spatial and temporal distribution of their impacts on the environment at the global scale. Both changes acting synergistically or antagonistically on net primary production, decomposition, leaching and other soil forming factors and processes, will undoubtedly alter the development of soils in ways that are difficult to predict.

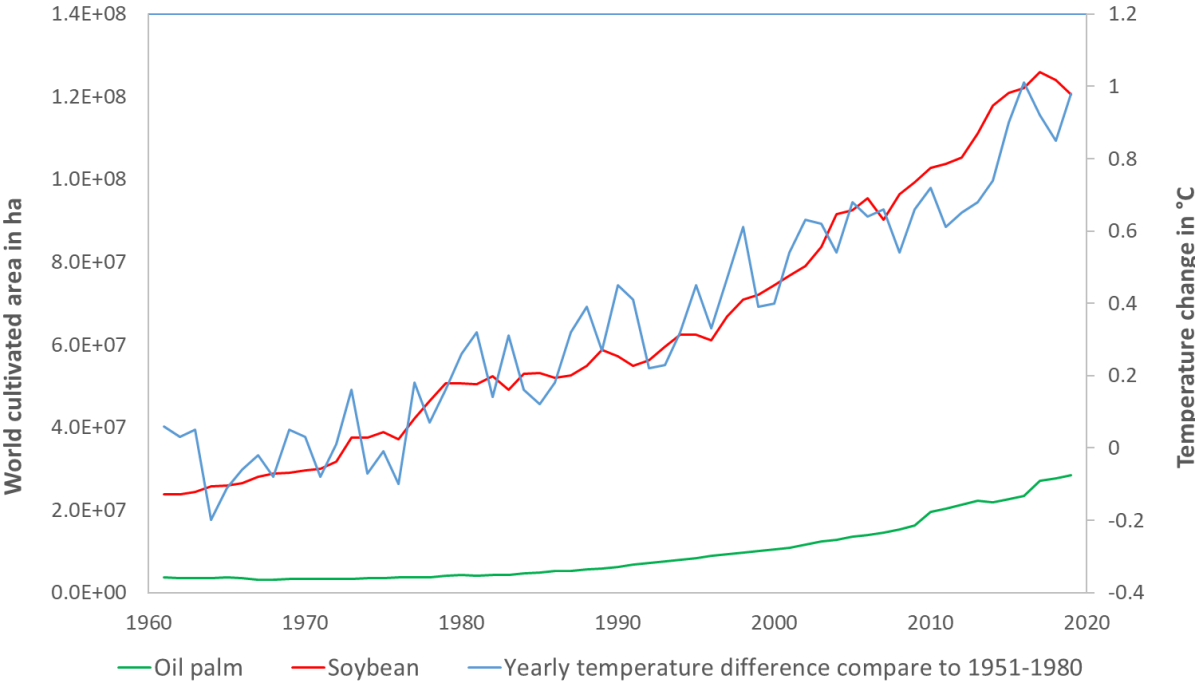


Figure 1: Climate change represented by the relative temperature increase 1951–1980 (NASA data: https://data.giss.nasa.gov/gistemp/graphs_v4/) and global land-use change represented by

the surface area converted to soybean and palm oil plantations (FAO data: <https://www.fao.org/faostat/en/#home>) between 1961 and 2020

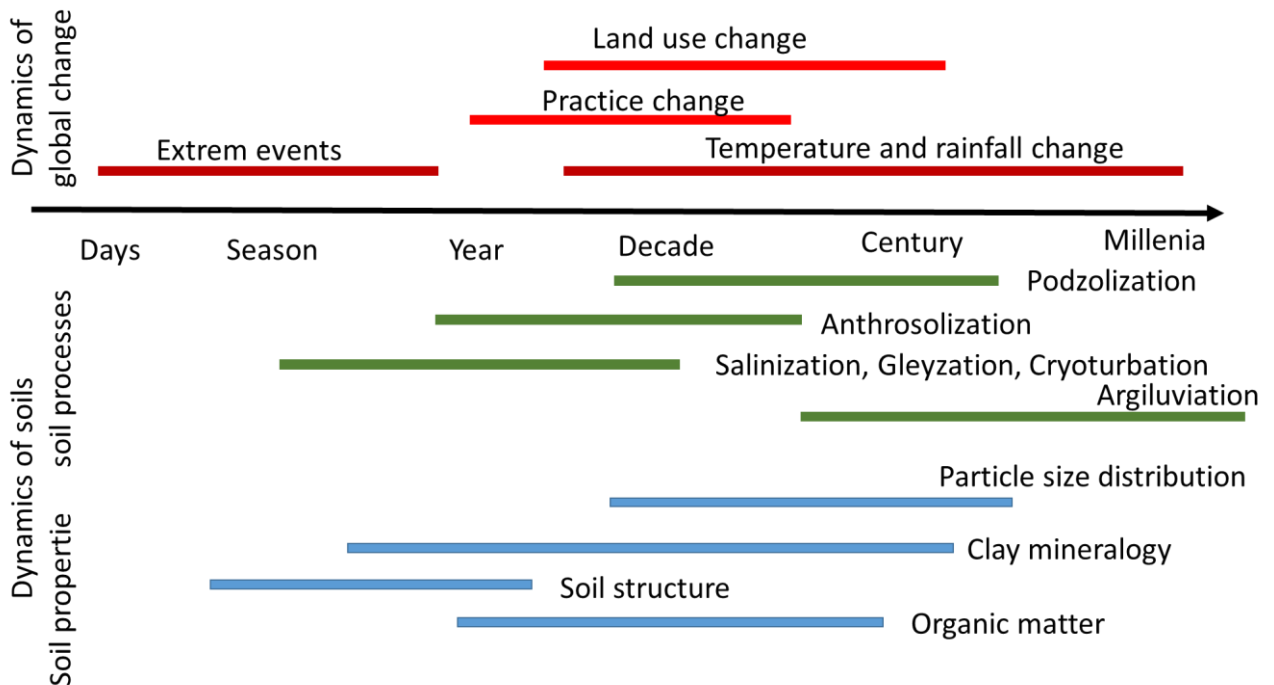


Fig. 2: Global change and examples of time steps in soil change (days to millenia).

Impact of Global Change on Soil Stocks, Structure and Fluxes

Soil is made up of organic and mineral solid phases (or soil stocks) that are spatially organized (soil structure) and form pores, within which water, gas and heat transfers take place. It is also the site of significant biodiversity, which interacts with the soil's solid phases and their structure. Both, climate and land use changes can act directly or indirectly on these soil stocks, structure and fluxes.

By increasing air temperature and modifying precipitation, climate change strongly affects the soil water regime and plant growth, and thus acts indirectly on the biologically mediated soil processes. An increase in annual precipitation leads directly to increased runoff and infiltration, while increases in temperature affect evaporation and transpiration. Temperature and water supply influence solute chemistry and rates of weathering through thermodynamic and kinetic interactions between minerals and solutions, with warmer and wetter environments experiencing higher rates of weathering (Rounsevell et al., 1999). Both air temperature and precipitation have a direct effect on organic matter turnover. Climate, through its control on plant community distribution, has an indirect effect on the quantity and quality of organic matter inputs into soil (Figure 3).

As mentioned above, land-use change includes a change in vegetation (land cover) as well as a large variety of management practices from tillage, irrigation, fertilization and amendments to more intrusive modifications such as artificial drainage or soil artificialization (mainly

urbanization, mining, industrialization and traffic), and soil construction. Large gaps in knowledge related to the effects of land management persist, in particular for human-induced changes in terrestrial ecosystems that do not result in conversions of land-cover. The impact of land use on soil stocks, organization and fluxes is therefore much more diverse than that of climate change and cannot be described in detail here mainly because of the current lack of understanding on this topic. Nevertheless, three main categories can be identified: i) practices that act mainly on soil stocks like fertilization, amendments and harvest; ii) practices that act mainly on soil organization and fluxes like irrigation, drainage and tillage, and; iii) land cover change (forestation, deforestation, artificialization, etc.) that act on soil stocks, organization and fluxes.

Changes in land cover induce direct changes in biotic diversity, actual and potential primary productivity (and therefore biogeochemical cycling), runoff and rates of erosion. The increase in tree cover and reduction of bare soil described above (Song et al., 2018) suggest that globally we could expect an increased accumulation of soil organic carbon (SOC) and potentially an increase in weathering with greater root activity. However, this net gain results from a net loss in the tropics that is outweighed by a net gain in the non-tropics. Thus, in the tropics, where deforestation and conversion of forests to farmland are prominent, a loss of SOC and soil by erosion (a destructive process) can be expected (Figure 4). Tree species selection can also affect various chemical and physical soil properties such as the interception of precipitation (less for evergreen species), water repellency of the forest floor (higher for coniferous species especially under dry conditions), mineralization and accumulation of organic matter and nutrients, soil pH (generally lower for conifers) and finally mineral weathering (Figure 3). Overall, the effect of tree species selection on soil properties depends on other environmental variables, e.g., climate and soil mineralogy (Augusto et al., 2014).

Soil artificialization brings elements to the soil by atmospheric deposition (airborne deposits) or by allochthonous material of natural or artificial (rubbles notably) origin. This results most often in changes in soil pH, increases in stoniness and decreases in SOC compared to natural soils, and in some cases - in the formation of a totally new soil type - Anthrosol (Cornu et al., 2021) (Figure 3).

Fertilization, amendments and harvest mainly act on soil stocks. In forests, harvest reduces standing biomass and soil C stocks, especially when wood residues are removed. The effect of crop harvest is mixed, and often depends on the presence and intensity of pre- and post-harvest management practices (Singh et al., 2018).

Fertilization is designed to increase plant productivity, which in turn increases C-inputs to the soil and ultimately the exchange of C between land and the atmosphere. In addition, N fertilization of croplands can lead to soil acidification, when not countered by liming, as demonstrated in Chinese soils, which experienced a 0.2 to 0.3-unit pH decrease in 20 years (Guo et al., 2010). Potassium and N fertilization have been shown to influence exchanges between the soil solution and the soil mineral phase with significant effects on clay mineralogy (Matocha et al., 2016).

Tillage, irrigation and drainage mainly act on the soil structure and fluxes that in turn modify soil stocks, including soil biodiversity. For example, tillage, designed to maintain soil porosity and control weeds, directly affects water fluxes in soils but it also has numerous indirect effects. It reduces soil biodiversity and modifies its composition, for example, the bacteria to fungi ratio or the relative abundances of epigeic, endogeic and anecic earthworms through various mechanisms among which the burying of soil litter is of primary importance. Ploughing disrupts aggregate structure, aerating the soil, activating microbial decomposition, releasing nutrients

from organic matter and thus depleting SOC. Some evidence indicates that for most soil types adoption of no-tillage practices after tillage-based management does not significantly increase SOC stocks (Powlson et al., 2014) but change its depth distribution. No-tillage does, however, generally reduce soil erosion.

Irrigation significantly enhances plant productivity where water limits plant growth with variable secondary consequences on SOC inputs and storage. By increasing water inputs, irrigation increases soil moisture, water fluxes through soil, and can generate anoxic soil conditions when water is in excess. Dissolved elements or particulate matter are brought into soil with irrigation water, some of them being quite relevant in soil development such as salts or contaminants, which can lead to soil salinization.

Similar to irrigation, soil drainage primarily affects water fluxes in soils because it is intended to eliminate excess water improving soil trafficability and productivity. However, by decreasing soil moisture and promoting better aeration conditions that formerly experienced anoxic conditions, and were generally richer in C, drainage tends to favour SOC depletion rather than SOC storage, especially in organic soils. By removing excess water from an initially largely closed soil system, drainage increases water and dissolved and particulate matter flows through and out of soils).

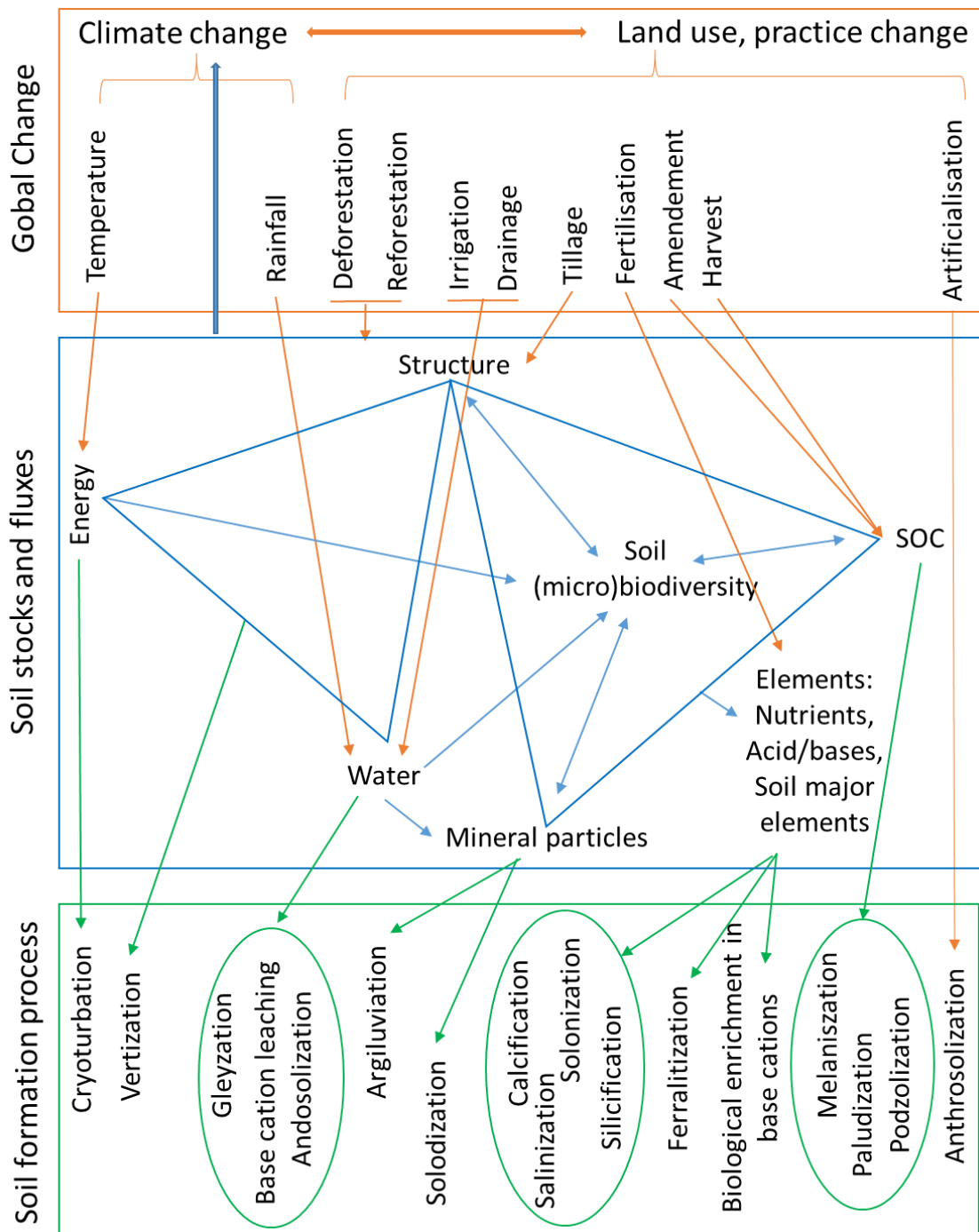


Fig. 3: Impact of global change on soil stocks (including soil biodiversity), structure and fluxes of matter and energy in soils, and their consequences for the evolution of soil processes.

Anticipated Soil Changes due to Global Change

Soil Resilience and Vulnerability to Global Change

At the global scale, climate is the main factor for soil formation. This shows a close dependence between soil processes and properties with soil temperature and soil moisture. Five main zones are commonly differentiated from polar to equatorial climates on the basis of the current global soil distribution (Figure 4). Soils from very cold climates are characterized by water that occurs primarily as ice and by cryoturbation processes. Cold and humid environments are dominated by the podsolization process, in which the degradation of soil organic material is hindered by cold temperatures and the percolation of organic acids completely leaches base cations from the soil and dissolves primary weatherable minerals. Toward the mid latitudes, with higher soil temperatures and precipitation, moderate leaching of base cations and transport of particulate matter dominate soil formation (argilluviation, solodization, Figure 3). The most humid and hot climates of the tropical zones are characterized by ferralitization involving fast mineralization of soil organic matter, almost complete chemical weathering of primary minerals, strong leaching of solubilized base cations and silicon (Si), and the accumulation of secondary kaolinite, iron (Fe) or aluminium (Al) oxides. In contrast to the humid climates of boreal, temperate and tropical zones, in which the soil formation is dominated by exportations, the soil formation under drier climates involves the accumulation of organic matter (melanisation), secondary carbonates and gypsum (calcification), secondary Si (silicification) or various kind of soluble salts (salinization). Despite the early recognition of the importance of climate on soil formation, it has in general been ignored in climate change research with the exception of some rare, mostly qualitative, and descriptive studies (Sombroek et al., 1990, Rounsevell et al., 1999).

Nevertheless, several consequences of climate change may be inferred from the zonal distribution of soil such as: i) a marked reduction of cryoturbation processes in the current polar climatic zone (Meredith et al., 2019; Figure 4); ii) an increase in organic matter turnover and leaching of base cations in either particulate or dissolved forms from the polar to humid cold and temperate zones where temperatures and precipitation are predicted to increase (Figure 4); and iii) decreasing organic matter inputs into soils and increasing accumulation of soluble salts of Na (sodium), Ca (calcium), Mg (magnesium) and K (potassium) in arid mid-latitude and subtropical zones where temperatures and precipitation are predicted to increase and decrease, respectively (Figure 4). The accumulation and leaching of base cations are both theoretically possible under climate change. However, losses in base cations are almost irreversible, therefore, climate change is more likely to induce losses of basic cations and reduce soil fertility than the reverse. Enrichment in basic cations and subsequent improvement in soil fertility may be expected only in the case of soil rejuvenation, with unweathered materials newly exposed at the soil surface. Such massive rejuvenation has occurred in the past, for example, in northern temperate areas after the last deglaciation, or in tropical areas after aridification .

At the extremes of the climate gradients, where climate change is most severe, thawing of Cryosols (World Reference Base) in polar areas and desertification in semi-arid to sub-tropical areas have already been observed. In the mid-latitudes, vegetation shifts to the north have been detected, as well as increases in surface and subsurface soil temperature in continental Europe (Khudyakov and Reshotkin, 2017). Such changes in the most dynamic soil properties are probably the first recordable signals of deeper changes affecting not only soils at the extremes

of the climate gradient but also soils under all types of climates. The speed of these changes is, however, poorly understood.

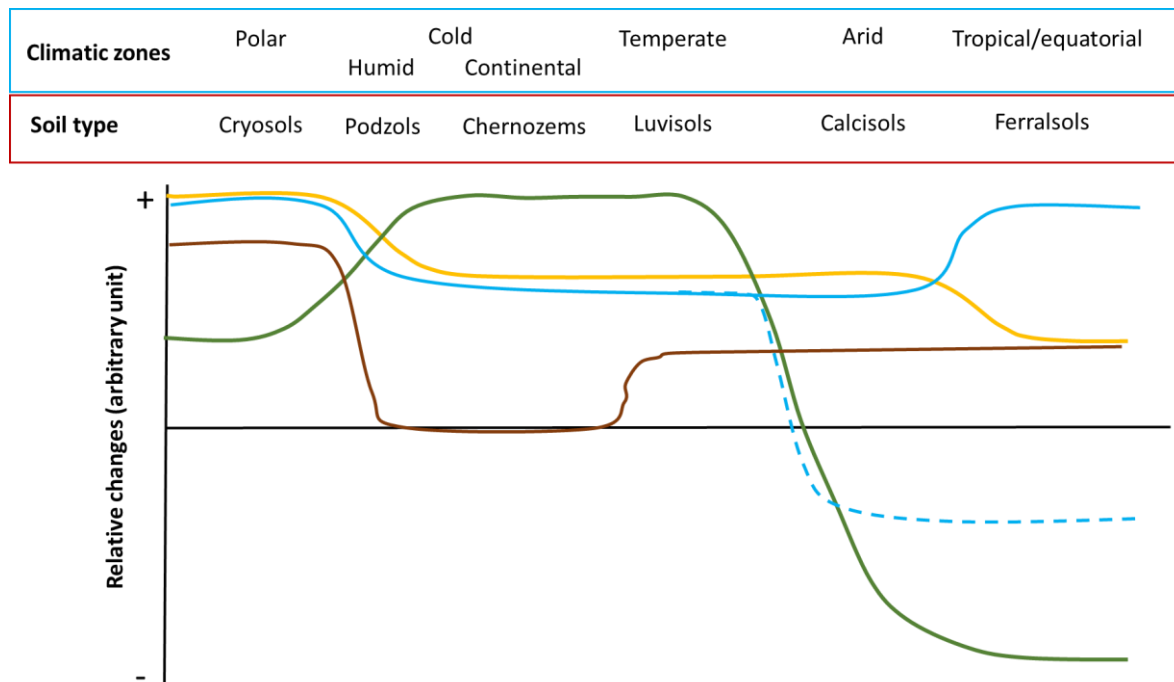


Figure 4: Climate (temperature and rainfall) and land use change trends for the main Köppen-Geiger climatic zones and resulting soil vulnerability to global change of the dominant soils. Blue colour represents rainfall, yellow - temperature, green - forest area, brown - soil vulnerability. In arid and tropical zones the solid blue line describes precipitation in Africa and the dashed line - South America. Increasing soil vulnerability is due to thawing in polar areas, weathering and leaching of base cations in the temperate zone, salinization or erosion in the arid zone and erosion after deforestation in tropical areas. In the cold zone, the limited soil vulnerability is due to either an advanced stage of weathering (Podzols) or a strong buffering capacity (Chernozems) .

In soils that will experience increased weathering of primary minerals or leaching of base cations, three main situations can be distinguished. Soils already completely depleted in primary minerals and base cations (e.g. Podzol and Ferralsol, World Reference Base) are likely to be affected little by climate change when not submitted to erosion induced by land use change (Figure 4). Soils rich in carbonates, clay minerals, or soil organic matter (e.g. Chernozem, World Reference Base), which act as buffers for soil processes such as argiluviation, podzolization or chemical weathering, should be resilient to climate change (Figure 4) provided that their stocks of these elements are not totally depleted. Exhaustion of these stocks would represent a clear threshold for the future evolution of these soils. The kinetics of dissolution of carbonates or clay minerals, or turnover of soil organic matter are key properties to consider in their evolution. For soils already poor in these constituents, the buffering capacity of the soil will be reduced quickly and the threshold reached rapidly. These soils are expected to have a limited resilience to climate change (Figure 4). This is especially the case for large areas of non-calcaric, clay-poor Cambisols and Luvisols (World Reference Base) in the cool, northern regions, which are among the most productive soils on Earth. Currently their development is

limited by their young age and cool climates, but it could be significantly and very rapidly affected by increasing temperatures and precipitation.

Human effects on pedogenesis are mainly discussed from a theoretical point of view, and quantification of the consequences on soil evolution remain fragmented. In the body of research studying human impact on soils, most deal with: i) soil degradation processes such as erosion, salinization and desertification, or soil contamination that are directly and strongly linked to human practices; ii) a single soil property taken individually such as soil porosity, soil water retention, soil organic carbon or earthworm populations to name just a few; and finally, iii) time scales rarely exceeding a few years (Richter et al., 2007). With its pivotal role on climate change and soil functions, changes in soil organic carbon contents have been widely studied, including time spans ranging from decades to centuries. It has recently been demonstrated, however, that human activities do not only affect soil organic carbon contents and related soil degradation processes but also most soil properties. Among these properties, carbonate or clay contents are of particular interest because of their capacity to buffer soil changes (Montagne et al., 2016). Furthermore, a large range of soil processes from podzolization to argiluviation in humid temperate climates is affected (Cornu et al., 2008; Montagne et al., 2016).

One of the main difficulties in identifying possible trajectories for human-induced soil evolution relies on the multidirectional impacts that land use and management changes can have on the buffering of soil properties and consequently on soil resilience. For example, afforestation is known to protect soils physically from rainwater, to increase soil organic carbon content and to contribute to the biological enrichment of base cations and consequently to increase soil resilience. At the same time, afforestation also favours weathering and soil acidification, particularly under coniferous forests, which can reduce soil resilience (Cornu et al., 2008). Similarly, N-fertilization or nutrient export through harvests hastens soil acidification in conventional cropping systems (Guo et al., 2010) and reduces soil resilience, but liming practices increase soil pH and improve soil resilience (Montagne et al., 2016). Finally, irrigation can lead to either leaching or the addition of base cations or clay particles depending on the quality and management of irrigation water. Human occupation and activities will have very contrasting, sometimes opposite, effects on soil evolution. They will depend on the precise combination of chosen practices and of their practical implementation as evidenced by the almost unlimited diversity of Anthrosols (World Reference base).

Impact of Global Change on Soil: Synergy or Antagonism?

Climate and human induced changes in land use and management may mutually reinforce each other. This is, for example, the case in semi-arid areas where the decreasing amounts but increasing intensities of rainfall lead to enhanced erosion and where deforestation for cultivation or (over)grazing exerts pressure in the same direction. This is also the situation in areas where rainfall is increasing and where extensive soil sealing prevents the infiltration of rainwater into soils. These two effects combine and cause flooding and landslides. When combined with events of extreme intensity or with soils of low resilience, synergies between climate and land use or management changes can give rise to extreme phenomena as exemplified by major wildfires in Australia, Canada, Greece, Russia or the United States, and by massive landslides and floods in the South of France or more recently in Germany.

Land use and management changes can, however, also counteract the impact of climate change. One example from polar and temperate regions is the increase in tree cover, which could partially or totally offset the increased turnover of organic matter caused by the increase in temperature. This might not, however, always be the case. Afforestation in the tundra, an

important carbon sink ecosystem, may lead to a reduction of the SOC storage (Hansson et al., 2021). In cultivated fields, practices that bring organic matter and other amendments to the soil surface may be of interest to regulate the stock of SOC, carbonates, clay minerals or base cations. For SOC, the “4 per 1000” initiative promotes land use and management changes that could offset the impact of the agricultural sector on climate change or even mitigate it. Human activities can increase stocks in soils through fertilization, liming or other amendments, whereas climate change can only redistribute or export current stocks. Although theoretically possible with soils, the practical mitigation of the effects of climate change suffers from several limitations. First, the effects of climate change are already being observed and affect large areas over the world, but the adoption of practices to counteract them depends on political, economic and sociological conditions that will be unlikely to evolve at the pace and spatial scales of climate change. The practice of N fertilization has, for example, induced the acidification of Chinese soils in the past twenty years (Guo et al., 2010) despite the fact that liming practices have been well known and used for millennia to maintain soil pH. Furthermore, when practices to counteract change rely on finite resources (e.g., phosphate fertilization) or consume energy (e.g., for extracting, transporting or spreading limestone amendments), their large-scale use will rapidly become unsustainable or have counterproductive effects on climate change. If changes in soil use and management are insufficient to mitigate climate change and its impacts significantly and globally, they must be designed and implemented to avoid further negative consequences.

Assessing Soil Change Under Global Change, a Scientific Challenge

As discussed above, some soil properties are already changing whereas others will change as a result of the complex feedbacks between the factors of soil formation, the direction and intensity of soil processes and soil properties. As far as the dynamics of soil properties are concerned, two types of soil properties are defined: those that can be managed by human activities (SOC, pH, nutrients, topsoil structure, i.e., the macroscopic organization of solid grains and pores) and the so-called inherent soil properties (texture, mineralogy, soil type, soil depth, horizon sequence, structure at depth). When addressing global change, time steps from a few decades to a century are important (Figure 2). Despite early recognition of the dynamic nature of all soil properties on a time scale ranging from several decades to a century, inherent soil properties are still considered stable in time. This is probably due to the lack of systematic research on the multi-decadal impact of land use and soil management on changes in soil properties. Disregarding this dependence of the soil’s inherent properties on time, which strongly affects the manageable ones as demonstrated for SOC (Mathieu et al., 2015), induces errors in predicting the dynamics of the manageable properties.

The quantification of medium to long-term changes in soil properties, in particular of inherent properties, is challenging. Long-term field experiments are the tools of choice for studying evolution of soil inherent properties (Filippi et al., 2016), however, they are too rare to provide an exhaustive characterization of all the potential combinations of soil resilience with changes in climate, land use or management. Another classical approach in studying change in soil is the use of soil sequences, in which only one pedological factor changes while others remain as constant as possible. This assumption is, however, sometimes difficult to verify (Filippi et al., 2016). Studies of soil sequences that vary mainly with climate (so called climosequences) were performed along latitudinal or altitudinal gradients. They demonstrated a significant impact of climate on soil evolution. However, in this approach both temperature and rainfall evolve

jointly in a way that may differ from that induced by climate change and the change of atmospheric CO₂ concentration is not considered. Some studies have also shown by an analogical approach with artificial drainage as a proxy for the projected increase in soil drainage due to climate change in temperate Luvisols (Montagne and Cornu, 2010), that the impact of climate on soil evolution could be significant over a few tens of years. Conversely, anthroposequences have been used to quantify the effect of different cultivation practices on soil, notably tillage reduction, artificial drainage, organic amendments among others. However, these studies were mainly performed on a local scale and for a few types of soil only. When considering global change, other approaches have to be considered, for example, monitoring networks that have been implemented increasingly over the last few years at the national scale. Their implementation is time- and resource-consuming, however, and their results do not elucidate the effects of global change unless at least two campaigns separated by a few decades are available at the global scale. A last, but challenging, option is the reuse of legacy data that are available worldwide (Filippi et al., 2016).

All these approaches involve studying past changes. They may be used to provide future projections, but because future combinations of climate, land use, and soil type are unknown, they may fail to deliver a good result. Modelling approaches are thus needed.

Two main types of modelling approaches exist in the literature: i) empirical or statistical, and ii) more deterministic models. Purely empirical or statistical predictions, despite being highly appropriate for applied purposes and decision-making, may not be useful for predicting future states of soils over the long term (century or more). Alternatively, deterministic modelling enables us to describe the interaction of soil processes with the pedological factors. Most of the existing models, however, depict the effect of various agricultural practices on the evolution of a single soil property (e.g. SOC content, sensitivity to erosion). Although they do not consider important soil internal feedbacks, they often integrate other soil properties in the form of input data (e.g. clay content in SOC dynamics models). A few attempts at pedogenesis modelling developed over the last decade explicitly consider the fluxes of solid constituents, solute and water transfers, agricultural practices and the feedback loops between soil functioning and soil structure at the profile (e.g. SoilGen, Finke, 2012) or the landscape scale (e.g. MILESD, Vanwallegem et al., 2013; HydroLORICA, van der Meij et al., 2019). They could, therefore, simulate the effect that changes in climate or human practices could have on soils because they (i) consider interactions between physical and chemical processes; (ii) take into account climate factors, land-use and agricultural practices as boundary conditions; and (iii) provide the depth distribution of a large range of soil properties. They do not, however, generally contain a dynamic description of the other compartments of the ecosystem, notably plant development. On the other hand, dynamic global vegetation models (DGVM) have been developed to predict the impacts and feedback of climate and land use on vegetation and carbon budgets. The DGVMs notably predict primary production, water, carbon and nitrogen fluxes to the atmosphere and surface water, as well as their storage in the soil (Le Quere et al., 2018). However, in these models, for which soil data availability is a key issue, soils are the least well described compartment (Dai et al., 2019). This situation leads to significant biases in DGVM predictions (Folberth et al., 2016), that can exceed the effect of climate variability (Koven et al., 2013). Therefore, while these models represent the best tool we currently have for simulating the long-term effect of human-induced global change on soil, they require a better description of the interactions and temporal evolution of soil properties.

Concluding remarks

In soil science, climate and human activities were recognised very early as significant factors for soil formation, but the understanding of current climate and land use or management changes on soil is limited to: i) a subset of soil degradation processes; ii) manageable soil properties, in particular organic carbon concentration and stocks; and iii) relatively short time scales in general. In addition, the precise dynamics of how soil responds to climate or human impact is still poorly understood. However, global change has already had an impact, and will continue to affect all soil fluxes and stocks with consequences not only on the manageable soil properties but also on a large range of inherent soil processes and properties. Moreover, the examples given above show that soil change may be faster than previously thought, especially for the inherent properties.

Predicting the impact of global changes on soil processes and properties remains a challenging task given i) the interlinking of different and complex changes in patterns of climate, land use and management as well as of soil resilience, ii) the shift from a pedogenesis driven by slow, low amplitude and continuous changes in soils to a pedogenesis driven by more rapid, large amplitude and irregular changes due to the increasing frequency of extreme climatic events and the globalization of land use and land management abrupt changes, and iii) the current lack of adequate tools to assess unprecedented combinations of climate, land use and management on a set of interacting soil processes and properties. Understanding these complexities is, however, becoming urgent as climate or human-induced changes in soil properties will inevitably have either positive or negative effects on the future delivery of soil-based ecosystem services such as biomass production, water storage and purification, climate regulation, erosion and flood regulation, etc. Climate change is more likely to induce additional removal of primary or clay minerals than the reverse. Similarly, while examples of soil deterioration due to human activities are frequent, examples of soil recovery are less common and climate and land use changes are generally considered as two major factors for soil degradation. Halting human-induced soil degradations, is unlikely to be sufficient to mitigate climate change significantly. It should, however, be at least the minimum objective to avoid or reduce cataclysmic changes and maintain sufficient resilience in the soil to climate change. This would give scientists and practitioners enough time to understand better the impact of global changes on soils, and to develop better approaches and tools that could help us maintain soil ecosystem services to at least the same level as they are now.

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