GLOBAL LAND OUTLOOK WORKING PAPER

THREATS TO SOILS: GLOBAL TRENDS AND PERSPECTIVES

A Contribution from the Intergovernmental Technical Panel on Soils, Global Soil Partnership Food and Agriculture Organization of the United Nations

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1. INTRODUCTION

An important product of the United Nations Food and Agriculture Organization (UNFAO) Intergovernmental Technical Panel on Soils (ITPS) was the publication of the *Status of the World's Soil Resources* (SWSR; FAO & ITPS, 2015). The report identified ten main soil threats, globally. Soil erosion, soil organic carbon (SOC) change and nutrient imbalance were considered the most severe threats to soil; this was followed by soil salinization and sodium affected soils (sodic soils), soil sealing and land take, loss of soil biodiversity, soil contamination, acidification, compaction and waterlogging. Besides providing an overview on the status of soils at the global and regional level, the report also contains technical recommendations and suggested actions for the future. It is the purpose of this chapter to discuss current trends regarding threats to global soils, and to debate the available future scenarios. Additionally, the chapter purports to be a platform from which to promote the development of future scenarios relative to threats which still remain overlooked.

Soils play a critical role in delivering ecosystem services. Healthy soils are a basic prerequisite to meeting varied needs for food, biomass (energy), fiber, fodder, and other products, and to ensuring the provision of essential ecosystem services in all regions of the world. However, soil resources are facing unprecedented pressures today, many of which are human-induced. Over the past three decades, there have been marked developments in our broader understanding of humankind's impacts on the earth, and of the frameworks with which to assess these impacts. Specific soil processes are central to earth-system processes that provide the safe operating space for humanity – the concept of 'planetary boundaries' that cannot be exceeded without causing potentially disastrous consequences for humanity (Rockström et al., 2009; Steffen et al., 2015). The ITPS presented a revised World Soil Charter, stating "Soils are fundamental to life on Earth but human pressures on soil resources are reaching critical limits. Further loss of productive soils will amplify food-price volatility and send millions of people into poverty. This loss is avoidable. Careful soil management not only secures sustainable agriculture, it also provides a valuable lever for climate regulation and a pathway for safeguarding ecosystem services" (FAO, 2015). The SWSR addresses soil quality status in relation to food security, fresh water availability, climate regulation, human health, and biodiversity.

The terms land and soil are often incorrectly used as synonyms. Land is the solid surface of the earth that is not permanently under water, and that supports agriculture, urban living, habitats, and other uses. Soil is the unconsolidated material on the land surface that has been subjected to soil forming processes, and that supports many ecosystem services to the benefit of society. Land use changes can influence soil, and soil supports many land uses.

2. SOIL EROSION

Soil erosion is broadly defined as the accelerated removal of topsoil from the land surface through water, wind or tillage. Water erosion on agricultural land occurs mainly when overland flow entrains soil particles detached by drop impact or runoff, often leading to clearly defined channels such as rills or gullies. Wind erosion occurs when dry, loose, bare soil is subjected to strong winds. During wind erosion events, larger particles creep along the ground or saltate (bounce) across the surface until they are deposited relatively close to field boundaries. Tillage erosion is the direct down-slope movement of soil by tillage implements where particles only redistribute within a field.

2.1 Status of soil erosion

Over the last decade, the figures published for ***water erosion*** are of an order of magnitude ranging from ca. 20 Gt (gigaton) yr^{-1} to over 200 Gt yr^{-1}. While this huge variation may at first seem to suggest that available estimates of global soil erosion are very uncertain, a more detailed analysis shows that estimates exceeding ca. 50 Gt yr^{-1} are not realistic. The most likely range of global soil erosion by water is 20–30 Gt yr^{-1}, while ***tillage erosion*** may amount to ca. 5 Gt yr^{-1}. Total erosion rates for ***wind erosion*** are highly uncertain.

Estimates of the total amount of dust that is yearly mobilized on land place an upper limit on dust mobilization by wind erosion on arable land at ca. 2 Gt yr^{1}. Approximately 430 million ha of drylands, which comprise 40% of the Earth's surface (Ravi et al., 2011), are susceptible to wind erosion (Middleton and Thomas, 1997).

Translating these global estimates into accurate local soil erosion rates is not straightforward, since soil erosion is highly variable, in both space and time. However, typical soil erosion rates by water can be defined for representative agro-ecological conditions. Hilly croplands under conventional agriculture and orchards in temperate climate zones are subject to erosion rates of up to 10-20 tonnes ha^{-1} yr^{-1}, while average rates are often <10 tonnes ha^{-1} yr^{-1}. Values during high-intensity rainfall events may reach 100 tonnes ha^{-1} and lead to muddy flooding in downstream areas. Erosion rates on hilly croplands in tropical and subtropical areas may reach values of up to 50-100 tonnes ha^{-1} yr^{-1}. Average rates, however, are lower and often around the benchmark of 10-20 tonnes ha^{-1} yr^{-1}. The high rates found in such hilly cropland tropical and subtropical areas occur due to the combination of an erosive climate (high intensity rainfall) and slope gradients, which are generally steeper than those on cultivated land in temperate zones. The incidence of erosion on steep slopes is due not only to specific topographic conditions, but also to high population pressure combined with low-intensity agriculture, leading to the cultivation of marginal steep lands (Figure 1).

Rangelands and pasturelands in hilly tropical and sub-tropical areas may suffer erosion rates similar to those of tropical croplands, especially when there is overgrazing. Rangelands and pasturelands in temperate areas are characterized by erosion rates which are generally much lower, and are most often below 1 tonne ha^{-1} yr^{-1}. The redistribution of soil within fields due to tillage erosion may occur at (very) high rates, on convexities (knolls), exceeding 30 tonnes ha^{-1} yr^{-1}, and with deposition rates, in hollows and at down slope field borders, exceeding 100 tonnes ha^{-1} yr^{-1}. These rates are not directly comparable to those of wind or water erosion, as soil eroded by tillage will not leave the field. However, tillage erosion may significantly reduce crop productivity on convexities and near upslope field or terrace borders (Pennock, 2003).

The accelerated loss of topsoil through erosion of agricultural land was recognized as being an important threat to the world's soil resources many decades ago. Furthermore, it was feared that soil was, in many areas, eroding at a rate much faster than that at which it could be replaced through soil formation processes. Estimated rates of soil erosion of arable or intensively grazed lands have been found to be 100-1000 times higher than natural background erosion rates. These erosion rates are also much higher than known soil formation rates, which are typically well below 1 tonne ha^{-1} yr^{-1} with median values of ca. 0.15 tonnes ha^{-1} yr^{-1}. Soil erosion has direct, negative effects for global agriculture. Soil erosion by water induces annual global losses of 23-42 Mt (megaton) of nitrogen (N) and 14.6-26.4 Mt of phosphorus (P) to run off from agricultural land. These fluxes may be compared to annual global fertilizer applications, which are of ca. 112 Tg (teragram) for N and ca. 18 Tg for P. These nutrient losses need to be replaced through fertilization at a significant economic cost. Using a United States farm price of ca. USD 1.45 per kg of N and ca. USD 5.26 per kg of P implies an annual global economic cost of USD 33-60 billion for N, and USD 77-140 billion for P. It is therefore clear that compensation for erosion-induced nutrient losses requires a massive investment in fertilizer use. In poor regions such as Sub-Saharan Africa, the economic resources needed to achieve such compensations for nutrient losses do not exist. As a consequence, the removal of nutrients by erosion from agricultural fields might be much higher than the amount of fertilizer applied; this also varies in function of the erosion rates of given farming systems, since the eroded soil often contains, per unit weight, about three times more nutrients than that which is left in the remaining soil (Young, 1989).

Soil erosion does not induce an important carbon (C) loss from the soil to the atmosphere; instead, erosion mostly induces a transfer of C from eroding locations to depositional locations. Net losses are limited, since the C lost at eroding locations is partially replaced through dynamic replacement, whereas the soil C that is deposited in colluvial and alluvial settings may be stored there for several centuries. However, other studies assume a net C loss due to soil erosion (Teague et al., 2016).

The direct negative effects of soil erosion are not limited to agriculture. The sediment produced by erosion also pollutes water streams with sediment and nutrients, thereby reducing water quality. In addition, sediment contributes to siltation in reservoirs and lakes.

2.2 Policies and strategies for soil conservation and protection

Soil erosion has, for a long time, been recognized as a critical threat to the sustainability of agriculture, the magnitude of which can today be correctly quantified. The technology to reduce erosion now exists and, over the last decades, significant efforts have been made to reduce erosion rates. These efforts have been partially successful. However, erosion rates are still high on much of the agricultural land of the globe; this is related to the lack of economic incentives for today's farmers to conserve soil resources for future generations. Tackling this issue requires that the soil erosion problem be reframed. Solutions need to be embedded in policies and programs that support the development of more sustainable agricultural systems.

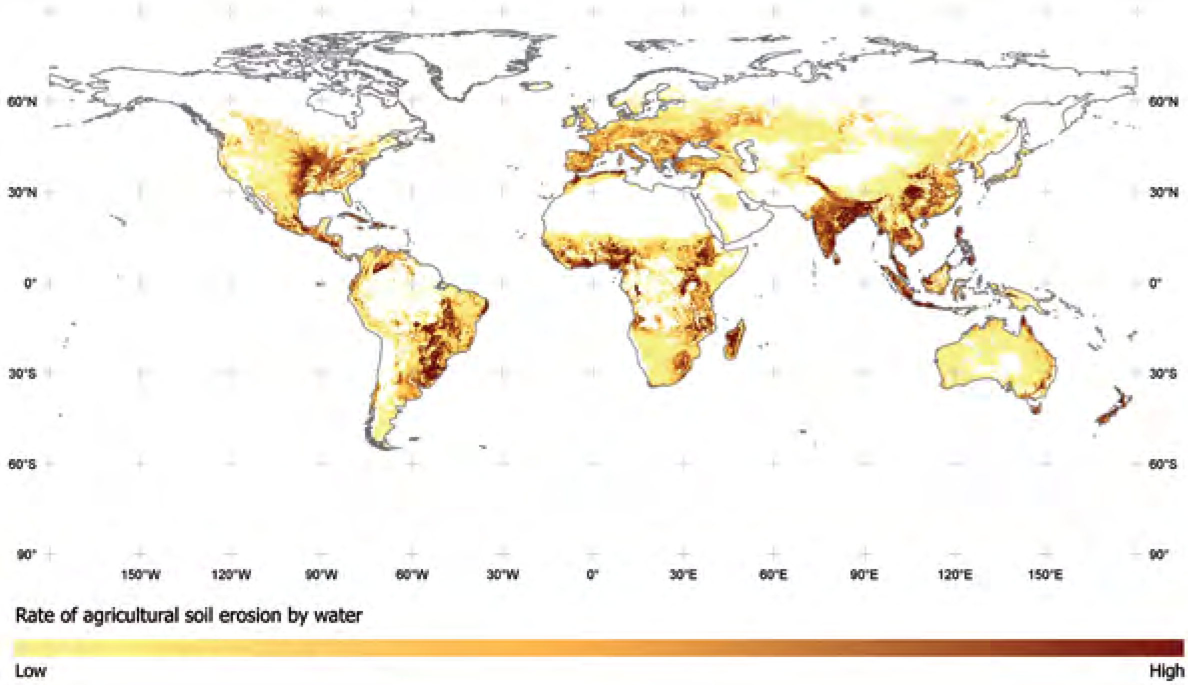


Figure 1: Spatial variation of soil erosion by water. High rates (>ca. 20 tonnes ha-1 yr-1) mainly occur on cropland in tropical areas. The map is derived from Van Oost et al., 2007 using a quantile classification. **FAO and ITPS, 2015**

Approaches to coping with erosion range from engineering measures such as terracing, sediment pit construction and waterways improvement, to vegetative measures, including agroforestry approaches, contour strips and cover crops (Agus and Widianto, 2004). According to estimations by Viglizzo and Frank (2006), the widespread adoption of no-tillage farming helped to control erosion losses, which were reported to have decreased to as little as 7 Mg ha^{-1} yr^{-1}. No-till farming is considered to improve topsoil physical properties, especially when combined with suitable crop rotations, pastures, and optimum soil cover (i.e., cover crops, crop residues and mulch) (Alvarez et al., 2014).

Mechanical measures - i.e., terraces, channels and drop spillways - can reduce soil loss by water erosion on steeper slopes. Studies have shown that erosion rates can be greatly reduced in nearly every situation through the application of appropriate management techniques and structural measures, such as terrace and waterway construction (see, for example, Pansak et al., 2008).

Measures to reduce erosion by wind include optimizing vegetation cover with drought-resistant species, using rotational grazing to sustain rangeland vegetation quality, and planting windbreaks perpendicular to the prevailing winds. Principally, keeping the soil protected with crop and surface residues is one of the main approaches to reducing wind erosion; regarding this technique, it is considered that rows of crop residue perpendicular to wind direction control wind erosion more effectively than parallel rows. No-tillage and stubble-mulch tillage techniques, meanwhile, will reduce the number of tillage operations and maintain residues on the soil surface for conserving water and controlling wind erosion (Fryrear and Skidmore, 1985).

Permanent vegetation, e.g., properly managed grasses, is the soundest method of lessening erosion on sandy soils. Equally, reducing the width of a field, or installing windbreaks or crop strips, can help prevent wind erosion; this is most effective when the field is oriented in a manner perpendicular to the prevailing erosive wind direction.

In many areas of the world, adoption of soil conservation measures is slow. While the reasons for this are diverse, a key point is that the adoption of soil conservation measures is generally not directly beneficial to farmers. This is as true in the case of intensive mechanized systems in the West, as it is for smallholder farming in the developing world. In other words, farmers do not have a direct incentive to adopt soil conservation measures, especially when they do not have land tenure (Abu Hammad and Børresen, 2006; FAO, 2012).

What is critically important is to determine how to incorporate soil conservation measures into an agricultural system that, as a whole, increases the net returns of farmers. In developing approaches that include incentives to soil conservation, it is vital to account for local conditions, including the extent to which local markets can themselves provide incentives to sustainable agriculture.

The potential for agricultural intensification is a fundamental point. In many areas around the world, crop yields are low and more land is cultivated than is strictly necessary. As a result, large tracts of steep, marginal land are at present used for agriculture without the implementation of proper soil conservation technology, with the result that these areas are subject to high erosion rates. Intensification of production on higher potential land is an option.

This not only reduces extension into marginal, highly erodible areas, but may also benefit biodiversity and overall SOC storage at the landscape scale.

Erosion can also be checked by reforestation. In many areas there is now a net gain of forest area. This reforestation, which is largely of marginal land, is related to four main factors: agricultural intensification; diminishing need for firewood; an increase in exchange and trade, making it possible to grow products in the most suitable areas; and an increased public awareness of the problems caused by deforestation. Development of conservation policies should consider these tendencies and stimulate them wherever possible.

3. SOIL ORGANIC CARBON (SOC)

3.1. Current status of SOC

The estimate of 1,502 billion tonnes of SOC for the first meter of soil was adopted by the Intergovernmental Panel on Climate Change (IPCC; IPCC, 2007). Current global estimates derived from the Harmonized World Soil Database (HWSD) suggest that approximately 1,417 billion tonnes of SOC are stored in the first meter of soil, and about 716 billion tonnes of SOC in the top 30 cm. Globally, the primary driver of SOC loss from soil is land use change. Wei et al. (2014) collated observations from 119 publications of 453 paired or chrono-sequential sites in 36 countries where tropical, temperate, and boreal forests were converted to agricultural land. The SOC stocks were corrected for changes in soil bulk density after land use change, and only SOC in the upper 0–30 cm range was considered. The SOC stocks decreased in 98% of the sites: by an average of 52% in temperate regions; 41% in tropical regions; and 31% in boreal regions.

A meta-analysis (Guo and Gifford, 2002) of 74 publications across tropical and temperate zones showed a decline in SOC stocks after conversion from pasture to plantation (–10%), native forest to plantation (–13%), native forest to crop (–42%), and pasture to crop (–59%). Soil organic C stocks increased after conversions from native forest to pasture (+8%), crop to pasture (+19%), crop to plantation (+18%), and crop to secondary forest (+53%). Broadleaf tree plantations placed onto prior native forest or pastures did not affect SOC stocks, whereas pine plantations reduced SOC stocks by -12 to -15%. In this study, soil depth varied from less than 30 cm to more than 100 cm and was not adjusted to account for changes in bulk density with land use change.

In a meta-analysis of 385 studies on land use change in the tropics (Don et al., 2011), SOC decreased when primary forest was converted to: cropland (-25%), perennial crops (-30%), and grassland (-12%). SOC increased when cropland was: afforested (+29%), under cropland fallow (+32%), or converted to grassland (+26%). Secondary forests stored 9% less SOC than primary forests. Relative changes were equally high in the subsoil as in the surface soil (Don et al., 2011). In this study, SOC stocks were corrected to an equivalent soil mass and sampling depth was on average 32 cm.

Poeplau et al. (2011) compiled 95 studies conducted on conversion in temperate climates. One finding was that topsoil (0-30 cm) SOC decreases quickly (~20 years) when cropland is converted from grassland (SOC -32%) or forest (SOC -36%). By contrast, long lasting (> 120 years) sinks are created through the opposite conversion - of cropland to forest (+16%) or grassland (+28%). Afforestation of grassland did not result in significant long term SOC stock trends in mineral soils, but did cause a net C accumulation in the labile forest floor (i.e., 38 Million g ha^{-1} over 100 years). However, this C accumulation cannot be considered as an intermediate or long-term C storage, since it may be lost easily after disruptions such as fire, windthrow or clear cut (Poeplau et al., 2011).

Peatlands (organic soils) store a large amount of C which is rapidly lost when they are drained for the purposes of agriculture and commercial forestry (Hooijer et al., 2010). A rapid increase in decomposition rates leads to increased emissions of carbon dioxide (CO_2), and nitrous oxide (N_2O), and vulnerability to further impacts through fire. The FAO emissions database estimates that there are, globally, 250 000 km^2 of drained organic soils under cropland and grassland, with total greenhouse gas (GHG) emissions reaching 0.9 Gt CO_2eq yr^{-1}, in 2010. The largest contributions are from Asia (0.44 Gt CO2eq yr-1) and Europe (0.18 Gt CO2eq yr^{-1}; FAOSTAT, 2013). Joosten (2010) estimated that there are >500 000 km^2 of drained peatlands in the world, including under forests, with CO_2 emissions having increased from 1.06 Gt CO_2 yr^{-1} in 1990, to 1.30 Gt CO_2 yr^{-1} in 2008. This is despite a decreasing trend in United Nations Framework Convention on Climate Change (UNFCCC) Annex I countries, from 0.65 to 0.49 Gt CO_2 yr^{-1}, primarily due to natural and artificial rewetting of peatlands. In Southeast Asia, CO_2 emissions from drained peatlands in 2006 were 0.61 ± 0.25 Gt CO_2 yr^{-1} (Hooijer et al., 2010).

A meta-analysis of 57 publications (Nave et al., 2011) showed that fire had significant overall effects on SOC (-26%) and soil N (-22%). Fires reduced forest floor storage (pool sizes only) by an average of 59% for C, and 50% for N, but the concentrations of these two elements did not change. Prescribed fires caused smaller reductions in C and N storage (-46 and -35%) than wildfires (-67 and -69%). Burned forest floors recovered their C and N pools in an average of 128 and 103 years, respectively. Among mineral soil layers, there were no significant changes in C or N storage, but C and N concentrations declined significantly (-11 and -12%, respectively). Mineral soil C and N concentrations were significantly reduced in response to wildfires but not after prescribed burning.

A large field study in the Amazon (225 forest plots) examined the effects of anthropogenic forest disturbance (i.e., selective logging, fire, and fragmentation) on soil C pools. Results showed that the first 30 cm of the soil pool did not differ between disturbed primary forests and undisturbed areas of forest, suggesting a resistance to impacts from selective logging and understory fires (Berenguer et al., 2014). However, impacts of human disturbances on the soil C are of particular concern in tropical forests growing on organic soils.

Forest fires produce pyrogenic carbonaceous matter (PCM), which can contain significant amounts of fused aromatic pyrogenic C (often also called black C), some of which can be preserved in soils over centuries and even millennia. In this vein, forest fires were found to be the reason for similar SOC contents in soil in Australia; this was seen in modeled scenarios, considering cases with and without burning: the loss in litter C input by fire was compensated by the greater persistence of the pyrogenic C (Lehmann et al., 2008). Similarly, dissolved pyrogenic carbon (DPyC) from burning of the Brazilian Atlantic forest continued to be mobilized from the watershed each year in the rainy season, despite the fact that widespread forest burning ceased in 1973 (Dittmar et al., 2012). Fire events, moreover, are a source of carbonaceous aerosol emissions - considered a major source of global warming (Kaufman et al., 2002).

A multifactorial meta-analysis of grazer effects on SOC density (17 studies that include grazed and ungrazed plots) found a significant interaction between grazing intensity and grass type. Specifically, higher grazing intensity was associated with increased SOC in grasslands dominated by C4 grasses (increase of SOC by 6–7%), but with decreased SOC in grasslands dominated by C3 grasses (decrease of SOC by an average of 18%). Impacts of grazing were also influenced by precipitation. An increase in mean annual precipitation of 600 mm resulted in a 24% decrease in grazer effect on SOC on finer textured soils, while on sandy soils the same increase in precipitation produced a 22% increase in grazer effect on SOC (McSherry and Ritchie, 2013).

3.2. Drivers of soil carbon loss

3.2.1. Land conversion In the regional assessments of soil threats (Section 9 of the SWSR), Africa, Latin America and the Caribbean all identified continuing pressure to convert forest and pasture to agricultural land, as a significant driver for the poor condition of SOC. The expansion of agriculture in the tropics accounts for most of the total CO_2 emissions from land clearing, and several recent studies have concluded that halting this expansion is essential for reducing C emissions. In Europe, the opposite is true in some regions – the abandonment of agricultural land in areas of Eastern Europe has led to SOC gain in the abandoned lands. This pool of stored C can, however, be readily emitted as CO_2 if re-conversion to agriculture takes place. All peatlands are very susceptible to SOC loss when they are drained for agriculture and commercial forestry – this is an issue in several regions, particularly Asia and Europe.

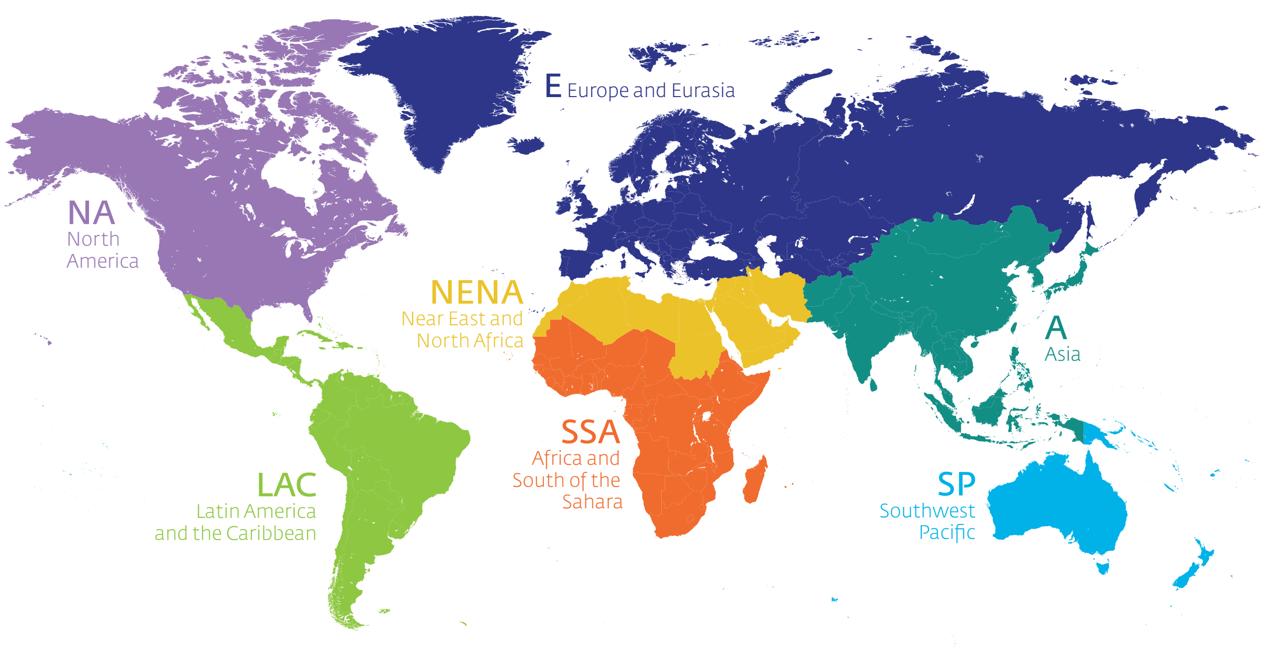


Figure 2: Regions as defined in the Status of the World's Soil Resources report. FAO and ITPS, 2015

Table1: Drivers of the decrease in SOC per region.

Source: FAO and ITPS, 2015

South Saharan Africa (SSA)
The replacement of the natural vegetation reduces nearly always the SOC level. Further C release from the soil is caused by complete crop removal from farmlands, the high rate of organic matter decomposition by microbial decomposition accentuated by high soil temperate and termite activates in parts of SSA.

Asia
Increase of crop yield retains SOC in croplands of East and Southeast Asia. Whereas, SOC is decreasing in South Asia, because crop residues are widely used as fuel and fodder, and not returned to the soil. The degradation of grassland has caused great losses of SOC stock.

Europe and Eurasia
The loss of SOC is evident in most agricultural soils. peatland drainage in northern countries also leads to rapid organic C loss. In Russia, extensive areas of agricultural lands were abandoned that resulted in quick organic matter accumulation; however, actually these areas partly returned to agricultural use.

Latin America and the Caribbean
It is promoted by deforestation, ploughing of grasslands and monoculture.

Near East and North Africa
High temperatures throughout most of the region result in a very high turnover of SOC. In addition, SOC change is sensitive to soil management changes.

North America
The majority of cropland in the United States and Canada has shown improvements in SOC stores due to the widespread adoption of conservation agriculture (e.g. reduced tillage and improved residue management). There is a lack of field validation sites to support the national-level modelling results. Loss of SOC from northern and arctic soils due to climate change is a major concern.

Southwest Pacific
The conversion of land to agricultural uses has generally caused large losses of soil organic carbon in soils. Improved land management practices have stabilized the situation but there is limited evidence for increasing soil carbon even under these more conservative management systems.

3.2.2. Agricultural management Agricultural management is the second critical driver of SOC change. The regional assessments for Africa, Asia and parts of the Southwest Pacific identify decreasing length of fallow periods, and competing uses for organic inputs, as substantial factors for the generally poor condition of SOC stocks. On the more infertile soils in Africa, the low yields of many crops under subsistence/extractive agriculture lead to low amounts of organic residue production. The combination of low organic inputs, competing uses for those inputs, naturally high rates of SOC decomposition, and naturally infertile soils leads to low SOC stocks in these regions.

3.2.3. Global climate change SOC levels, as well as contributing to global climate change, are also affected by it. Changes in global temperatures and precipitation patterns will, in other words, affect SOC levels. The effects of warming on soil organic matter (SOM) decomposition are governed by complex and interactive factors, and are challenging to predict. This is a particular concern for organic and tundra soils, which constitute considerable terrestrial reservoirs for C and GHG. The 5th assessment report of the IPCC states that there is high confidence that reductions in permafrost due to warming will cause thawing of some currently frozen C and methane (CH_4), however, low confidence regarding the order of magnitude of such emissions.

3.3. Regional trends in the condition of soils

The regional assessments of the state of soils form a key element of the SWSR report (Figure 2). Table 1 summarizes the drivers of the decrease in SOC per region. The analysis shows that SOC is decreasing in all regions.

3.4. Future perspectives of SOC

SOM is composed of about 58% C and is a crucial soil component which affects most of the processes relevant to soil functions and food production. Changing SOM (and hence SOC) affects the capacity of soils to buffer against environmental change, and changes the provision of ecosystem services required for crop production. SOM, therefore, closely regulates the resilience of the agricultural system to climate change. The SWSR report highlights that, although more C is stored in soil than in the atmosphere and plant life combined, a large portion (33%) of the world's soils are degraded and organic matter has been lost as a result. The reversal of soil degradation, through the build-up of SOM and the sustainable management of soils, therefore, offers large potential to contribute to climate change mitigation by sequestering atmospheric C into the soil. In addition, this process would increase the capacity of soils to act as a buffer against climate change, which, in turn, would improve the resilience of agricultural systems to the impacts of climate change. For example, In Asia, under a cereal-based cropping system, there is severe deficiency of SOM (C) that negatively influences soil health and reduces crop productivity. Therefore, the addition of plant residues and animal manures improve both soil and crop productivity (Amanullah et al., 2016a; Amanullah and Hidyatullah, 2016; Amanullah and Khalid, 2016).

4. SOIL NUTRIENT BALANCE

Soil nutrient balance implies nutrient inputs and losses from the soil system are equal while an imbalance is the net gain or loss of plant nutrients from the zone of soil that is accessible by plant roots. The plant nutrients considered here are those that must be supplied from the soil to the plant, either from nutrients that occur naturally in the soil, or that are added to the soil, for normal growth and development. Macronutrients include nitrogen (N), phosphorous (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg). Micronutrients include zinc (Zn), iron (Fe), copper (Cu), molybdenum (Mo), manganese (Mn), boron (B), and chlorine (Cl). Material regarding soil nutrient imbalances usually focuses upon macronutrients; N, P, and K, in particular, because of their important role in supporting plant growth and development. However, nutrient imbalances relative to micronutrients are also significant, and can have profound impacts on crop productivity and human health.

A negative nutrient balance indicates a net loss of nutrients, i.e., that one or more plant nutrients are leaving the soil system faster than they are being replenished. Loss mechanisms include removal of plant materials from the soil surface, leaching below the root zone, losses in surface runoff, or conversion to gaseous forms that are lost to the atmosphere. A positive nutrient balance indicates a net gain of nutrients, i.e., that one or more plant nutrients are entering the soil system faster than they are being removed. Plant nutrients can enter the soil system through inorganic amendments (fertilizers), organic amendments (manures, crop residue, biochar, composts, green manures), biological N fixation, wet or dry deposition, sedimentation, and run-on.

On a global scale, soil nutrient balances for N and P are positive for all continents except Antarctica, and are predicted to remain stable in future, or to increase by up to 50%. Bouwman et al. (2009, 2013) present four future development scenarios, based on the Millennium Ecosystem Assessment, regarding nutrient balances for the year 2050, describing contrasting future development possibilities relative to agriculture nutrient use under a changing climate. In the most pessimistic case, the global N balance may increase by 50% in the coming decades. Even in the case of proactive policies, that aim to rectify the nutrient imbalance, the N balance is expected to remain constant, at 150 Tg yr^{-1}. Regarding P, all scenarios predict a future increase in global soil P balance. These global balances hide large variations across regions and land uses. Positive nutrient balances represent the following: inefficient use of natural resources (energy and finite resources such as P and K deposits); negative impacts, contributing to, inter alia, global climate change, and worsening the quality of both surface and ground water resources; and a significant perturbation to natural plant nutrient cycles, even in areas not under agricultural production. In some regions, such as the United States and Western Europe, N and P surpluses are predicted to decrease as environmental and economic pressures work to increase efficiencies. However, positive nutrient balances should not be viewed as necessarily environmentally harmful. Possible negative environmental externalities should be weighed against the benefits of food security, economic welfare and social well-being. To minimize the negative externalities, the best nutrient management approaches should be promoted through judicious policies.

On a regional and local scale, nutrient balances can be decidedly negative and limit plant growth due to the deficiency of one or more plant nutrients. A negative balance may contribute to a reduction in the provisioning ecosystem services provided by the soil resource, with negative consequences for human nutrition, both from the perspective of meeting human caloric needs, as well as discrete nutritional requirements such as protein or micronutrients. Tan et al. (2005) estimated that 45.4, 14.6, and 71.9 Mha of land in Africa, Asia, and South America, respectively, was affected by nutrient depletion. It was noted that a high proportion of land in these same regions was classified as having severe, or very severe, constraints on nutrient availability (Fischer et al., 2008). Table 2 shows the estimated losses in crop yields and total production due to N, P, and K soil depletion.

A variety of factors further exasperate the problem of soil nutrient depletion in many developing countries or regions. Areas with low crop yields due to nutrient depletion are also likely to have a high demand for crop residues and manure for use as fuel, and, in the case of the former, also as fodder. In such cases, where crop residues and manure are being repurposed, a significant opportunity to return plant nutrients to the soil is lost, as are the additional benefits associated with soil C. Inorganic fertilizers can, moreover, be in limited supply or prohibitively expensive in some developing countries (Amanullah and Hidayatullah, 2016; Amanullah and Inamullah, 2016). In contrast, in other developing areas of the world, inorganic fertilizers are heavily subsidized, which can lead to inefficient use. These interactions illustrate the economic, social, and ecological complexities which need to be considered when attempting to improve soil nutrient imbalances using proven practices.

Overall, the global use of inorganic fertilizers is likely to decrease in developed countries and increase in developing countries. Increases in developing countries can be attributed to greater demands for food from rapidly increasing populations and desires for a higher standard of living. Positive nutrient balances will become more pronounced or prevalent in such areas. Prices for commodities and fertilizers will heavily influence the rate of change for fertilizer use and supportive governmental policies and agricultural aid programs may be necessary to encourage the use of fertilizers in areas where current usage is low (Amanullah et al., 2016b). The concept of sustainable intensification - which supports judicious use of inorganic fertilizers - coupled with those of biological fixation, improvements in soil health, and maximizing return of plant nutrients to soil via crop residues and manures, are essential for the sustained fertility of the soil resource (Pretty and Bharucha, 2014). Indeed, through the efforts of the International Fertilizer Development Center and others, the role of plant nutrient additions to soils in improving soil and human health is being actively promoted.

5. SOIL SALINIZATION AND SODIFICATION

Salt affected soils are those adversely affected by an excess of neutral salts, sodium, or both. Saline soils have an excess of neutral salts generally comprised of combinations of cations, such as Ca, Mg, K, sodium (Na), and anions such as chloride (Cl), sulfate (SO_4), bicarbonate (HCO_3), and carbonate (CO_3) - such that a saturated paste extract of the soil has an electrical conductivity of 4 dS m^{-1} or greater. Sodic, or sodium-affected, soils have an excess of Na on the cation exchange sites as indicated by an exchangeable sodium percentage (ESP, the fraction of the cation exchange sites occupied by Na) of 15 or greater. Such soils have a low salinity and a soil pH > 8.0. Saline/sodic soils have high salinity and an ESP $\geq$ 15.

Excess soil salinity can have a negative impact on plants in a variety of ways. The most significant is through the osmotic effect, which accounts for the propensity of salts or water to move in response to a gradient in either of these factors, e.g., water will move from a less saline area in the soil to a more saline area. This same effect will make it difficult for a plant or seed to obtain water from the soil when the soil is saline because water would need to move against the salt gradient. Seeds cannot absorb enough water to initiate germination and plants growing in moist, saline soil can be wilted and appear to be suffering from drought. Other negative impacts include the possibility of plant toxicities due to high concentrations of certain elements associated with salinity (e.g., B, Na, and Cl) and the promotion of adverse soil physical properties. Sodic soils have significant limitations due to dispersion of clays and aggregates that can result in very low infiltration rates and hydraulic conductivity. Saline/sodic soils share a combination of all the effects produced by excessive salts and sodium.

Table 2: **Estimates of the effect of soil nutrient depletion on losses of crop yields and production in developed and developing countries for the year 2000.**
Source: Tan et al. (2005).

	Average yield loss[1]			Total production loss[1]		
Country category	N	P	K	N	P	K
	kg ha^{-1} yr^{-1}			Tg yr^{-1}		
Developed	-575	-1074	-24	-61.9	-162.5	-0.03
Developing	-706	-1108	-1401	-123.6	-295.8	-397.0
Least Developed	-796	-1061	-1157	-25.0	-33.8	-36.5
Global Mean	-670	-1093	-1372	-210.6	-491.5	-433.4

[1]based on equivalent rice grain yield

Excess salts and/or sodium can occur in soils naturally, or be directly or indirectly induced by human activities. Salts and/or sodium will accumulate in soils if added at rates exceeding the rate of removal, via leaching of salts below the root zone, as a result of precipitation or irrigation. Weathering of soil parent materials, contact with sea water, and wet or dry atmospheric deposition of salt from the oceans are natural processes that can produce saline and sodic soils over large areas. In general, such areas are more prevalent where precipitation is limited. Humans can induce soil salinity and sodicity problems by using high salt or sodium irrigation water, through poor management of salts and sodium in soils, and by way of practices that allow groundwater to rise to near the soil surface. Practices that promote the rise of the groundwater table include the replacement of deep-rooted vegetation with plants that have a shallow root system, and insufficient soil drainage.

Globally, some 955 Mha of land is impacted by salinity and/or sodicity, with 70 Mha directly influenced by human activities (Metternicht and Zinck, 2003). It is estimated that 20% of irrigated land has salt-induced yield declines, with a corresponding economic loss of USD 27.3 billion (Qadir et al., 2014). For instance, estimated yield losses of 39 to 63% for rice, wheat, cotton, and sugarcane due to salinity have been reported for the Indo-Gangetic Basin in India.

Regardless of the source of the salts or sodium, crop and drainage management practices have a profound impact on the salinity and sodicity status of agricultural soils. Prevention of the accumulation of salts and sodium through the use of high quality irrigation water, and limiting the use of poor quality irrigation water, is the best strategy. Quality is defined by analyzing the total salinity of the water and the ratio of sodium to other cations in the water. Even when using high quality water, however, salts and sodium can accumulate if the amount of water passing through the soil is insufficient, and thus unable to move salts below the root zone. Adequate soil drainage is then required to ensure the salts are leached out. The use of drainage tiles and/or drainage ditches may be necessary if the soil's naturally occurring internal drainage is limited. The environmental and ecological impacts of salt and sodium discharges to surface waters can, however, be significant.

At any given location, salt and sodium management practices alone may not be sufficient to maintain soils free from restrictions due to salinity and sodicity. One way of countering the accumulation of sodium is by the occasional application of gypsum; shifting to more salt tolerant crops is another common approach. The cost of such practices can, however, be considerable.

Climate change will likely enhance issues related to salinity and sodicity, in terms of both severity and area impacted. Rising temperatures increase evapotranspirational demand, which makes it more difficult to leach salts out of the root zone. Water shortages increase the likelihood that low quality irrigation water will be used. Rising sea levels will increase the area of soil impacted by salt water intrusion and coastal flooding, particularly in delta areas with intensive agriculture - a situation common in countries such as Bangladesh. Areas that are already marginally saline or sodic will, with the discrete impacts of climate change, be likely to become more intensively saline or sodic. Globally, salinity and sodicity problems are reducing yields on 0.3 to 1.5 Mha of land each year (FAO & ITPS, 2015). On a more positive note, there are known technologies and management practices which allow for an improved management of salts and sodium; in other words, the possibility already exists for the implementation of strategic investments in key agricultural areas, to maintain or improve productivity.

6. SOIL BIODIVERSITY

6.1 Flora and fauna in soil

Soil ecosystems harbor a large part of the world's biodiversity, organized in highly complex networks (Table 3; Figures 3 and 4). By far the most abundant group of organisms are the soil microbes, e.g., bacteria and fungi decomposing SOM. The soil fauna consists of, e.g., herbivorous nematodes, which feed on roots and protozoa (amoebae, flagellates, ciliates), which, in turn, feed on microbes, nematodes (bacterivores, fungivores, omnivores, and predators), mites (bacterivores, fungivores, predators), collembola (fungivores and predators), enchytraeids and earthworms. Together, these organisms form the soil food webs which can be viewed as the engine of soil ecosystem processes, such as C sequestration and nutrient cycling (de Ruiter et al., 1993); moreover, given the dimensions of the materials they process, soil food webs are considered to be responsible for substantial components in the global cycling of materials, energy and nutrients (Wolters et al., 2000). In sum, soil food webs play a key role not only in the provision of soil ecosystem services – in the form of food productivity (Brussaard et al., 2007) – but also in the conservation of aboveground biological diversity (Hooper et al., 2000).

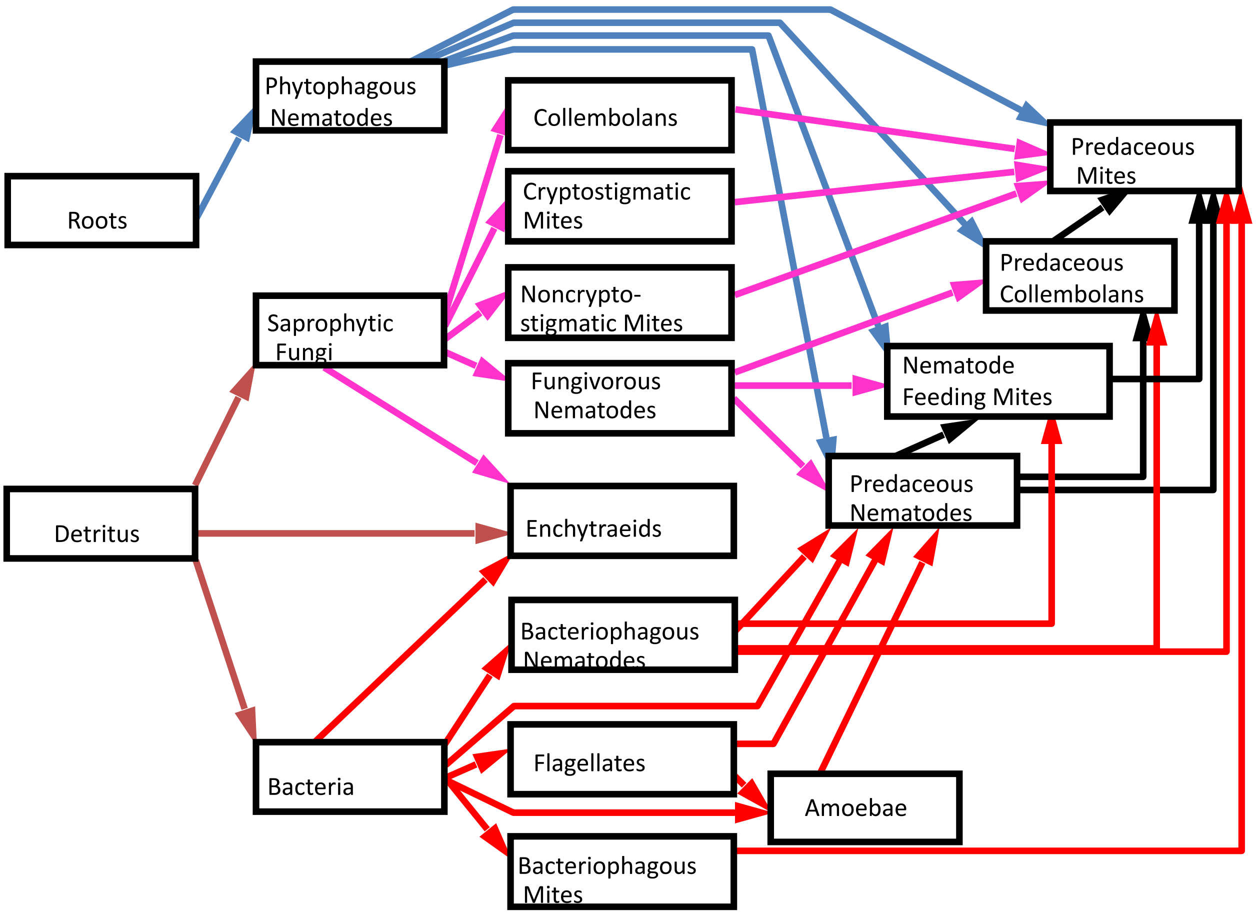


Figure 3: Diagram of a soil food web. Boxes represent functional groups of soil organisms. Functional groups aggregate species that share the same food and predators, e.g., occupy a similar trophic position in the soil food web. Arrows represent trophic interactions, where the arrow head points to the consumer.

Figure 4: Soil organisms. Upper row, from left to right and top to down: bacteria, fungi, bacterivorous nematode, amoebae; lower row, from left to right: fungivorous mite, collembolan, predatory mite

6.2. Status and loss of soil biodiversity

Soils possess an enormous amount of biological diversity, but certain forms of agricultural practices and methods of land use management can pose a threat to it. These practices reduce soil biodiversity and hence lessen soil ecosystem services provided by soil organisms. Main threats to soil biodiversity are the use of pesticides, the use of high levels of fertilization, soil contamination and soil tillage.

6.3. Major roles of soil biodiversity

It is increasingly recognized that soil organisms play an important role in key soil processes and soil ecosystem services. Additional important functions of soil include regulating pests and diseases, supporting pollinators and reducing chemical pollution.

Other salient points include:

- Soil biodiversity is worth trillions of dollars (Gnacadja, 2010);
- Of about 100 crop species that provide 90% of food for 146 countries, 71 are bee-pollinated. If we lose these "keystone" species, the whole edifice will collapse (FAO, 2005);
- Over 80% of plant species can act as hosts to Vesicular Arbuscular Mycorrhiza (VAM) fungi - which are the cornerstone of a second Green Revolution (Roy – Bolduc and Hijri, 2011);
- Ants, termites and earthworms are ecosystem engineers;
- Preservation of biodiversity protects drylands (Zanu, 2010).

Table 3 **summarizes the most relevant soil functions and the groups of organisms that carry them out. Source: USDA (2010)**

Soil Biota	Examples	Functions
Macrofauna	Earthworms	Major decomposer of dead and decomposing organic matter, deriving nutrition from bacteria and fungi leading to recycling of nutrients Generate tonnes of casts each year, drastically improving soil structure Stimulate microbial activity Mix and aggregate soil Increase infiltration Improve water holding capacity Provide channels for root growth Improve water quality
	Nematodes	Many help in controlling diseases; Recycle nutrients Help in dispersal of microbes Plant parasites
	Arthropods (e.g., insects, springtails, beetles)	Shred organic matter Stimulate microbial activity Enhance soil aggregation Mineralize plant nutrients for bacteria and fungi Burrow, improving water infiltration Control pests
Macroflora	Fungi	Nutrient cycling through their hyphae (VAM) Water dynamics Disease suppression Decompose organic matter
	Bacteria	Decomposer Convert energy in SOM into forms useful to the rest of the organisms Decompose and breakdown pesticides and pollutants Retain nutrients in their bodies Mutualists N-fixing, nitrifying, denitrifying Obtain energy from components of N, S, Fe or H instead of C compounds
	Actinomycetes	Degrade recalcitrant compounds
	Protozoa	Mineralize nutrients making them available for use by plants and other soil organisms, thus helping nutrient recycling

7. SOIL CONTAMINATION

Soil contamination can be defined as the presence of one or more substances in soil, at concentrations higher than would either occur naturally, or through sustainable soil management practices. As such, substances used responsibly, as agricultural inputs, would not be considered contaminants in the soils to which they were applied, although they would, in any other soil or off-site environment (e.g., surface or ground water). The degree of contamination can be such that soil ecosystem services become constrained (Pierzynski et al., 2005).

Sources and means of contamination are highly varied. Common soil contaminants would include heavy metals, trace elements, radionuclides, pesticides, plant nutrients, fuels, solvents, crude oil, other organic substances, pharmaceuticals, and personal care products. Means and sources of contamination include routine applications of agricultural inputs, mining activities of all types, combustion of fossil fuels, spills, wet and dry deposition, land application of by-products, and flooding. Sources are divided into diffuse (nonpoint) or non-diffuse (point). In the case of the former, small amounts of the contaminant are dispersed over a wide area, or a series of small sources of the contaminant impact a single receiving body, such as a lake or river. In the case of the latter, meanwhile, i.e., non-diffuse sources, this refers to an acute spill, or single point of discharge, where a contaminant enters the environment. The implications for control of point versus nonpoint sources are quite different. Soils impacted by acidification or salinity and sodicity can fall within the context of contamination – be it from diffuse or non-diffuse sources – but are generally considered separately.

The extent of soil contamination is difficult to assess; this is due to: the highly variable nature of potential contamination; technical difficulties in assessing contaminant concentrations over large areas; and lack of clarity as to what is considered contaminated. It is clear that evidence of anthropogenic activities can be found across the globe, including within the soil environment. However, for the purposes of this discussion, contamination is considered to reflect contaminant concentrations that impact, or threaten to impact, soil ecosystem services. For developed countries with strong environmental regulations, the number of contaminated sites that have been discovered, remediated or are awaiting remediation, can be estimated. In Western Europe, for instance, approximately 342,000 contaminated sites have been identified (Joint Research Centre [JRC], 2014); in the United States, meanwhile, the Office of Land and Emergency Management (OLEM) oversees 540,000 contaminated sites, impacting 9.3 Mha (Office of Land and Emergency Management [OLEM], 2014) and the Environmental Protection Agency manages approximately 1,400 highly contaminated Superfund sites (United States Environmental Protection Agency [USEPA], 2016). Such inventories are not available for most areas of the world. Furthermore, inventories for land impacted by diffuse contaminant sources, such as smelters or other mining activities, are not generally available; if they were, however, they would highlight a significant portion of the land resource.

Contaminated soils can have ecosystem services impacted; the most commonly affected services being: loss of productivity (reduction in provisioning), and reduction in regulating services (contaminating the surrounding environment, and effecting a negative impact on the health of humans or other organisms, which can occur through direct contact with the soil, or via food-chain transfer of contaminants). In many countries regulations exist to protect the soil resource from such impacts, but much of the world does not have such protections in place. In developed countries, the extent of soil contamination is likely to only slowly increase, or perhaps even improve as environmental regulations reduce the amounts of contaminants released into the environment, and remediation of existing contamination progresses. In developing countries, however, the extent of contamination is likely to increase, since – in addition to suffering increased pressure on the land resource due to a number of factors – they also often lack the regulatory framework required, or the ability to enforce it. Fortunately, such regulatory frameworks are being considered and developed in China and other countries.

8. SOIL ACIDITY

Soil acidification refers to the possibility that the soil aqueous phase (the soil solution) has a pH in the acidic range, where pH values of less than 7.0 are considered acidic. The true pH of the soil solution cannot be easily measured, so water or salt solutions are added to a soil sample to create a slurry (at varying proportions of soil to liquid); the pH of that mixture is then used to assess acidity, and is referred to as the soil pH. While any pH value of less than 7.0 is considered acidic on the pH scale, values of less than 5.5 indicate soil acidification that could present limitations to soil functions. Such effects can be important for both surface and subsurface soil horizons. Estimates suggest that as much as 30% of the ice-free land surface on earth is occupied by acid soils, equivalent to approximately 4,000 Mha (von Uexkull & Mutert, 1995).

Soil acidification is a natural process promoted by precipitation amount and vegetation. Precipitation is generally acidic and the decomposition of plant residues produces acidity. Thus, the soil weathering process, which slowly removes basic cations (Ca, Mg, K and Na) from the soil, and increases the relative proportion of acidic cations (aluminum (Al) and Fe), leads to soil acidification over long periods of time. Removal of basic cations through crop harvests or burning of forests will also contribute to acidity.

Areas that have old soils (e.g., not impacted by the most recent glacial events) and a humid climate would be more likely to have naturally occurring acidic soils. As shown in Figure 5, the northern boreal forests and the humid tropics have a high proportion of the world's soils affected by soil acidification.

The oxidation of sulfides in the soil can induce significant acidity. Acid sulfate soils form in areas that were once inundated with sea water, and then drained and exposed to atmospheric oxygen. The most common scenario would be coastal areas near mangrove forests, salt-marshes, and floodplains. Acid mine soils occur when sulfide-bearing mine spoils, left over from coal or metal mining activities, are exposed to the atmosphere. Acid mine drainage from such areas can cause significant off-site acidification with negative ecological impacts.

Soil acidification can also be accelerated by other anthropogenic activities, such as soil and crop production management practices, or the combustion of fossil fuels and subsequent acidic deposition. The use of ammonium-containing fertilizers causes significant acidification as the nitrification process converts ammonium to nitrate. Many of the world's most common inorganic fertilizers including anhydrous ammonia, urea, ammonium sulfate, diammonium phosphate, and monoammonium phosphate contribute to this issue. Wet and dry acid deposition occur because of the combustion of fuels that leads to the emission of sulfur and nitrogen oxides, which are then returned to the soil as acid precipitation, or acid forming dry deposition. Ammonia emissions to the atmosphere, primarily from fertilizer use and intensive livestock production, also contribute to soil acidity as the ammonia returns to the soil via precipitation and undergoes nitrification.

There are three primary negative effects of soil acidity on plants. In general, plant nutrients in the soil have optimal availability for plant uptake when the soil pH ranges approximately between 5.5 to 7.5. Thus, soil acidification can limit the availability of plant nutrients, and even induce deficiencies. Calcium, Mg, K, P, and Mo are the primary nutrients of concern. A second aspect is that highly acidic soils (pH <5.0) can have high levels of soluble Al and Mn, which can be toxic to growing plants. Indeed, Al toxicity is a major limiting factor for crop productivity worldwide. Soluble Al levels generally begin to increase significantly at a pH of approximately 5.0 (this will vary slightly by soil); the free Al ions then undergo a series of hydrolysis reactions that not only further enhance acidity, but also greatly increase the amount of lime required to neutralize it. Thus, managing soil pH to remain above this critical level is extremely important when aiming to minimize the impacts of soil acidity. Sumner and Noble (2003) estimated that 67% of the acidic soils across the world were at risk of having phytotoxic levels of Al.

The third main negative effect refers to the microorganisms responsible for biological N fixation. These become inhibited under highly acidic conditions thus limiting legumes' ability to fix N.

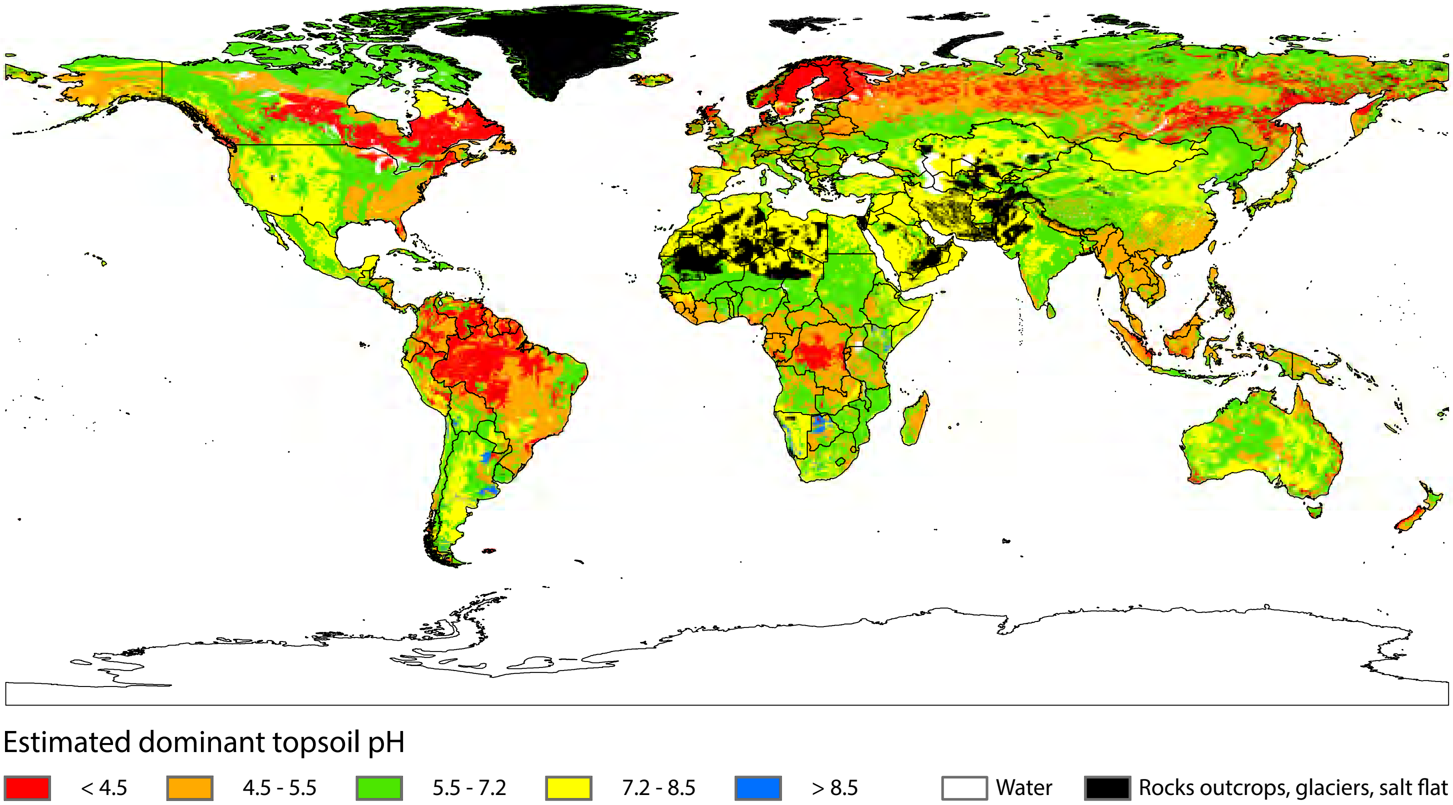
Soil buffering capacity is the capacity of a soil to resist changes in soil pH – whether an increase or a decrease. It is an important characteristic that influences the tendency of a soil to become acidic, as well as the ease at which acidity can be later corrected using lime. Organic matter content, clay content, having basic minerals as the parent material for the soil, and calcium carbonate content are all positively correlated with buffering capacity. This suggests that it would take a greater amount of acidity to reduce the soil pH for soils rich in these materials. In other words, a sandy soil low in organic matter would have a low buffering capacity, as compared to a finer textured soil with a higher content of organic matter. Anthropogenic effects on soil acidity are most pronounced in the case of soils sensitive to acid-forming processes; this occurs, for instance, in areas such as eastern Canada and Eastern Europe, which receive acid deposition from the United States and Western Europe, respectively. Native vegetation present on acid soils is well-adapted to its conditions. Efforts to minimize deforestation in the northern latitudes and in the tropics, as well as to reduce the conversion of savannah and grasslands into agricultural production, will, therefore, serve to minimize the area of acid soils that needs to be managed. Acid soil issues generally become worse when the native vegetation is disturbed, as soil C is oxidized and erosion increases. A reduction in N and S emissions to the atmosphere in developed countries has also been successful in reducing acid precipitation.

For soils already utilized for agriculture, correction of soil acidity is best accomplished through the use of lime containing calcium carbonate ($CaCO_3$). A sufficient amount of lime must be added to overcome the soil buffering capacity, so as to allow the soil pH to be raised to a target level, generally at least above the pH at which Al toxicity is no longer a concern. The primary limitations of this practice are the cost involved, and the availability of lime. Application amounts can easily exceed 2 tonnes ha^{-1}; transportation costs for the lime, from the source to the point of application, can therefore be significant. Small amounts of pelletized lime can also be added directly with seeds or transplants. If lime is not available locally, then liming may not be feasible. A variety of other materials can have some liming benefits, although each would need to be evaluated individually. Gypsum ($CaSO_4 \cdot 2H_2O$) applications can help alleviate Al toxicity without raising the soil pH. This has been particularly useful for treating subsoil acidity, as the gypsum is somewhat soluble and can leach below the surface soil horizon. Finally, subsurface band applications of P fertilizers can also be helpful, as the P reacts with soluble Al and helps reduce Al toxicity creating a small zone of soil with improved growing conditions for roots.

Another strategy involves the use of acid tolerant crops and/or acid tolerant cultivars within a given crop. A preventative strategy via the use of N fertilizers that do not contain ammonium (e.g., calcium nitrate) may be a better option, as compared to the use of N fertilizers with ammonium, with an in-built future need for lime to correct the acidity they cause.

Global efforts to minimize land use conversion will likely have the biggest impact as regards reducing the areal extent of acid soils that impact ecosystem functions at a given location. Additionally, efforts to reduce emissions of N and S to the atmosphere need to be extended to developing countries. Continual efforts will be required to maintain or improve pH conditions for acidic agricultural soils so as to prevent further declines in productivity.

Figure 5: Estimated dominant pH of the soil surface horizon. Source: FAO and ITPS, 2015.



9. SOIL COMPACTION

Compaction – which occurs as a result of compression and shearing – is perhaps the most severe problem soils around the world face today. It worsens their long-term sustainable productivity, not only with regard to food production, but also as relates to climate change processes. It is also one of the main reasons for the increase of surface runoff and water erosion; this occurs through mechanical stress-induced reduction of vertical water infiltration because of the heterogeneity in both pore size distribution and pore continuity. The most pronounced effects are seen when platy structures with very low permeability occur below the plow pan, thus, simultaneously, preventing downwards flow, while enhancing lateral flow, of water, mud and sediments. If a complete homogenization of soil layers due to shearing occurs, both hydraulic fluxes, and linked stabilizing matric potential effects, may be fully interrupted; this, in turn, may lead to intensified soil loss by wind erosion (Hartge and Horn, 2016).

Soil compaction – especially subsoil compaction – is widely considered to be one of the ten main threats leading to soil degradation, worldwide. Compaction reduces pore space; this is particularly problematic in the case of coarse pores. Pore systems, which were initially equally arranged, undergo three-dimensional changes, shifting to completely horizontal anisotropic conditions in platy structured soil horizons. This process has severe consequences for hydraulic, gas, and heat transport processes, as well as for nutrient storage and accessibility. Soil compaction is often also defined as an increase in soil mass per volume; this definition, however, does not allow for the direct prediction of any changes in physical, chemical, or biological properties and functions. Furthermore, if a shear-induced rearrangement of particles occurs during wheeling, trampling or tillage tool applications, the configuration of soil particles per volume can, instead, become less dense, which leads to very weak soil structure with limited pore continuity and gas exchange (Hartge and Horn, 2016).

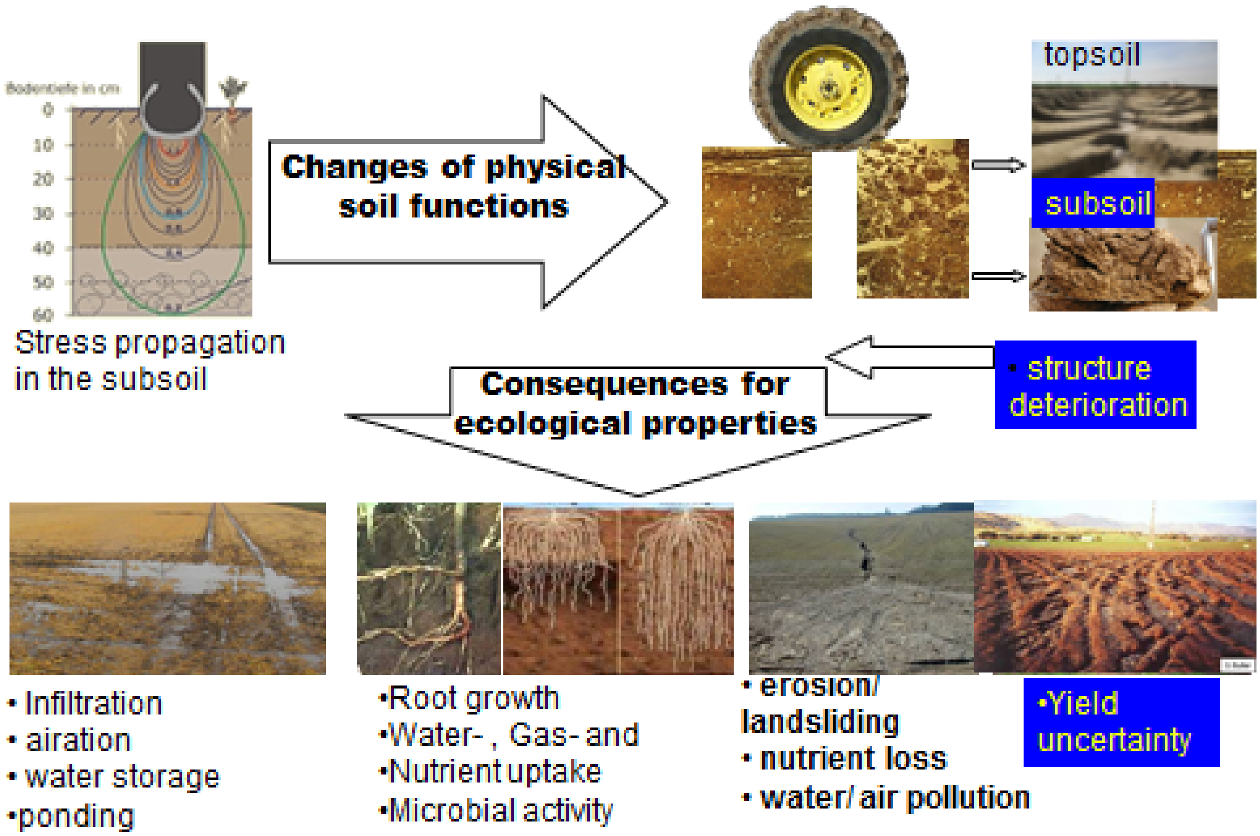
Stress-induced changes can be detected deeply beneath the soil if the stress distribution exceeds the internal soil strength in the various soil horizons. Such a situation can cause a further change of pore functions, until a new and more compacted equilibrium is reached. Thus, the most severe – and mostly permanent – degradation of soil functions occurs as a result of subsoil compaction. These soil horizons have little chance of natural soil loosening or of maintaining soil functionality, since pore functions will not be renewable for a substantial period of time, spanning from decades to centuries, depending on the scenario (Horn, 2011; Horn and Peth, 2011). The European Soil Framework Directive (2006) also states that soil compaction is one of the main threats leading to soil degradation, alongside water and wind erosion. It is estimated, that 32% of the soils in Europe have subsoils that are highly degraded, with 18% being moderately vulnerable to compaction. This problem is not limited to crop land or forest areas (especially because of non-site adjusted harvesting machines), but is also prevalent in rangelands and grassland, and even in so-called natural non-disturbed systems. Wheeling is one of the primary causes for soil compaction issues in both agricultural and forested regions; this has, moreover, increased due to the larger masses of the machines used, and more frequent occurrence of the practice so as to overcome unfavorable site conditions (Riggert et al., 2016). Shear- and vibration-induced soil deformation enhances the deterioration of soil properties, especially if the soil water content is very high, and the internal soil strength, very low. The same is true, in the case of moist-to-wet pastures, for animal trampling in combination with overgrazing. This causes denser (e.g., reduced proportion of coarse pores with smaller continuity) but still structured soil horizons that will end up in a compacted platy structure. Shearing due to trampling in the case of a soil with high water content can finally result in a fully muddy, homogeneous soil, devoid of structure (Krümmelbein et al., 2013).

Site management of arable, forested, or horticulture soils requires a sufficiently rigid pore system, which guarantees water, gas and heat exchange, as well as nutrient transport and adsorption, and an optimal rootability in order to avoid subsoil compaction. Such a pore system also guarantees sufficient microbial activity and composition in order to facilitate decomposition. It is therefore essential that well-structured horizons dominate in soils, with at best subangular blocky structure; or, in the top A- horizons, a crumbly structure due to biological activity. The formation of a platy structure at deeper soil depths, and/or the deterioration of a continuous pore system, is indicative of degraded soil. A dominating anisotropy of pore functions causes lateral soil and water movement. Dörner and Horn (2006) documented the increasing effect of stress and shear on hydraulic and gas permeability, leading namely to horizontal anisotropy. Stress and shear also coincide with a retarded gas exchange, and an altered soil gas composition (e.g., CO_2 or even CH_4) that hinders the normal population growth of soil microorganisms. If the internal soil strength is exceeded, the microbial composition and activity is converted to anoxia, and even results in the emission of CH_4 (Haas et al., 2016). Furthermore, the accessibility of nutrient adsorption places, as well as connections between the pores within the compacted soils, is decreased; this results in a retarded ion mass flow, and diffusion within the plats and/or in between the soil horizons. For more details, see Soane and van Ouwerkerk (1990), Pagliai and Jones (2002), Zink et al. (2011), Duttmann et al. (2014) and Horn et al. (2005). Site-specific sustainable soil management is one approach to stop further soil compaction. Amelioration of compacted soil horizons, however, requires many decades, and can only be achieved provided that the soil strength is not exceeded.

This essential goal may be tackled, in many regions worldwide, by the use of long-term reduced or conservation tillage (Derpsch et al. 2010; Silva et al. 2007).

The final concluding picture (Figure 6) underlines the multidisciplinary effects of soil deformation on site properties.

Figure 6: Soil degradation threats.



Documentation of the effects of soil compaction exists for all scales (from the world scale 1:1000000 to the farm scale 1:5000) given that information is available for all soil types, properties and functions. At the 1:1000000 scale, the soil type dependent variations are less detailed; however, based on available regression equations, both horizon specific soil strength, and stress dependent changes in soil functions – such as, inter alia, air permeability or pore size distribution – can be classified. In contrast, the degree of detail at the 1:5000 scale is very precise, due to existing input data on a much smaller grid (Simota et al., 2005; Horn et al., 2005). See, for instance, three soil strength maps: for Germany (Figure 7); for Europe (Figure 8), always at a scale of 1:1000000); and for an individual farm (140 ha; scale 1:5000, Figure 9). Stress dependent changes in soil functions can be determined by the analysis of pedotransfer functions, which allow for the classification of soils and sites according to their internal physical or chemical properties. A detailed description can be found in Simota et al. (2005), Horn et al. (2005) and Horn and Fleige (2009).

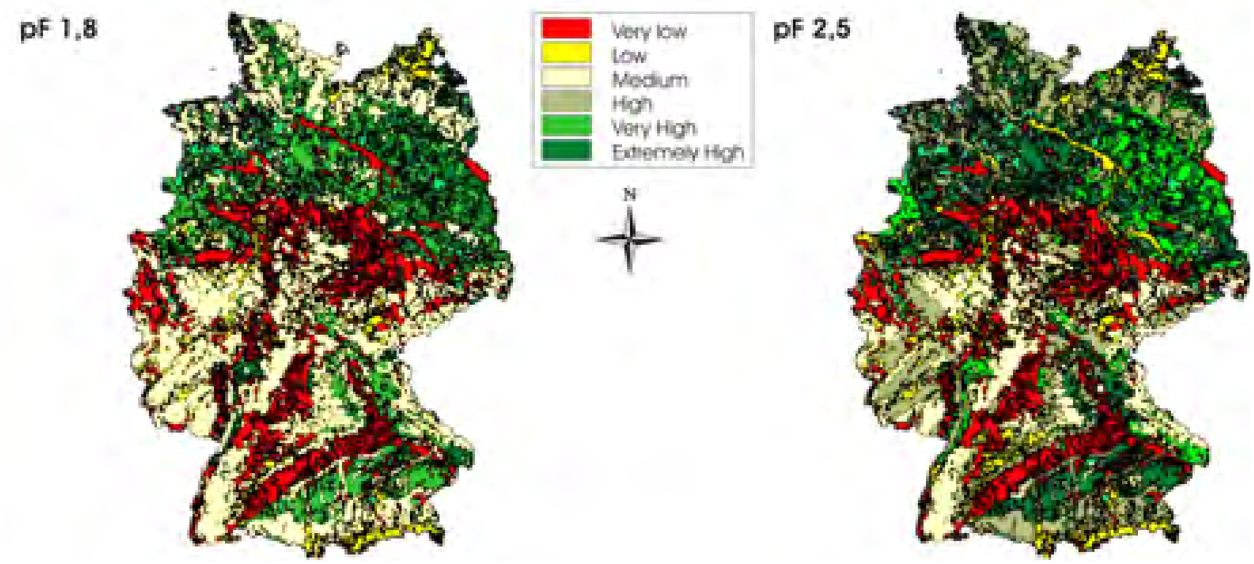


Figure 7: **Soil strength map of Germany – scale 1:1000000 for the subsoil depth: 30-60 cm assuming wet conditions (after snow melt = pF 1.8 left side) and during summertime (dry = pF 2.5, right side)**

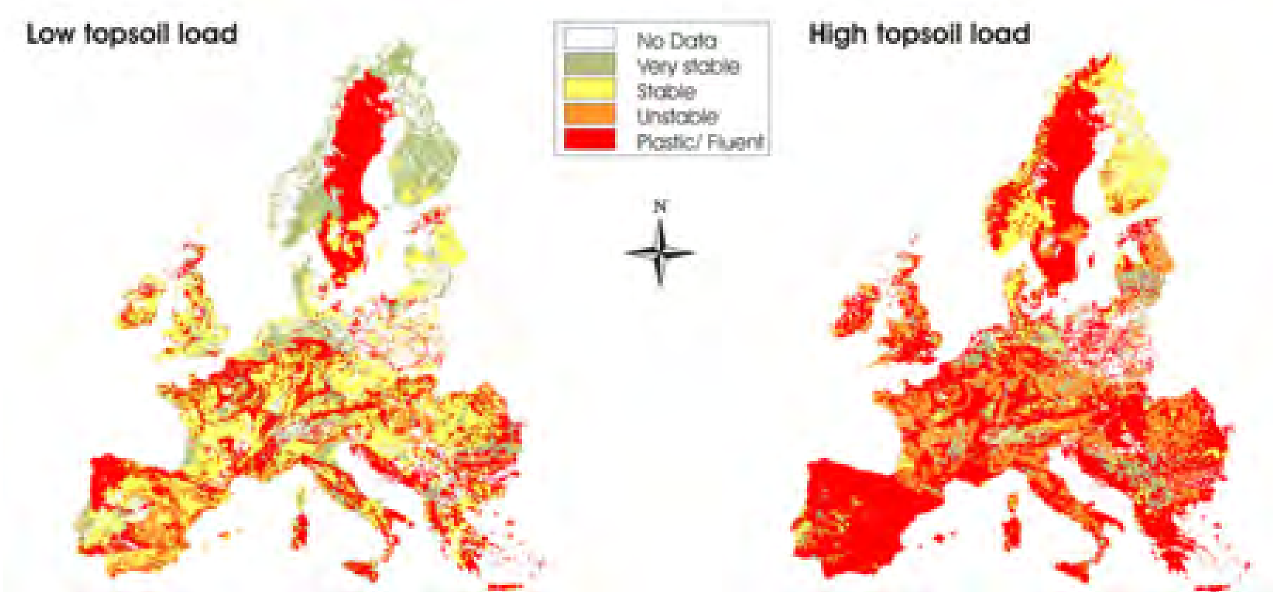


Figure 8: **Precompression stress at a given pore water pressure pF 1.8 for topsoils in Europe in relation to a given low topsoil stress (tyre inflation pressure: 60 kPa), high topsoil stress (200 kPa).**

Classification of the effective soil strength based on the relationship of pre-compression stress to the actual applied soil stress: >1.5 very stable, elastic deformation, 1.5-1.2 stable, 1.2-0.8 stable, >0.8 unstable, additional plastic deformation.

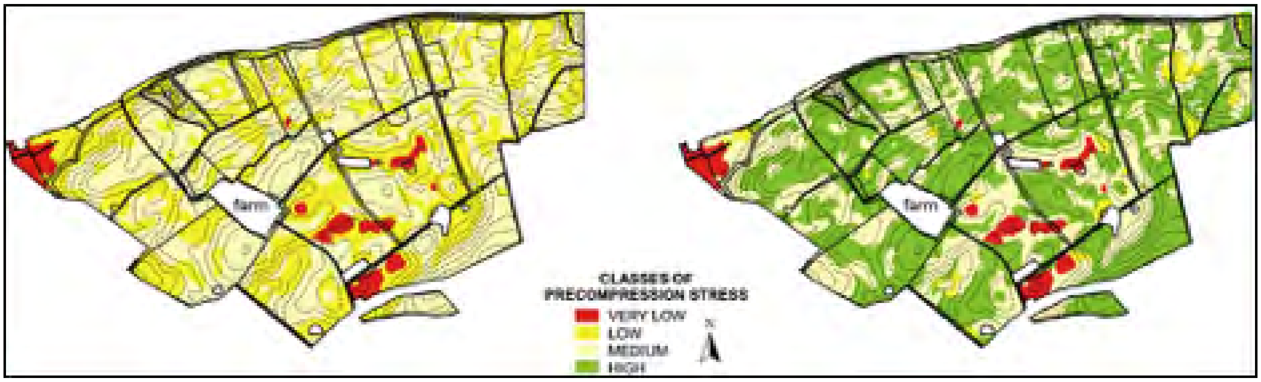


Figure 9: Soil strength defined as precompression stress at farm level - scale 1:5000. Research station Lindhof, CAU Kiel, Germany. Subsoil depth 30-60 cm assuming wet conditions (after snow melt = pF 1.8 left side) and during summertime (pF 2.5, right side)

10. SOIL SEALING

Worldwide, the needs and demands of rapidly increasing populations have been the principal driving force with regard to the allocation of land resources to various kinds of uses, with food production as the primary one. The pressures of high population growth rates, rapid urbanization, and a lack of land use planning have led to soil sealing, aggravated the agro-ecological situation, and undermined ecosystem services, notably in less developed regions (Darwish et al., 2004). A scenario of population pressure combined with increased competition among different land users has highlighted the need for more effective land use planning and policies to protect the soil resources.

10.1. Impact of chaotic urban sprawl on land resources

Chaotic urban expansion has been observed worldwide on fertile and productive lands, causing agricultural activity to shift from productive-level lands towards less productive lands, which are vulnerable to degradation, marginal or sloppy, and which require additional land rehabilitation costs. Chaotic urbanization is threatening food supply and, thus, food security of heterotrophic organisms. Urban areas include not only the primary city, but also its suburbs and the sprawl that goes hand in hand with both.

Methodology of automated human settlement mapping, developed by the United Nations Human Settlement Program, is highly necessary for the utilization of historical satellite data archives, so as to address the urgent issue of urban growth, at both the global and national scales. Gathering of global data with spatial resolution of 10-100 m has been achieved by certain initiatives using satellite imagery resources, ASTER, Landsat, and TerraSAR-X; the next goal, thus, regards the development of time-series data, which can contribute to studies of urban development with background contexts of socio economy, disaster risk management, public health, transport and other development issues (Miazaki et al., 2016).

Urbanization is threatening food supply in both developed and developing countries. With the rapid urbanization rate, by 2050, more than 80% of productive soils are expected to be lost. The rapid growth of suburbs in North America is, in general, chaotic (Figure 10 and 11), with little planning and little servicing (Mason, 2016). In some European, Asian and African inland, coastal and deltaic areas, more than 60% of productive soils have been sealed and converted into concrete. With the rapid urbanization rate, by 2050, more than 80% of productive soils are expected to be lost in this way. Besides the negative impact on food security and socio-economic aspects, this practice reduces the natural recharge of groundwater. The accompanying increase in water demands and excessive pumping from coastal wells contributes to seawater intrusion into coastal aquifers and deterioration of groundwater quality.

China's urbanization has resulted in significant changes in both agricultural land, and agricultural land use (Li et al., 2013). To better comprehend the relationship between the two primary changes China's agricultural land is undergoing – namely, the urban expansion on arable land, and agricultural land use intensity – a panel econometric method was used. Urban expansion was found to have led to a decline in agricultural land use intensity. The area of cultivated land per capita – a measurement which highlights land scarcity – was found to be negatively correlated with agricultural land use intensity. Applying the similarity index (SI) in long time series regarding urban land-cover change detection in China showed that the level of China's urbanization increased from 18% in 1978, to 41% in 2003, and that this figure may exceed 65% by 2050 (Zhang & Liu, 2016).

Figure 10: **Urban expansion on arable lands in USA**

Figure 11: **Development of infrastructure and urban growth on fertile delta in Canada**

Similarly, earth observation using aerial photos and satellite images in Saharanpur City (India), between 1988 and 1998, showed that the unplanned residential area increased from 905 ha to 1,617 ha (Figure 12), gaining land from agriculture and vacant areas (Fazal, 2000). All city expansion occurred on agricultural land alone, which decreased from 5,178 ha to 3,495 ha, resulting in heavy losses of fertile agricultural land (Figure 13). This land transformation in Saharanpur was clearly the result of urban land market operations, notably land values causing a recession in agricultural activities with land owners waiting for the increase of land value to sell their fertile lands.

Monitoring land use changes in the metropolitan fringe of Bengaluru, India, over the time period of 2007 to 2014, revealed that built-up land had spread by 446.55 km^2, causing a corresponding decrease of agricultural land by 16% (Kavitha et al., 2015). Expansion of current and projected built-up areas poses threats to land, and food security; the protection and conservation of farmlands via adequate policies and guidelines becomes, thus, imperative. Assessing spatial Land Use and Land Cover (LULC) information is essential for decision-making and management of landscapes (Selin & Mehmet, 2016). This is particularly true in fast-growing cities, where

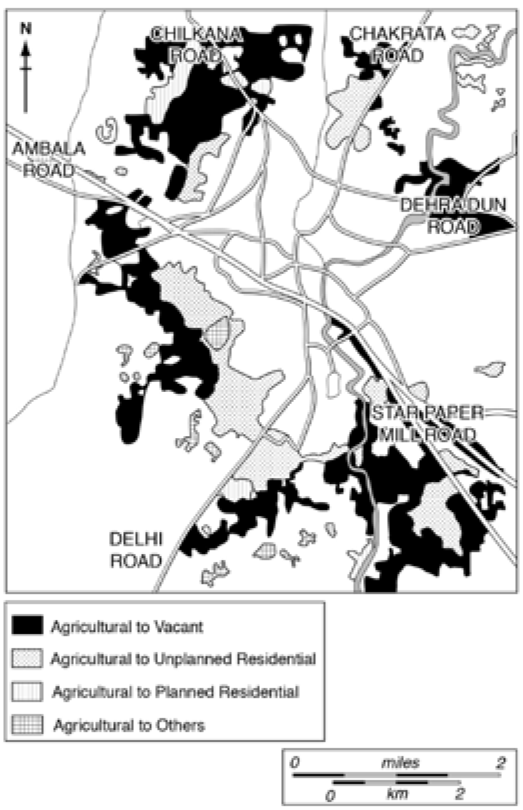


Figure 12: **Land transformation in Saharanpur City 1988-1998. Source: Fazal, 2000**

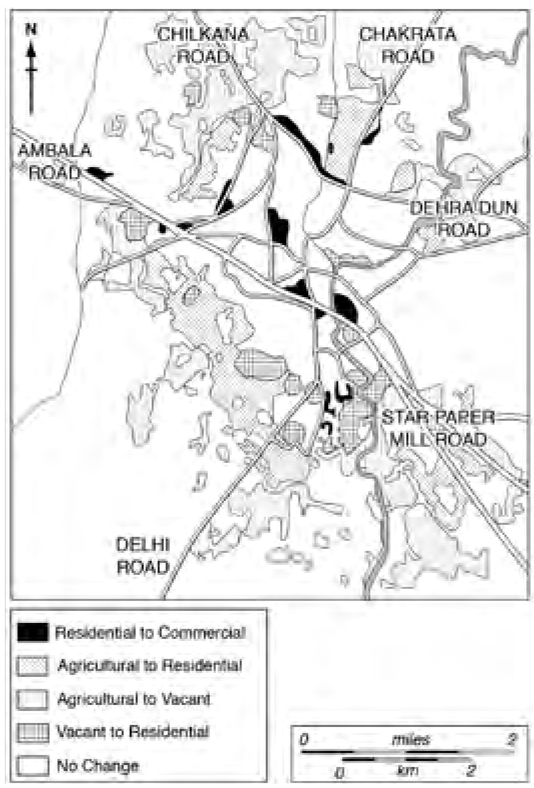


Figure 13: **Transformation of agricultural lands in Saharanpur City 1988-1998. Source: Fazal, 2000**

LULC has changed dramatically. These changes, which are predominantly characterized by unplanned and uncontrolled urbanization, result in a variety of serious land use problems. Observation of land use change in Izmit – one of a growing number of metropolitan cities in Turkey – over the past 30 years, between 1985 and 2015, has shown an increase in urban areas of up to 2,177 ha, and the resultant decline of 1,211 ha of farmland. Urban morphology analysis aids in the understanding of the transformation of urban development, and of the evolution of urban structure (Cheng, 2011). Mecca (Saudi Arabia) has undergone significant changes in land cover to accommodate the growing number of pilgrims and citizens (Ayman et al., 2016). Urban morphology analysis, using remote sensing, revealed the north-eastern and south-eastern parts of Mecca to possess higher opportunities for growth and expansion than others; urban development increased in the two areas between 1998 and 2013, by 89% and 76%, respectively, due to the increase in public services, buildings and road networks connecting different pilgrimage site facilities. Such studies are essential to quantify, and understand, land cover change behavior; they can, moreover, serve as a basis for future planning and development activities, which may further promote or control urban growth. Urban development, with its corresponding loss of agricultural land, often has pernicious effects, however. For instance, in poor rural areas of Uyo, Ethiopia, the loss of agricultural land led to hunger and increased poverty, while boosting the agricultural business of neighboring states (Njungbwen & Njungbwen, 2011).

Between 1984 and 2000, LULC change in Tripoli, Lebanon's second largest city, was quantified using satellite technology, namely Landsat and IRS-1C (Figure 14 and 15). This study showed an increase in urban area of 208%, with a decrease of 35% in agricultural lands. Secondary forests and shrubs replaced the orchards on the abandoned lands (Darwish et al., 2004). Urban expansion occurred at the expense of rare fertile soils; for instance, citrus orchards, previously planted on the most productive agricultural soils, such as Fluvisols, Luvisols and Cambisols, occurring on Lebanon's coastal plains, were removed to make way for urban growth.

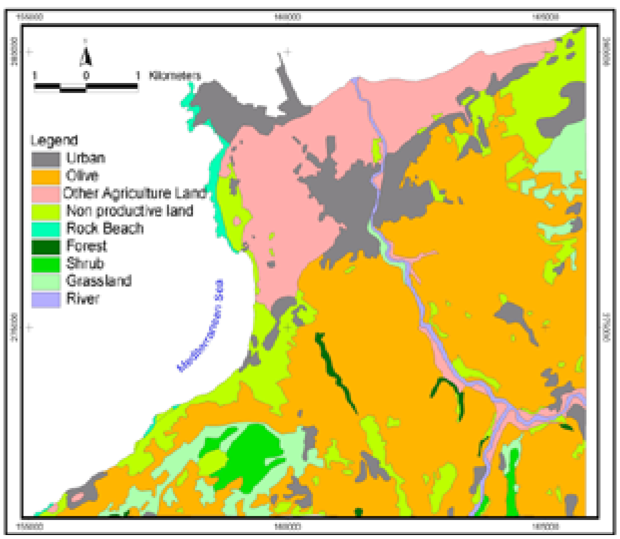


Figure 14: **LULC in 1984, detected from aerial photos. Source: Darwish et al., 2004**

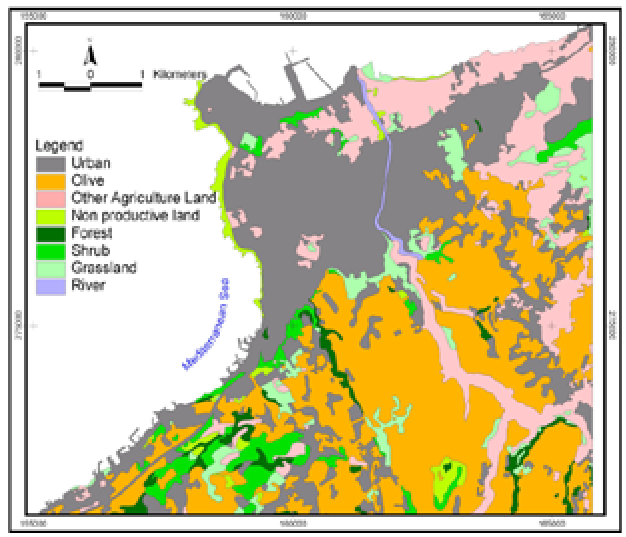


Figure 15: **LULC in 2000, detected from IRC 5-m resolution merged with Landsat TM (30m). Source: Darwish et al., 2004**

Urban expansion leads not only to land abstraction but also to contamination risk. For instance, in the city of Damascus, the primary sources for heavy metal contamination of urban soils were considered to be vehicle emissions (transported by air and sewage water), and household and industrial sewage effluents (Moeller et al., 2005). These contaminants were considered to be responsible for the increased heavy metal concentrations found in the soils of the central Barada area.

There is, however, a need to update all this information so as to meet the requirement of continuous assessment and monitoring, which leads to better knowledge bases, and improved decision-making, for the conservation and support of soil ecosystem services.

10.2. Land use planning for sustainable use of land resources

Land use planning starts with land evaluation – i.e., the assessment of land performance when used for a specified purpose, considering land characteristics, so as to identify and compare the best land use, taking into account options for maximal profit and minimal environmental impact. Land quality depends on a number of factors, such as: geology (rock infiltration and stability); landform (relief and slope gradient); soil type and characteristics (soil fertility, productivity and erosion risks); vegetation type, use and value; climatic conditions and constraints; market conditions; and social attitudes and preferences. The assessment of land suitability is based on the requirements of the specific land use, as well through balancing the land quality with the land use requirements. A comparative analysis of trade- offs for inputs versus benefits relative to a given land use is made; this is framed within the physical, economic and social context. Additionally, an assessment of potential environmental impacts and sustainability is implemented so as to support policy, legislation and decision-making.

Every year about 20 Mha of agricultural land is converted into urban and industrial developments, often pushing farmers to become city dwellers or to shift their activities elsewhere, putting more pressure on marginal lands, already highly prone to degradation. The uncontrolled expansion of human settlements constitutes a challenge for sustainable land use planning and management. The concentration of people, and corresponding proliferation of cities – in coastal areas, particularly – increases the demand for limited land resources. Coastal areas are among the most crowded regions in the world, with more than 80% of such areas being built-up, and densely populated (Huybrechts, 1997). Rising populations in most developing countries, alongside climatic variability and weak preparedness, put multiplying pressures on limited land resources, causing both over-exploitation and land degradation.

The disintegrated and single-objective approaches used to alleviate land abandonment problems have often resulted in inadequate results. It remains unclear whether subsidizing certain crops in some developing countries can lead to better socio-economic outputs. Be that as it may, policies ought to be crafted so as to better support the agricultural system as such. Other key goals include: promoting efficient extension services; improving water harvesting, water allocation and distribution practices; developing modern and sustainable water and fertilizer application, leading to higher water productivity. Taken together, this is one of the goals elaborated by many countries within the United Nations Convention to Combat Desertification (UNCCD) in the shape of National Action Programs (NAPs). The goal of these NAPs is to stop and reverse land degradation as a result of climatic conditions and anthropic activities, however action plans to implement them are still at the embryonic stage. Increasing the efficiency of water use, and implementing balanced fertilization practices and cropping patterns (i.e., more yield, at better quality and lower cost) will boost the return on investment from irrigated lands. This economic stimulus will highlight the value of national agriculture, giving it the status it deserves in less developed countries, where between 30% and 60% of the population is directly involved in agriculture. This value-improvement of agriculture can also occur in more developed countries, where far fewer people are involved in production and more intensive agricultural systems are utilized. Land use planning is not, however, a simple land valuation. This would be very attractive for urban developers and detrimental for agriculture. Neither is it a land capability classification. It is, rather, a land use policy with integrated production and conservation components. Land use policy is essentially an expression of the government's perception of the direction to be taken on major issues related to land use, and the proposed allocation of national land resources over a fixed period of time (FAO, 2016). Thus, an integrated approach is required, involving all stakeholders, accommodating the qualities and limitations of each land unit, and generating feasible and sustainable land use options to conserve productive arable lands for current and future generations. To protect large agricultural lands, Lebanon and Jordan, for instance, are supporting the development of peri-urban agriculture. This involves, inter alia, developing the cultivation of wheat in vacant lands, with support of conservation practices and rotation. I The cultivation of legumes is also encouraged, since this produces a number of benefits, including: preserving farmers' income levels; improving soil fertility and water-use; bettering soil health; and reducing the use of fertilizers. LULC changes have been considered as some of the most critical threats to soil resources today; this regards, for instance, soil erosion after deforestation, and conversion of denuded and marginal lands into agriculture. Impacts of LULC change can also be noted as regards increased soil salinity following the expansion of irrigation, and transformation of rain-fed lands into weakly-managed irrigated lands. The time required for the full rehabilitation of degraded irrigated lands varies considerably: taking three-to-five years, after an acceptable drainage system has been installed; five-to-seven years, after land abandonment; five-to-ten years, to improve eroded rain-fed cropland; and as much as fifty years to return rangeland in drier areas to a good range condition (Dregne and Chou, 1992; Darwish et al., 2005). In view of the interconnectivity between multiple land uses, land use planning covers all potential uses of land, including areas suitable for agriculture, forestry, urban expansion, wild life, grazing lands, and recreational areas. It proposes workable and attractive land use options for the population with minimal impact on environmental resources.

Integrated land use planning is, therefore, a "systematic and iterative procedure carried out in order to create an enabling environment for sustainable development of land resources and communities which meet people's needs and demands" (GIZ, 2011). In this regard, shared information on the spatial distribution of lands, including different potentials and constraints, is required. Alternative land uses are compared and analyzed, to determine whether they are physically possible, as well as socially relevant and accepted. The adverse physical, social and economic impacts associated with each land use are assessed in the planning process. Similarly, the necessary and relevant inputs or management changes required to reach the desired lifestyle and production targets – while minimizing the adverse impacts – are elaborated. Land categorization is implemented, and legal limits are defined regarding permissible urban expansion on arable lands, being then enforced by law. National and local action plans for the prevention and protection of green spots, and rehabilitation of hot spots, are elaborated. Indicators are also developed to aid in the planning and monitoring of the system. Such plans and policies are developed in an integrated, participatory manner, and the role of different stakeholders is defined together, so as to ensure the sustainable management of ecosystem services for current and future generations.

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