SCIENCE DIVISION

UN environment

FORESIGHT
Brief

012

May 2019

Early Warning, Emerging Issues and Futures

Putting Carbon back where it belongs - the potential of carbon sequestration in the soil

Abstract

Soil's contribution to climate change, through the oxidation of soil carbon, is important. However, soils – and thus agriculture - can play a major role in mitigating climate change. Through multiple agricultural practices, we could help store vast amounts of atmospheric carbon in the soil, while at the same time regenerating soil fertility, plant health and whole ecosystems. This is a no regret option that offers multiple benefits and deserves high-level visibility.

Introduction

Agricultural practices have the potential to store carbon in the soil and plants, and thus help mitigate climate change, while at the same time increasing soil fertility and water-holding capacity, improving yields and good nutrition, creating drought-tolerant soils, restoring degraded cropland and grasslands and nurturing biodiversity, with positive consequences on local economies. Together these represent an across-the-board winning set of solutions.

The industrial farming systems succeeds in producing large volumes of food for the global market. However, it also engenders numerous negative outcomes such as significant soil erosion[1–8], biodiversity losses [9–20] little is known about the patterns of change in most pollinator assemblages. By studying bee and hoverfly assemblages in Britain and the Netherlands, we found evidence of declines (pre-versus post-1980 and pollution of freshwater bodies [21–23]. It also promotes a high dependency on the agro-industry and its products, and an enormous freshwater [22,24,25] and nitrogen [26] footprint, along with agriculture's large share of up to 25% of all anthropogenic GHG emissions [27–30]. Earth's population growth, climate change (with increased occurrences of weather extremes such as droughts and storms), potential shortage of mineral fertilizers, soil erosion and decrease of soils' fertility, heavy dependency on fossil fuels, decline of pollinators and other factors collectively represent serious challenges for the current agricultural system.

Can alternative approaches to, for example, increasing soil fertility, employed via a versatile set of methods, regenerate soil resources and create win-win solutions, such as sequestering carbon in the soil to help mitigate climate change? An entire series of innovative and new approaches for such purposes are explored in the following pages.

Why is this issue important?

"Modern" or "industrial" agriculture in the early 21st Century is facing many problems and challenges as described above. One of the biggest - although not so much in the awareness in todays societies - threads humankind and the planet is now facing is the loss of soil, and thus soil fertility, due to agricultural practices (**Figure 1**): The fragility of soils, the thin layer of the earth which is the foundation of nearly everything growing and almost all that we eat, puts the "sustainability" of industrialized agriculture into question.

In many regions, soil fertility has been decreasing for decades, and large amounts of fertile soil have been (and continue to be) washed into rivers, lakes and oceans - gone forever, and with it, much carbon, originating from the oxidation of soil organic matter (SOM, commonly known as "humus"), has been released into the atmosphere in the form of CO$_2$, all of these with severe economic implications.

Figure 1: In cold climate countries, soil erosion mostly takes place on the surface, but can generate erosion gullies as well (photo from Germany), as it does in more brittle environments, washing away large amounts of soil. *Photo: Stefan Schwarzer*

Twenty-four billion tonnes of fertile topsoil extending to 12 million hectares are lost every year [2,8]. This is equivalent of a land area almost the size of Greece or Malawi or to 192 million train wagons full of soil, every year. In the US only, this equates to 15.7 tons/ha/yr [31,32] and in Europe to 2.5 tons/ha/yr of fertile cropland soil [7]. "Overall, soil is being lost from agricultural areas 10 to 40 times faster than the rate of soil formation imperiling humanity's food security" 8. Along with this topsoil loss is the ever-increasing degradation of agricultural soils. Twenty-five percent (25%) of the earth's surface has already become degraded.

Figure 2: Left: 10 years no-till with cover crops and rotational grazing, 2.1% SOM. Right: Conventionally tilled wheat-fallow-wheat rotation, 0.5% SOM. Both soils are silt loam, 50m apart. *Photo: Michael Thompson*

A third of the CO_2 emitted through human activities into the atmosphere from 1850 to 1998 came from agricultural activities [33,34]. Estimates range between 133 gigatonnes of carbon (GtC)[i] since the dawn of agriculture through loss of soil organic matter and soil erosion [35–37], and 379 GtC through forest clearing and burning [38,39]. In general, 50-70% of soil carbon stocks have been lost in cultivated soil[ii] [40,41]. Agricultural fields today often contain less than 2% SOM [42], while at time of conversion from grasslands or forests SOM often amounts to 8-15% or even more. The loss of SOM has multiple negative consequences, one of these being the generation of CO_2 through oxidation of the organic material. If large parts of that CO_2 in the atmosphere come from the land and the soils, can it somehow be recaptured? That is, can CO_2 be re-sequestered in the soil or living organisms, and help mitigate climate change? This is a key issue, because scientists have calculated that extensive terrestrial CO_2 removal through managed biomass and soil carbon sequestration is required in order to avoid the currently projected temperature "overshoot"[43–46].

What are the findings?

The amount of carbon in the atmosphere is 760 GtC and in the biologic pool 560 GtC[33,47]. Globally for the year 2010 Sandermann suggested that global soil organic content (SOC)[iii] stocks were 863, 1,824 and 3,012 GtC in the upper 0.3 m, 1 m, and 2 m of soil, respectively [36]. This is equivalent to each hectare classified by the International Geosphere-Biosphere Programme (IGBP) as cropland as an average of 62, 127 and 198 tC/ha.

The average historic SOC depletion is estimated at 20–30 tC/ha in forest/woodlands and 40–50 tC/ha in steppe/savanna/grassland ecosystems. On average, conversion of native grasslands to crop production results in approximately 50% loss of SOC [35,36].

The most prominent carbon sequestration initiative "4 per 1000", launched by the French Government at the 21st Meeting of the Conference of Parties to the UN Framework Convention on Climate Change (COP-21), set a global aspirational goal to increase SOC stock at an annual rate of 0.4% per year (or 4 per 1000) in all land covers/uses, including forests. This increase would relate to the first 30-40 cm of topsoil, which sum up to 690±90 (30 cm) and 860 (40 cm) GtC 48. A 0.4% increase would thus sequester 2.8 and 3.4 GtC in these layers per year respectively. The annual increase of CO_2 emissions is approximately 0.2 GtC globally[iv], and this sequestration rate would thus decrease the CO_2 concentration of the atmosphere over time.

Equally important however, is the fact that increasing carbon in the soil leads to manifold advantages, improving agronomic yields of crops and pastures: (1) it increases the available water capacity, (2) it improves the plants' nutrient supplies, (3) it restores soil structure, and (4) minimizes risks of soil erosion 49. The visible difference between rich humus and impoverished soil is quite obvious even for untrained eyes (**Figure 2**).

Adoption of improved agronomic practices can result in relative annual SOC increases that are often much higher than 0.4% [48,50–52], depending on the methods used and the amount of carbon present in the soil, as well as on economic incentives and existing expertise.

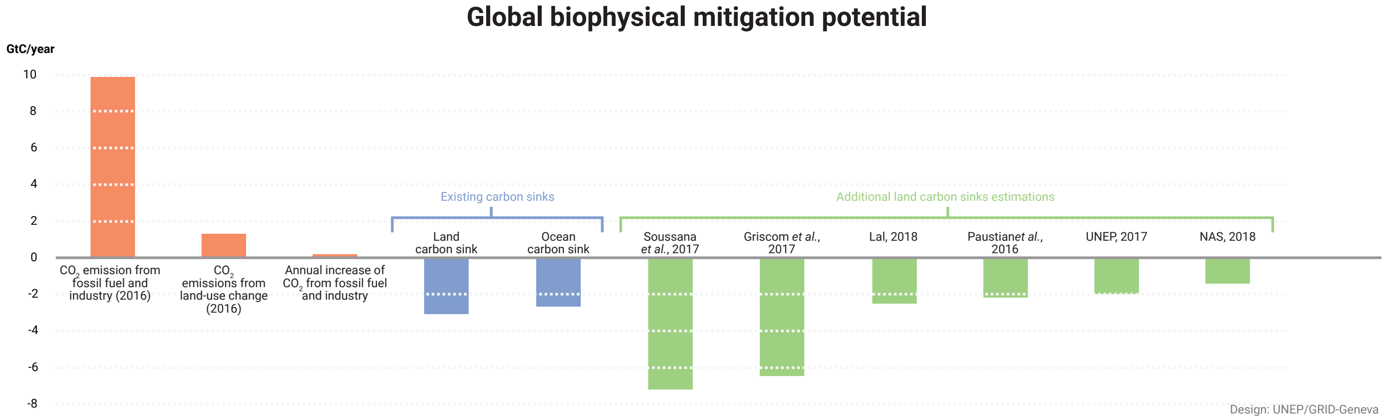

Figure 3: Carbon emissions and global potential for carbon sequestration in soils and vegetation - estimates from various sources. *Graphic: UNEP/GRID-Geneva*

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[i] 1 gigatonne = 1'000'000'000'000 kilograms; 1 GtC = 3.67 $GtCO_2$
[ii] http://www.fao.org/global-soil-partnership/resources/highlights/detail/en/c/239815/
[iii] SOC is a component of SOM, and is commonly calculated as SOM * 0.58
[iv] http://www.globalcarbonproject.org/carbonbudget/17/data.htm; average 2000-2017

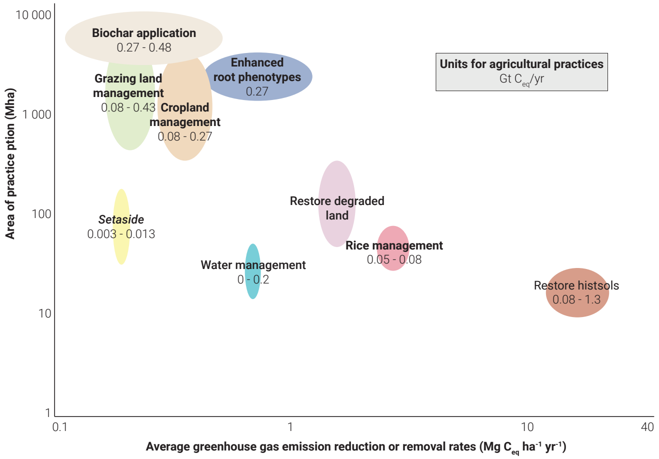

Figure 4: Global carbon sequestration potential ranges for different methods (note log scales), adapted from [53]

Estimates for carbon sequestration through improved practices vary considerably (**Figure 3**) as the understanding of the interactions and especially the knowledge of the behavior of soils is still limited. Various studies indicate theoretical potentials of 0.8 to 8 GtC per year [35,40,44,51,53–57], partially including af-/re-forestation practices, and reaching up to 10 GtC/yr of additional carbon on agricultural land [41,55,] while practically achievable carbon removal amounts are rather located in the lower range of 1.5 to 2.5 GtC/yr [30,53,58]. With global carbon emissions in 2016 from fossil fuels and industry of 9.9 GtC plus 1.3 GtC due to land-use changes (such as deforestation)[v] [38], the potential for carbon sequestration through regenerative agricultural practices looks rather promising, although the implementation of such practices comes with different social, economic and expertise-related and other caveats. It requires funding and collaboration amongst scientists, policymakers, practitioners and multiple other stakeholders. Soil carbon sequestration has a large but not infinite sink capacity, and, importantly, is reversible through bad management. Global efforts to gradually change land use practices are difficult to implement, reducing thus the theoretical mitigation potential [60].

Agricultural practices which can increase SOC include, *inter alia*, agroforestry methods, use of cover crops, use of crops species and varieties with greater root mass and deeper roots, use of nitrogen-fixing leguminous plants, integration of livestock into the cropping system, large-scale crop rotation, improved grassland management, increased residue retention and amendments such as compost and biochar[vi] [44,45,48,51,53,55] (**Figure 4**).

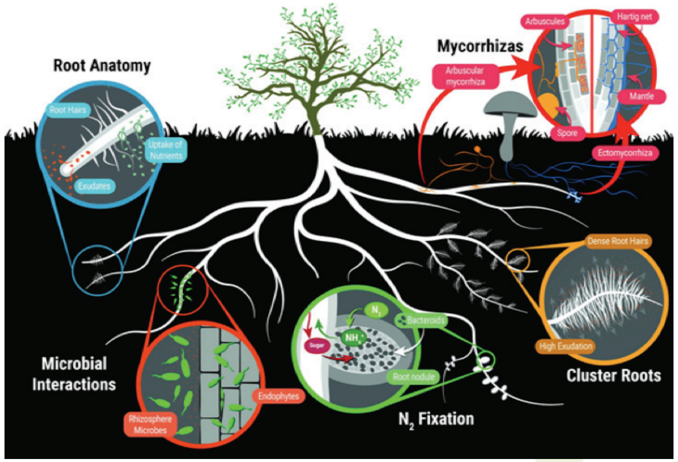

Figure 5: Many interactions take place in the “rhizosphere”, the active zone where roots meet bacteria and fungi. Drawing: Scott Buckley , *Source: PlantsInAction*

Increasing SOM, and adapting agricultural practices accordingly, requires an understanding of the fundamentally important **relationship between plants and soil life** (**Figure 5**). Plants interact intensively with a vast number of microorganisms, in particular microbes and fungi, in the soil. In a single gram of healthy soil one can find 10^8-10^9 bacteria, 10^5-10^6 fungi and much of other microscopic life [61,62] which influences the plant’s growth and health, as well as nutrient and water storage in the soil [63–68]. The underground so called *wood wide web alias www* [69,70] shares nutrients and water with the plant, as well as signals from the plants which influence defense against insect herbivores and foliar necrotrophic[vii] fungi [71,72]. Plants on the other hand transfer up to 50% of their photosynthesis products (essentially carbohydrates) via root exudates[viii] with this highly diverse system of life [66,68,73–78], building a complex natural symbiosis. Plant diversity and microbial soil diversity influence each other positively [68,79–83,] supporting plant health and plant mineral concentration [84], which leads Pieterse to express: “Indeed, roots and their plant health–supporting microbiome may hold the key to the next green revolution” [85]. Whereas the excrements of bacteria as well as their dead bodies constitute an important part of the carbon pool in the soil, mycorrhiza[ix] produce a gooey, carbon-rich glycoprotein known as “glomalin”, which is crucial for soil stability and water retention [86,87] and builds an important reservoir of carbon, pulled from the atmosphere [87,88.] In addition, it is the roots, through their process of exudates, which increase SOC 2.3 times more than the composting process of dead above-ground biomass [89,90].

As recently demonstrated by Sanderman [36,91], a higher carbon return management system results in a soil with more carbon, which supplies more nutrients back to the crop and increases crop productivity. A higher amount of nutrients in the soil would translate into diminished quantities of chemical fertilizer input needed. Chemical fertilizer is a major source of greenhouse gas (GHG) emissions in conventional agriculture, both through the energy-intensive production and the resulting reaction of microbes [92]. It is pertinent to know that LaCanne and Lundgren came to the conclusion that “profit [of regenerative farming systems] was positively correlated with the particulate organic matter of the soil” [93]. Not surprisingly, a 1% loss in SOC can be translated to a societal loss of natural capital, due to declines of ecosystem services and associated soil fertility, amounting to about $163/hectare [94]. Another study estimated the societal value of carbon in the soil at $120 per ton [95].

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[v] Total greenhouse gas emissions (thus including the emission of methane and other gases too) without land use, land-use change and forestry (LULUCF) amount to 13 GtCe plus 4.1 GtCe from LULUCF 59

[vi] A long-time stable form of charcoal produced through pyrolysis of biomass, see later in this article.

[vii] A parasite that kills its host, then feeds on the dead matter.

[viii] Exudates are fluids, often rich in carbohydrates (or sugars) emitted by a plant via roots and other pores.

[ix] Mycorrhiza is a symbiotic association between a fungus and the roots of a plant.

The following is a list of agricultural practices, which can help sequester carbon in the soil, although detailed data about their carbon sequestration potential is sometimes yet limited.

As tillage is one of the most important drivers for the mineralization of SOM and soil erosion, changing to **reduced or no-tillage systems** can have a positive impact on soil organisms and SOC, and can save up to 70% of energy and fuel costs and machinery investment [96,97]. Under most no-till systems, soil carbon in the upper layer (<10 cm depth) is increasing; however, this is not the case in deeper layers, where SOC is partially diminishing [98–100]. Nevertheless, research shows that the activity of both bacteria and especially fungi as well as soil structure are often improved [96,98,101–103]. No-till helps to protect soils; however, it often comes with the use of herbicides, such as glyphosate[x], which in turn have negative consequences on soil biota and other living organisms and may harm human health [104]. In order to benefit from no-tillage and store additional carbon, this practice must be integrated into more diverse agro-ecosystems, where for example multi species cover crop help loose the soil with deep reaching roots, transfer carbon into that rhizosphere, stabilize soil aggregation and suppress weeds and pests [42,105–108].

Crop management practices, which can be used to store additional SOC at rates of up to 0.4 GtC annually 109, include selection of crop species and varieties with greater root mass and with deeper roots, use of crop rotations providing greater C inputs, use of cover crops during fallow periods, increased residue retention and addition of amendments such as compost and biochar [110]. **Cover crops** - the growing of beneficial plants during and for times of rest - and **crop rotations** can both improve soil fertility due to multiple effects: keeping the soil covered, feeding the micro-biome year-round, amending nitrogen to the soil through nitrogen-fixing plants and thus increasing SOM [109], reducing soil erosion and suppressing weeds as well as pests, as many studies have shown [111–116]. Increasing the diversity of crop varieties, within a culture as well as between subsequent cultures, can lead to important economic gains (higher yields, less pesticides use) due to greatly decreased weeds and insect pests, as this positively alters the supply of aphids’[xi] natural enemies [55,117–119]. **Crop species** with deep roots (especially helpful for cover crops) can perform all of the following key roles: sequester more carbon, help break up plough compactions, tap into the subsoil for additional nutrient accumulation, aerate the soil, provide beneficial conditions for earthworms and other soil life and can positively influence the root diameter of the subsequent crop [66,68,120–122].

The abundance of earthworms is a key indicator for soil activity and soil health. Improving conditions for their activity is critical, as they dig (bio)pores that help aerate the soil, infiltrate and rapidly store water, increase humus levels through the integration of organic material in the soil and their highly nutrient-rich castings, and help to tap into the nutrient-rich subsoil [64,113,123,124]. **Crop residue retention** and **mulching** are key approaches for increasing soil fertility as well as soil carbon and at the same time limiting soil erosion [4,33,93,125–127].

Intercropping, the simultaneous production of multiple crops on the same area of land, can increase net plant growth and thus sequester carbon in the soil, increasing yields while at the same time decreasing weeds [128–132]. Estimated numbers for SOC are however rare: Cong *et al*. demonstrate a 4% ± 1% SOC increase in strip intercrop systems compared to ordinary crop rotations [133] and Oelbermann models a 47% increase of SOC after years in maize/soybean strip rotation in comparison to 21% and 2% increase in single-crop cultivation. This can be explained by higher leaf surface area, increased mycorrhizal activity, increased communication and exchanges through root networks and through complementary requirements on the soil, i.e. the plant species using different amount of mineral nutrients [83,131,134–136].

Figure 6: An undersown helps protect the soil, feed the soil organisms and push carbon into it. *Photo: Andrew Howard*

Undersown (or “**living mulch**”) (**Figure 6**) helps to protect the soil when the main crop does not fully cover the soil. It helps to suppress weeds and can (if for example leguminous plants are being used) boost the main crops’ growth due to furnishing organic nitrogen to the crop [137–140] while increasing SOC [141].

Another factor is that in the summer months of the temperate regions, the potential photosynthesis rate is at its highest. However, with the grain crops ripening, this energy is not translated into the production of carbohydrates. As one farmer puts it, *“I am harvesting sun! I never wonna have spilled sun on my operation!”* [xii]. As the undersown continues to produce photosynthetic products in that period of the year, it continues at the same time to add carbon to the ground, while delivering nectar, pollen and seeds to insects and birds and advancing biological pest control [140,142–144].

The application of **compost** to crop- and grass-lands stimulates both above- and below-ground NPP[xiii] and - even if applied only once - leads to increased carbon

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[x] See the foresight brief on glyphosate

[xi] Aphids are small sap-sucking insects.

[xii] https://www.youtube.com/watch?v=9yPjoh9YJMk

[xiii] NPP = Net Pri¬¬mary Productivity; the net amount of CO_2 taken in by vegetation in a particular area, describing the plant’s productivity rate.

accumulation of 2-5 Mg C/ha over subsequent years [145–147]. It augments soil life through the fungi and bacteria in the compost itself. And it stimulates soil life activity, while bringing additional carbon and nutrients to the soil, improving soil structure and water holding capacity at the same time.

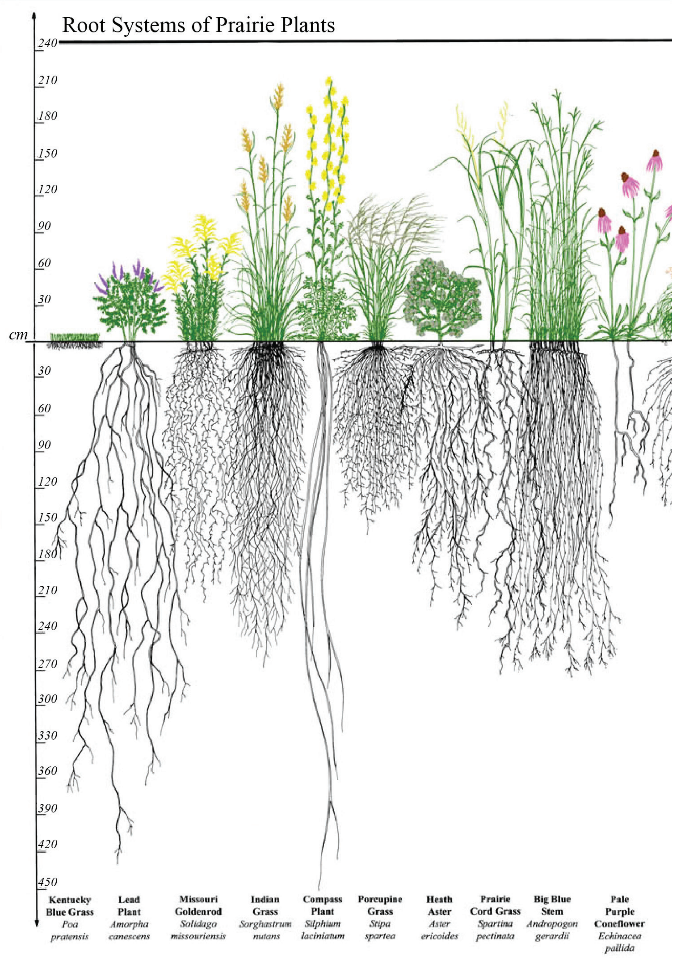

Figure 7: Native prairie plants develop deep root systems, whereas the often-planted Kentucky Bluegrass (first one on the left) roots very shallowly. As approximately 2/3 of the SOM increase will come from roots, those plants have a much higher potential of storing carbon deep in the soil, while at the same time offering habitat and food for insects and birds, delivering versatile and nutrient-rich material to grazing animals and protecting the soil. *Drawing: Heidi Natura*

Native grass pastures: Pastures are often replanted in a regular manner with low-rooting species (such as Kentucky Bluegrass) and with a low variety of grasses. The "ancient" prairies of the USA (as well as Europe) were however composed of a large variety of native plants, many of these rooting - and thus putting carbon - very deeply into the soil [37,148]. Whereas typical seeded grasses reach depths of not more than 50 cm, native plants easily grow several meters deep, while including different root forms (**Figure 7**).

Crop-livestock integration, that is, using animals to graze off cover crops or stubbles, creates synergies among system components that may improve resilience and sustainability while fulfilling multiple ecosystem functions. It can increase SOM as well as economic return, diversify agricultural production systems, improve drought resistance and reduce soil erosion [115,149–153]. Using animals to graze off cover crops or stubbles not only improves the soil through the bacteria- and nutrient-rich excrements, but can at the same time substitute for the use of herbicides (such as glyphosate). Colin Seis' **(Box 1**) "pasture cropping system" goes even one step further, and combines perennial pastures with the growth of annual crops, giving impressive results in terms of soil carbon increase (9 tC/ha/yr for the years 2008-2010), biodiversity and yields [154–156].

Improved **grassland land management** such as lower stocking rates, several types of rotational or short-duration grazing, seasonal grazing, inclusion of legumes and a high variety of plants, can lead to sequestration of up to 1.8 GtC and annually [37,41,45,48,49,53]. This is especially true of **adaptive multi-paddock (AMP) grazing [or holistic grazing management** or **mob grazing**, **(Figure 8**)], where herds graze in a rather small parcel for a very short amount of time (usually from half a day to 2-3 days) before being led to the next parcel, while offering several weeks to months of regeneration following the grazing. In contrast to a continuous grazing scheme, where the net effect of carbon reductions can be outweighed by N_2O and CH_4 emissions from the animals and their excrements, new research and an increasing number of practitioners' report growing rates of SOM, increasing soil fertility and biomass and increasing plant diversity. While taking the methane emissions from the animals into consideration, one still arrives at a net carbon benefit [41,157,158] thus "indicating that AMP grazing has the potential to offset GHG emissions through soil carbon sequestration" [159].

Figure 8: Mob grazing promises to be a powerful tool to raise rapidly soil fertility and soil carbon. *Photo: Tom Chapman*

Agroforestry, the intentional integration of trees and shrubs into crop and animal farming systems (**Figure 9**), can create multiple environmental, economic and social benefits. It can increase SOC [160,161] and sequester between 0.2 and 5.3 GtC per year in soils [48,55,162,] not counting the carbon sequestered in the wood, with most carbon sequestration in the tropics and subtropics [162,163]. It also increases biodiversity, stabilizes the soil, improves water infiltration and diversifies the farmer's yields [164,165]. Agroforestry and conservation agricultural approaches in sub-Saharan Africa and tropical countries showed that larger increases of soil carbon than 0.4% are often attainable, while at the same time being of higher economic and environmental value [125,163,166]. The addition of trees to agricultural mitigation practices such as conservation agriculture or managed

Figure 9: Agroforestry system in southern France, combining successful trees and crops. *Photo: Christian Dupraz (INRA)*

grazing can increase carbon sequestration rates by 5–10 and increase soil carbon stocks by 3–10 times [167].

Intensive **silvopasture** systems - combining trees, livestock and grazing - can be developed to increase SOC 168 and to achieve a net carbon capture (thus, accounting for the animals' methane production) of 4-12 tC/ha/yr, while at the same time increasing the production of meat and milk on the same area of land 163,169. Naranjo et al. found that emissions from livestock were equal to a quarter to half of the carbon sequestered in soil and biomass [170].

Afforestation, by converting marginal and degraded (agricultural) soils into forests and perennial land use, can enhance the SOC and living carbon pool (wood), and has many other advantages as well (food through the use of nut or fruit trees, fiber, fuel, mulch, reduced soil erosion, increased water infiltration). The magnitude and rate of carbon sequestration with afforestation depends on climate, soil type, species and nutrient management [33,48,163,171,172]. McKinsey & Company estimated that by 2030, afforestation could sequester 0.27 GtC globally per year in soils and biomass [173]. Trees have an extensive root system that can grow deeply into the soil [121,174] and root-derived carbon is probably the most important source for SOC storage [57,122]. However, afforestation cannot be developed at the expense of cropland, as it would compromise food security. **Reforestation** measures have similarly a great potential and could account for 1-2.7 GtC/year globally [29,48,55,175]. Through the selection of perennial food producing shrubs and trees, global food production could be improved. Globally, the carbon dioxide removal potential through afforestation and reforestation is significant and has been estimated at 1-3.2 GtC per year [30,48,] 4 GtC through tropical re-/afforestation alone [176] and up to 7.6 GtC [55].

Restoration of histosols: Peatlands (with soils called "histosols") are very high in organic matter and store large amounts of the world's terrestrial biological carbon pool [177]. While the carbon stocks have been partially depleted through drainage and tilling, there is significant potential of avoiding additional carbon losses as well as carbon sequestration capacity through their restoration [172,178]. Long-term sequestration rates in histosols range from 0.3 - 1.3 GtC globally [53,55,57,179]. However, histosol restoration implies stopping to crop them, which imposes a difficult trade-off between food production and other ecosystem services (e.g. climate regulation, biodiversity protection).

Biochar, produced through pyrolysis[xiv] of biomass, is a long-term stable form of charcoal. Biochar has multiple benefits, many of which are not yet understood. It is resistant to decomposition [180,181] and can stabilize organic matter added to soil [182]. Biochar can also form long-term carbon pools in the soil [183], sequestering up to 0.5 GtC/year globally [48,53,55,184,] and in an extreme if unrealistic case up to 8.3 GtC [48]. The application of biochar provides a range of soil fertility and soil quality co-benefits, such as the promotion of fungi and bacteria growth, improved water and nutrient retention, decreased pathogen impacts [185,186,] increased soil porosity and higher crop yields if pre-composted [187,188]. However, large-scale use of biochar would require major inputs of biomass and may be challenging to implement [189–191].

Box 1: Success Studies

Gabe Brown is a prominent conventional farmer in the US, who turned his farm, formerly based on a monocultural model, into a prolific business with increasing levels of humus (from <2% in the early 1990's to >6% more recently), water holding capacity and diminishing amounts of herbicide use. He also uses a broad mix of cover crops, has integrated livestock into his cropping system via a holistic grazing management plan and stopped tilling his fields.

Colin Seis is an Australian rancher, well-known for his "Pasture Cropping" system - an innovative land management technique that enables annual crops to be grown opportunistically on dormant perennial pastures or pastures whose competitive capacity have temporarily been suppressed by grazing, and/or selective herbicides to enable the successful growth of annual crops.[xv]

Joel Salatin[xvi] is a well-known North American farmer, who intensively uses "mob grazing", extended by a "follower system"; that is, a system where different animals can follow each other based on different forage needs, such as cows, sheep, chicken and turkeys. His soil fertility increased steeply, at the same time augmenting the diversity of plants in his meadows.

[xiv] Pyrolysis is a treatment, which can be applied to any organic (carbon-based) product, whereby the material is exposed to high temperatures in the absence of oxygen.

[xv] http://www.pasturecropping.com/articles

[xvi] http://www.polyfacefarms.com

The 4p1000 initiative is the most prominent and political active movement to advance the subject of carbon sequestration in combination with agroecological practices. This initiative, launched by France in December 2015 at the COP-21, consists of federating all voluntary stakeholders of the public and private sectors (local, regional and national governments, companies, trade organizations, NGOs, research facilities etc.) under the framework of the Lima-Paris Action Plan (LPAP). Almost 40 countries and over 320 institutions and organizations worldwide have joined this movement. The 4p1000 initiative provides a space for collaborative interaction between scientists, policy makers and practitioners to make sure that actions are science based. The initiative is very active on the political side and it promotes science, as it also proposed a research program to sustain the goals of the initiative. In addition, Regeneration International, a collaborative effort of more than 150 companies, farms and institutions, works toward awareness and scientific knowledge in this field, as well as on the applied side.

Meanwhile, small advances can be observed around the world: “Australia’s Coalition Government is investing $450 million in a Regional Land Partnership program and $134 million in Smart Farms program to improve soil health. The Government of Andhra Pradesh has launched a scale-out plan to transition 6 million farms/farmers to (a) 100% chemical-free agriculture by 2024. The programme is a contribution towards the UN Sustainable Development Goals. A new bill will be brought before the UK parliament this year mandating, for the first time, measures and targets to preserve and improve the health of the UK’s soils.”[xvii] There are other initiatives on a practical and scientific level as well, raising awareness among and bringing together farmers, and investing government money in new approaches, as well as studying in more detail the effects of soil carbon sequestration and impacts on soil and plant fertility.

Box 2

The five principles of soil carbon storage and regenerative agriculture based on “how nature does it”. Nature has hundreds of thousands of years of “research and development” behind it, including what worked, what didn’t work out and what disappeared. What works is known and present. Let’s learn from nature:

1. Always protect the soil surface
2. Minimize soil disturbance
3. Use high diversity of plants and animals
4. Keep living plant-root networks
5. Integrate animals into the crop

Clearly, putting the above-mentioned methods into practice is challenging, as they require much knowledge and need to be adapted to local conditions. Some of these efforts will take several years of persistent implementation in order to demonstrate reliable results, and the bearing of financial risks and critiques from the more conservative farmer community. There already exists a small although increasing number of farmers using (some of) these techniques, and with positive results. The chances rise that others will follow. Interest for field days of those innovative farmers is rising steadily around the world.

It must be stated that numbers on the potential of carbon sequestration vary considerately, while new research almost every week offers additional, sometimes contradictory, information to the puzzle. Some of the critiques being expressed concern the non-permanence of SOC through bad land management, conflicting uses of residue inputs, competition between natural restoration and cultivation of food, lack of communication and expertise on how to adopt the varying practices and non-existing incentives and governance for these approaches.

[xvii] http://www.pasturecropping.com/articles
http://www.polyfacefarms.com
ative-agriculture-movement-is-growing/

What are the implications for policy?

A key conclusion of this Foresight Brief is that only a combination of approaches can help mitigate climate change. But even more importantly, it broadly demonstrates how agricultural practices that increase soil organic matter are supportive of enhanced food production, increased biodiversity, enhanced water retention and drought resistance and other important ecosystem services, and offer in reality a win-win solution for farmers and society as a whole (Figure 11). Current structures which sustain the "industrialized agricultural system" are complex and well established, and include farmers, machinery and chemicals manufacturers, markets and commerce, taxes and subsidies, low consumer prices and other factors. Broad implementation of the approaches described above can only be achieved with the active support of governments, while the development of the regenerative agriculture movement remains currently mainly a bottom-up one [192].

Although many of the above mentioned practices come at a cost, some will actually bring revenues and cost savings 5[7]. The cost we are willing to pay for them will determine the amount of carbon pulled back from the atmosphere. Price tags vary, but indicate that at 20-100 US$ per ton/C, a good share of the technical potential of carbon sequestration could be achieved [30,55,173].

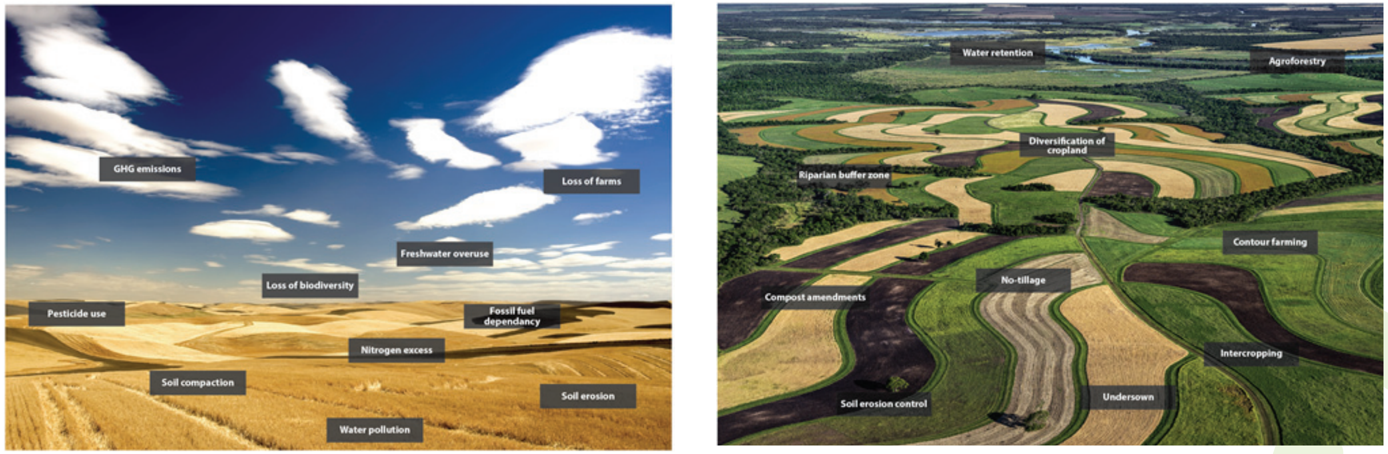

Figure 11: Problems related to industrial agriculture and benefits of regenerative agriculture. Design: UNEP/GRID-Geneva, Picture right: Luis Franke

In order to help boost practices which increase SOM, the following cross-cutting actions should be priorities for policy-makers [30,192,194–198].

- ***Address land degradation and support land regeneration restoration:*** Agricultural practices have decreased soil fertility and degraded large areas of the land. Given the regenerative forces of nature, such land can be restored, but the proper knowledge needs to be applied.
- ***Encourage agro-ecological practices that increase the quantity of SOM and pay farmers for soil carbon storage:*** A small but increasing number of farmers use a variety of new or recent tools which use nature as a model to improve SOM, and in consequence many other "ecosystem services" as well. These best practices should be supported, communicated and spread widely where relevant, both at national but also at international level.
- ***Mainstream agro-ecology and holistic food systems approaches into political, education and research agendas:*** The whole-system thinking in the above-mentioned methods can be considered as a paradigm shift in the agricultural realm, making an immediate breakthrough difficult. The knowledge about these agro-ecological approaches should be promoted through political, educational and research institutions to make a transition more rapid and efficient.
- ***Improve knowledge, communication, training and networking of/for practitioners on improving SOM levels, sustainable soil management and agro-ecological practices and approaches:*** The way such knowledge currently spreads is through local initiatives and small regional to international networks. Governments and other institutions should support these bridges towards a new future of farming.
- ***Support agriculture and forestry as sectors potentially contributing to mitigation of climate change:*** Agriculture and forestry can be important realms for mitigating climate change, as they have the capacity of storing large quantities of carbon in the biophysical

Goal #	Objective	Impact from increased SOC
1 NO POVERTY	No poverty	Increase farm income
2 ZERO HUNGER	End hunger	Enhance quality and quantity of food
3 GOOD HEALTH AND WELL-BEING	Good health	Produce nutritious food
5 GENDER EQUALITY	Gender equality	Improve crop productivity of women farmers
6 CLEAN WATER AND SANITATION	Clean water and sanitation	Improve water quality
8 DECENT WORK AND ECONOMIC GROWTH	Economic growth	An engine of economic development
10 REDUCED INEQUALITIES	Reduce inequalities	Enhance and sustain farm productivity
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	w consumption	Reduce input of water, nutrients
13 CLIMATE ACTION	Climate action	Sequester carbon and mitigate climate change
15 LIFE ON LAND	Life on land	Increase activity and species diversity of soil biota

Figure 11: Advancing the SDGs through management of soil health [48,56,193]

realm, and offer at the same time important benefits for our society (**Figure 12**).

- ***Support campaigns to preserve and build soils, such as SaveOurSoils and 4p1000.org:*** There are several international initiatives working to advance this subject within political agendas. The prominent ‘4p1000’ initiative is being supported by almost 40 countries and many international and national institutions and organisations.
- ***Focus not only on total yields, but as well on other “ecosystems services” that farmers can contribute to (carbon sequestration, climate regulation, water storage and filtering, erosion control, biodiversity, nutritious-dense food and others):*** Our current system looks mainly at the parameter “yield per hectare” as an indicator of success, neglecting other important factors of sustainable practice. These should be brought more into focus through education.
- Restructure successively subsidies for fossil energies and agrochemical goods, to encourage more diversified agro-ecological practices: The current practice of large-scale agriculture is heavily dependent on inputs and threatens the underlying basis of its own production system - the soil, biodiversity, water system and climate. Shifting the focus towards diversified agro-ecological practices can help nurture the very resources we depend on for the production of diverse and healthy food products.
- ***Work for the opening of carbon markets and/or stimuli to new sectors such as agriculture and agroforestry:*** Although the success of existing carbon markets is limited, an integration of agriculture and agroforestry into existing schemes and the adjustment of the schemes to favor regenerative practices which support carbon sequestration should be an important part of the political agenda.
- ***Develop policies for the supply of agricultural products that encourage sustainable soil management through public procurement where appropriate:*** The transition to sustainable soil management practices may in the first years raise costs and/or reduce yields for the farmer. As the current economic model mostly does not incorporate land degradation in production costs, the farmer should receive support from governments, markets and consumers in order to develop appropriate farming practices.
- ***Enhance research for soil carbon sequestration practices to generate knowledge to support actions:*** Best practices must be identified, monitored, verified, reported and promoted with science-based harmonized protocols and standards to increase reliable knowledge of successful approaches.

The potential for carbon sequestration in soils via agriculture can play an important role in mitigating climate change. However, although the calculated values do portray important contributions, the realistic feasibility to put all these techniques on a global scale into practice, in a short period of time, is somewhat limited. Nevertheless, as the benefits of regenerative agriculture is so manifold, improving soil fertility and plant health, storing larger amounts of water, reducing soil erosion, enhancing biodiversity, ensuring a better outcome for small farmers and many others, there should be an overarching interest in investing into regenerative agriculture methods.

Crop livestock integration

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