Chapter

The Role of Organic Fertilizers in Transition to Sustainable Agriculture in the MENA Region

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Abstract

Organic fertilizers can serve as an element of transitions to sustainable low-input agriculture in semi-arid regions of the MENA region. They play a key role in supporting soil biota and soil fertility. Yield improvements, availability and relatively low costs make organic fertilizers an attractive alternative for farmers. In semi-arid regions, important considerations are improved soil quality, which in turn affects soil water retention, while better root development helps crops resist heat and water stress. Organic fertilizers thus support climate adaptation and regional food security. Soil quality is crucial for carbon sequestration, at the same time that increased nutrient retention reduces impacts of agricultural runoff on groundwater and water bodies. Factors that impede the generalised use of organic fertilizers include lack of expertise, subsidy structures, constraints of the wider food and agricultural systems, and difficulties in transitioning from conventional agriculture. Such obstacles are aggravated in countries affected by security issues, financial volatility or restrictions in access to market. Against the background of both general and local constraints, the chapter examines possible pathways to benefit from organic fertilizers, in particular synergies with other sustainable agricultural practices, as well as improved access to expertise.

Keywords: organic fertilizers, sustainable agriculture, transition pathways, smallholder farmers, semi-arid regions, low-input agriculture, soil health, soil carbon, GHG emissions, conservation agriculture, water management, climate adaptation and mitigation

1. Introduction

Organic fertilizers are a highly diverse family of products used in agriculture for soil improvement and to provide nutrients. Their characteristics and benefits will depend on their origin and processing, as on how they are used or combined in particular contexts [1–5]. The main common denominator is therefore that organic fertilizers provide a sustainable option to avoid the negative impacts of chemical fertilizers for long term soil fertility [6], decrease vulnerability to climate stress and weather variability, while reducing the impacts of agriculture on the environment [7, 8].

The term 'organic fertilizers' refers to a very wide range of products, as do the terms chemical, inorganic or synthetic fertilizers. It is therefore exceedingly difficult to make sweeping generalisations concerning the respective benefits or characteristics of these types of fertilizers. The task becomes all the more challenging, since outcomes will depend on numerous factors. These include how the fertilizer matches soil characteristics, crops, climatic and topographical questions, landscape characteristics, but also irrigation and tilling practices, time and manner of application of the fertilizer, as well as details concerning source and manner of producing the fertilizer. Undesirable effects may result from inappropriate fertilizer production processes, and the presence of metals and other contaminants in source materials is a major concern [9, 10]. There are also challenges linked to the overall or local availability of source materials.

Using organic matter to improve soils is not only related to fertility, but also to effects on physical, chemical and biological soil properties, including aeration, permeability, water-holding capacity and nutrient preserving capacity [11]. Benefits will depend on the exact type of organic fertilizer used, as well as on soil characteristics [7, 11]. Organic fertilizers can be used alone, or in combination with other fertilizers. For instance, a study under experimental conditions suggests that under deficit irrigation conditions, a combination of chemical fertilizer with vermicompost produced better results than chemical fertilizer alone [12]. The use of organic fertilizers appears particularly interesting in conditions of stress and weather variability, while a tailored combination with micro-nutrients suitable for crop and soil enhances yields (see e.g., Parmar et al. [13]). However, much of the literature on fertilizers reduces outcome to the question of crop yield rather than resilience, and more specifically short-term gains in crop yield under normal circumstances.

The use of synthetic fertilizers was generalised as part of the so-called green revolution [14, 15], which stood for a vision of modernising agriculture through use of agricultural machinery, synthetic fertilizers, pesticides, and systematic improvement of crop varieties. The ambition was to dramatically increase food production, and thereby alleviate hunger globally, so the focus on short term crop yield is therefore not surprising. The vision of the green revolution was also very much part of an industrial paradigm, with a simplified vision of agriculture as resembling other industrial production processes, with a flow consisting of input and output, controlled process, and output, where success was measured in production units. Today, however, we have come to a realisation that this oversimplification brought with it a very high cost to the environment, human health, as well as a degradation of planetary conditions necessary for food production in the long term. Crop yields remain important, of course, but there are other implications of our choice of agricultural practices that equally need to be considered. While much of agronomical research investigates linear correlations between a small set of isolated factors under relatively stable conditions, Hou et al. [16] argue for the need to consider soil health holistically, dynamically and from an interdisciplinary perspective.

Besides the narrow focus on productivity, the industrial paradigm within which agriculture was placed has tended to favour a comparatively linear and mechanistic understanding, while disregarding the complexity of ecosystems below ground, above ground, and in water bodies. Soil exchanges gases and chemical substances with air, and aerosols from erosion, burning and vegetation affect cloud formation, precipitation and greenhouse effects [17–19]. Also, as farmers have always known, weather is highly unpredictable, and far from the controlled conditions that industrial production supposes. In view of current rapid climate change [20], farmers are facing increasing weather variability, a greater number of extreme events, and a greater extent of uncertainty with respect to future developments [21, 22]. The use of organic fertilizers alone is not sufficient to address these challenges but can, in combination with other sustainable agricultural practices, constitute an important ingredient in farmers' climate adaptation and mitigation strategies.

2. Agriculture in the Middle East and North Africa

Soil types, crops and trade patterns vary considerably across the Middle East and North Africa (MENA) region [23], but all countries are affected by water scarcity. The region comprises arid, semi-arid and hyper-arid areas, but even comparatively water-rich countries are affected by severe water stress [24], caused in part by economic incentives to cultivate water-intensive crops. Crop choice therefore plays an important role [25]. The water crisis is aggravated by deterioration of water quality caused by pesticides and nutrient runoff [26, 27], while groundwater is impacted by leaching and excessive pumping [28, 29]. Rural flight and decline of rural populations in several countries, such as Iran and Turkey [30] can reflect reduced need for labour due to mechanisation but may also reflect insecure livelihoods and difficult conditions of farmers [31, 32], while rural populations are also affected by displacement caused by disasters related to extreme weather, including forest fires, flooding and crop failure. The region is heavily dependent on imports of cereals. Both price fluctuations and transitions away from hydrocarbons globally will lead to decline in hydrocarbons exports on which many states of the region depend, affecting their ability to ensure food security through imports [23]. However, vested interests in exploiting hydrocarbons for the production of petrochemicals for agricultural use, as well as the existence of major phosphate deposits are likely to influence national economic diversification policies.

Large parts of the Middle East and North Africa are affected by protracted conflicts, internally displaced populations, and high volatility [33, 34]. Political and economic crises are affecting access to food, clean water and energy for large population groups [35], while agriculture is impacted by rising costs of fertilizers, pesticides, fuel and machinery, combined with disruptions to infrastructure and processing, storage and distribution systems for agricultural produce. These challenges will increasingly be aggravated by climate change [36–41] and environmental degradation. Consequently, resilient food systems and food security will become issues of major concern for the region [42, 43], highlighting the question of climate adaptation strategies for farmers [31, 44–46].

Research on organic fertilizers in the MENA region from an environmental perspective is as yet relatively limited. Thus, a Scopus search on October 14, 2021, with the search term 'organic fertilizers' yielded 517 articles and reviews in English concerning agricultural sciences in the MENA region for the period 2017–2021, compared to 6558 worldwide for the same period. Publications in this field were dominated by Iran, Iraq, Egypt and Turkey (92%). Only 102 (20%) of the 517 MENA publications related to environmental or earth and planetary sciences. Within these 102, a mere 5 directly dealt with water-related issues, (including keywords such as irrigation, water quality, water stress, arid regions or groundwater), and none of the overall 517 publications on organic fertilizers mentioned climate adaptation or mitigation. In view of the interrelated urgent challenges that climate change and food security pose for the region, I will therefore draw on the international literature, to situate the use of organic fertilizers with respect to these challenges.

3. Environmental impacts of agriculture

Climate and environmental impacts of fertilizer use and soil management practices include not only emissions and pollution from production of fertilizer [47], but also those linked to the mechanised and chemical-intensive agricultural production systems they are associated with, impacts of nutrient runoff and chemicals [48, 49] on receiving water bodies, as well as impacts connected to food processing, storage, transport and waste. Effects on the world's oceans are concerning. Unsustainable land use poses a threat for climate and biodiversity [20, 36, 50]. Agricultural land use and soil management practices are from a climate and environmental perspective of relevance for carbon storage [51], but also with respect to nutrient runoff, and persistent chemicals, and to emissions of N_2O and CH_4 [52]. According to the IPCC, the use of fertilizers has increased nine-fold since 1961 [53], and soil management accounts for half of greenhouse gas (GHG) emissions of the agricultural sector [54].

3.1 IPCC estimates of climate impacts and mitigation potentials

No global data are available specifically for agricultural CO_2 emissions, and there is considerable uncertainty concerning net balance of CO_2 land-atmosphere exchanges. However, land is an overall carbon sink, with a net land-atmosphere flux from response of vegetation and soils of −6 ± 3.7 GtCo2yr (averages for 2007–2016). The capacity of land to act as a carbon sink is expected to decrease as an effect of global warming. The major impacts of agricultural land use (food, fibre and biomass production) on CO_2 (5.2 ± 2.6 GtCo2yr) are connected to deforestation, drainage of soils and biomass burning rather than to the net flux balance directly caused by different fertilization practices. Numbers regarding CO_2 emissions from land use can be compared to net global anthropogenic CO_2 emissions, which are estimated at 39.1 ± 3.2 GtCo2yr. In addition to land use impacts, agriculture causes CO_2 emissions in the order of 2.6–5.2 GtCo2yr through activities in the global food system, including grain drying, international trade, synthesis of inorganic fertilizers, heating in greenhouses, manufacturing of farm inputs, and agri-food processing [55].

Agricultural land use directly represents 40% (4.0 ± 1.2 GtCo2eq yr) of total net global anthropogenic CH_4 emissions, and represents 79% (2.2 ± 0.7 GtCo2eq yr) of total net global N_2O emissions. CH_4 emissions are mainly caused by ruminants and rice cultivation. Half of N_2O emissions are caused by livestock, and the rest mainly by N fertilization (including inefficiencies). Total average net global GHG emissions (CO_2, CH_4 and N_2O) for all sectors 2007-2016 are estimated at 52.0 ± 4.5 GtCo2eq yr, of which agriculture directly contributes with 17-22% (not including impacts of agriculture on land available for forests), or 21-37% (including agricultural land expansion and other contributions of the food system) [55]. Importantly, agricultural soil carbon stock change is not included in these statistics. Irrigation and agricultural land management contribute to making forests vulnerable to fires, while desertification [37] amplifies global warming through release of CO_2, but such emissions as well as impacts from runoff on net fluxes from wetlands, water bodies and oceans are not included in the above figures.

Although net GHG emissions are often converted to CO_2 equivalents for accounting purposes, different gases remain in the atmosphere for different periods of time and will consequently have different impacts on the progression of global warming. The specific proportions of GHG will affect the likelihood of crossing critical thresholds and tipping points, setting off cascades (cf. Lenton et al. [56]) with ecosystem collapse and mass extinctions, while driving biophysical processes that further aggravate the dynamics. Effects of mitigation measures also have varying timelines.

The creation of reactive N in agriculture has significant environmental impacts [57], and excessive application of nitrogen can increase nitrous oxide emissions without improving crop yields [54]. On average, only 50% of N is used, but in countries with heavy N fertilization the efficiency can be much lower, and the potential for mitigation therefore increases [7, 36]. Use of fertilizer is responsible for more than 80% of N_2O emissions increase since the preindustrial era [58]. Ruminant livestock is the overall main source of CH_4 from agricultural practices [55, 59], and among organic fertilizers cattle manure has therefore been widely studied. Rice cultivation makes the greatest contribution to CH_4 emissions from agricultural soils [60]. Both water logging and soil compaction also contribute to CH_4 emissions [61].

4. Climate mitigation potentials in agriculture

In view of the imminent threat to planetary life systems posed by climate change [20, 56, 62], research has in recent years accelerated on potentials for carbon offsetting and impacts on GHG emissions of different land use and management systems [63–67], as well as with respect to climate adaptation [68] and food security [69, 70]. Large areas of the MENA-region are exposed to desertification, including relatively water rich countries. For instance, at least half of Turkey is affected [37]. Desertification amplifies global warming through the release of CO_2 linked with the decrease in vegetation cover, GHG fluxes, sand and dust. In dry areas, net carbon uptake is about 27% lower than elsewhere, reducing the capacity of land to act as a carbon sink. A rise in temperatures accelerates decomposition, at the same time that moisture is insufficient for plant productivity. Further SOC is lost due to soil erosion. An estimated 241–470 GtC is stored in the top 1 m of dryland soils [37]. In 2011, semi-arid ecosystems in the southern hemisphere represented half of the global net carbon sink [37].

Integrated sustainable practices are essential for climate adaptation, but estimates with respect to mitigation potentials vary. The chapter on interlinkages in the IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [8] considers technical and economic feasibility of possible mitigation measures, as well as impacts on livelihoods and human health. Some measures that specifically concern cropland and soil management are summarized in **Table 1**.

There is some overlap in the categories listed in **Table 1**, since different interventions could be envisaged for the same land, and the integrated measures discussed by Smith et al. [8] notably result in increased carbon storage in soils. The category

Improved cropland management	1.4–2.3*
Increasing soil organic matter stocks	1.3–5.1*
Reduced deforestation and forest degradation	0.4–5.8*
Reduced conversion of grasslands	0.7*
Agroforestry	0.11–5.68**
Reduced conversion of coastal wetlands	0.11–2.25**
Biochar	0.03–6.60**
Cropland nutrient management N_2O	0.03–0.71**
Manure management N_20 and CH_4	0.01–0.26**
Improved rice cultivation CH_4	0.08–0.87**
Reduced enteric fermentation CH_4 (ruminants)	0.12–1.18**
Soil carbon sequestration in croplands	0.25–6.78**

**[8].*
***[36].*

Table 1.
Yearly global climate mitigation potential of different interventions (IPCC estimates in $GtCO_2eq$ yr).

'improved cropland management' includes practices such as reduced tillage, cover crops, perennials, water management and nutrient management.

4.1 Uncertainties in estimates and critical issues

The type of management system that farmers adopt, will substantially determine the capacity of soil to act as a carbon sink, and the extent to which agricultural land will contribute to GHG emissions. However, estimates regarding the potential of agricultural soil management practices to mitigate climate change vary considerably, and have been calculated in various manners. While Minasny et al. [71] estimate that raising soil organic matter could offset 20–35% of total GHG emissions, Schlesinger and Amundson [72] believe that the combined use of biochar and enhanced silicate weathering on agricultural land will not offset more than 5% of emissions. Differences in what is included in calculations, as well as in assumptions regarding anticipated conditions and future projections naturally affect conclusions. Biochar has attracted considerable interest for its ability to improve soil fertility and immobilize pollutants, while offering potential for long term storage of carbon [51]. However, the stability of biochar and its long-term impacts will ultimately depend on conditions that affect biochar aging [73]. With respect to upscaling enhanced silicate weathering as a climate mitigation strategy, uncertainties and possible negative environmental impacts need to be taken into account [74, 75].

Types of organic fertilizer that contain organic matter will directly contribute to soil organic carbon (SOC) content, but fungi and microbes contained in certain types of organic fertilizer, as well as impacts of pH and the proportions of other nutrients and micro-nutrients, will all affect the dynamics of soil biota and ecosystems. This leads to indirect positive or negative affects not only on fertility, water retention and resilience, but also on net GHG emissions (see e.g., Galic et al. [7], Walling et al. [47], Xu et al. [52]). Among other factors, annual precipitation significantly affects SOC dynamics [37, 76], and must be considered in arid and semi-arid regions.

4.2 Carbon sequestration

Carbon stocks in agricultural soils have been depleted worldwide, affecting productivity (see Droste et al. [77]). However, these losses do not all necessarily correspond to release of CO_2 into the atmosphere, and Chenu [78] therefore makes the distinction between carbon sequestration, which aims to counteract global warming, and carbon storage in soils. Numerous approaches are developed to enhance carbon sequestration. In New Zealand, for instance, 'flipping' is used for podzolized sandy soils with pasture grassland, to avoid water logging. Burying topsoil led to long term SOC preservation, while new organic matter could accumulate in the surface soil under these conditions [79]. However, as for most practices, impacts will be dependent on local circumstances, since disrupting soil ecosystems will alter SOC dynamics, thereby carbon contained in above-ground vegetation or root systems, while exposure of topsoil can lead to erosion. Madigan et al. [80] compare different approaches to managing pasture and argue that full-inversion tillage (FIT) during pasture renewal has potential in an Irish context, particularly when combined with re-seeding.

While many of the approaches aiming at carbon sequestration and reduction of GHG emissions [65] bring benefits for agriculture through soil improvement, increasing water retention, reducing agricultural runoff and effects of heat stress, as well as conserving ecosystems, there are nevertheless risks associated with the need to rapidly offset GHG emissions produced by the burning of fossil fuels. From the point of view of agricultural production, organic matter is urgently needed to counter loss of topsoil and soil degradation, while equally urgent ambitions to rapidly achieve long term sequestration of carbon at a large scale, will reduce the amount of organic material available. Some approaches to carbon sequestration keep soil organic matter (SOM) in soil layers and forms that remain available to vegetation, while others such as flipping [79] bury the SOM in lower layers in order to slow down metabolic processes. However, yet others aim to bind carbon in forms that are not bioavailable or bury it in deep sediment or geological layers that remove both carbon and nutrients contained in organic waste from biological cycles.

Soil microbial activity is beneficial to crops and supports agricultural productivity but can also result in a net increase of GHG emissions, depending on balance and conditions. The use of agricultural lime to improve acidic soils can either lead to increased release of CO_2 in the atmosphere, or to carbon sequestration. For instance, Bramble, Gouveia and Ramnarine [81] found that combining the application of agricultural lime with poultry litter prevented CO_2 emissions. Finally, it is important to also consider energy conservation in climate mitigation strategies. Soil organic content substantially affects energy requirements, and Hercher-Pasteur et al. [82] therefore argue that this should be included when calculating optimal uses for biomass.

5. Sustainable agricultural practices

Choice of fertilizer cannot be understood in isolation, but as part of overall soil and land management practices in agriculture. In the following, some examples of sustainable practices are given, that are supported by the use of organic fertilizers, but which can also enhance their benefits. Combinations of approaches lead to synergies, not only with respect to bioavailability of nutrients, but also with respect to water balance, prevention of erosion [37], pest and pathogen control, and resilience to other stressors. For instance, improving tillage practices and incorporating residue was found to increase water-use efficiency by 30%, rice–wheat yields by 5–37%, income by 28–40%, while reducing and GHG emissions by 16–25% [8]. Further options of interest include perennial crops [83–85], polyculture [86], mosaic landscapes [87] and the use of pollinator strips or other habitat [88, 89], which support crop productivity through ecological intensification [90].

5.1 The role of soil health and microbial activity

Loss of soil health exposes crops to various diseases [54]. Among the numerous challenges for soil health in arid and semi-arid regions is the risk of salinization [37, 54, 91], which is driven not only by evaporation and low precipitation, but also by use of synthetic fertilizers and reduced moisture retention in soils with low content of organic materials. Soil organisms are essential for soil fertility, by making nutrients available to crops. A healthy soil ecosystem decomposes organic matter, makes nutrients available, prevents nutrient leaching and fixes nitrogen. It also protects plants from pathogens [54], improves soil structure and promotes well-functioning root systems. However, microbial activity can contribute to GHG emissions, and net effects under different conditions therefore need to be carefully considered.

The fungal to bacteria biomass ration (F/B) is one of the important indicators of soil health. Optimal F/B ratios depend on intended use. While grains and vegetables require bacterial dominance or a balance between fungi and bacteria, orchard trees need a dominance of fungi, which are more effective at immobilizing nutrients, preventing leaching. For grasslands, higher F/B ratios are an indication of more sustainable systems, with less environmental impacts [92]. It should be noted that biomass in itself is not a complete indicator for fungal and microbial activity [92] and that the distribution across various depths is also important for fertility and GHG flux dynamics.

Fiodor et al. [54] point to the potential use of specific plant growth promoting microbes (PGPM) that protect against a wide range of stressors and pathogens, and which can be applied by methods such as inoculation. Although microbial communities can in many respects be interchangeable from a functional point of view, unique strains of PGPM that mitigate effects of biotic and abiotic stressors are especially relevant in the light of rapid climate change. Research on how organic fertilizers can support such microbes is therefore called for, as is research soil ecosystems and plant-microbial symbiotic relationships (see e.g., Porter and Sachs [93]). Impacts of antibiotic residues in organic fertilizer [10] also require attention.

5.2 Conservation agriculture

Soil conservation practices are needed for sustainable productivity [94]. Conservation agriculture (CA) conserves soil moisture and reduces both erosion and runoff, improving water quality, as well as promoting biodiversity and above-ground ecosystems [95], with potentials for pest control and pollination. CA has been found to reduce water use substantially, as well as decreasing energy inputs [96]. It is of particular interest under extreme climatic conditions, due to its ability to mitigate heat and water stress, thereby increasing crop yields [96] and resilience.

In an Indian context, Battacharya et al. [94] compared performance of CA practices with farms applying conventional tillage over a nine-year period, using a wide range of measurements for soil health and sustainability. In this Indian study, conservation agriculture was shown to increase SOC, while requiring low input. However, Palm et al. [95] underline that CA will not necessarily increase soil carbon sequestration in all contexts. In studies they reviewed, only about half reported increased sequestration with no-till practices. Furthermore, in Sub Saharan Africa, Palm et al. [95] found that lack of residues was a significant obstacle to implementing CA for smallholder farmers. Use of organic residues for soil amendment in these contexts competed with other uses that had higher values, primarily as fodder for livestock. They conclude that it is important to distinguish between high-input CA systems applied in large-scale mechanised farms, and which require large inputs of herbicides to control weeds, with conditions for smallholder systems in the tropics and subtropics.

5.3 Tillage practices

No-tillage systems and suitable cover crop management can improve SOC, total N, available P, exchangeable K-Mg, CEC, bulk density, soil penetration resistance, and substrate-induced respiration, as exemplified in a Japanese study concerning Andosols [97]. Inversely, tillage will increase microbial activity that contributes to emissions, accelerate decomposition, but the disturbance will reduce microbial communities over time [97]. However, according to the review made by Palm et al. [95], no-till systems in cooler and wetter climates are more likely to result in lower soil carbon and reduced crop yields.

5.4 Cover crops

Cover crops conserve water, moderate soil temperature, and help to control weeds. Cover crops can further increase fungal biomass and improve the biological structure of soil [92]. Long-term use of cover crops improves soil fertility through the accumulation of SOM [92]. Disrupting soils through tillage kills fungi, and therefore shifts the balance towards bacteria. Legume intercrops or cover crops can lead to higher soil carbon storage and slower decomposition in no-till rotation systems [95]. Palm et al. [95] found that while quality of organic inputs affected short-term carbon dynamics, it did not appear to substantially affect long-term storage. Quality could be modified by addition of lignin. Materials with a high carbon to N ratio could result in reduced crop yields, while residues with a lower C:N ratio, as in the case of legume residues and legume cover crops, increased N availability. Legumes are not only of interest for their N-fixing properties, but for other facilitation effects as well [98–100].

5.5 Agroforestry

Agroforestry brings benefits for soil fauna and generally improves soil quality [101–103], and soil organic carbon sequestration [51, 104]. Depending on conditions, reduced light can affect yields of crops that are grown with trees, but agroforestry is also deliberately used to provide shade and create beneficial microclimates to mitigate heat stress and loss of water through evapotranspiration, as well as to adjust for lower or more variable rainfall [105], which is highly relevant for arid and semi-arid regions. With global warming, weather systems will contain more energy, and agroforestry therefore can play a role in preventing erosion and loss of soil from wind [37], as well as from extreme rainfall. Agroforestry systems can offer valuable habitat for pollinators and fauna essential for pest control, but trees should be selected for climate resilience and the precise combinations of species of orchards, crops or other vegetation in these systems needs to be considered, as well as spacing, orientation and adjustment to topography.

6. Water conservation and pollution prevention

Major landscape changes, with loss and deterioration of wetlands [26, 106], mean that nutrient flows from agriculture rapidly move on into the oceans, destabilizing ecosystems [107]. Drainage, to claim land for agriculture or other purposes, and extensive irrigation in agriculture cause wetlands to dry [108], while other drivers of wetland loss are urbanisation and surface sealing for road networks, industrial use of water and large dams. With climate change, water is no longer released gradually over the year through snow smelting, and forest fires [41], use of woodlands for fuel or commercial logging create additional disruptions in the water systems on which wetlands depend [109]. The amount of carbon stored in wetlands and peatlands constitutes in the order of 30–40% of terrestrial carbon [110, 111].

According to UN Water, 72% of all water withdrawals globally are used by agriculture [112]. Besides practices such as no-till, reduced till, cover crops or terracing and contour farming to retain water and reduce erosion [37], leaving crop residue on the surface also serves these purposes [113]. Importantly, demand for water can be further reduced by supporting complex agricultural landscapes that include trees and other vegetation, and by shifting to crops and cultivars that require less water. Alongside conventional approaches to water conservation such as drip irrigation, such approaches are necessary to address the water crisis, which will in many regions be aggravated by climate change [39–41]. For arid and semi-arid regions in particular, conservation agriculture and other sustainable practices are crucial for their role in preserving soil moisture and reducing irrigation needs. Both organic fertilizers and other methods of increasing SOM play a role in reclaiming land and combatting desertification [8, 37, 59, 99, 114–116]. Several solutions to the issue of polluted water [26, 106] have been suggested, including phytoremediation or the use of agricultural waste to serve as biosorbants [117–119].

Bhattacharyya et al. [120] suggest nutrient budgeting as an effective approach to preventing soil-water-air contamination from crop-livestock systems. Excess nutrients do not only impact rivers, lakes and coastal waters, but also affect groundwater quality [28, 29]. Nutrient surpluses are linked to use of fertilizers and manure, as well as to low nutrient utilization efficiency of plants. Leaching, runoff and erosion are therefore all significant for sustainable agricultural practices. In this respect, a slower release of nutrients and improvements in soil structure are important potential benefits of organic fertilizers, compared to chemical fertilizers. Contributions to soil and ecosystem health of sustainable practices reduce the need for pesticides to control pests and pathogens, thereby increasing availability of good quality water [49] and protecting the world's oceans [121, 122].

The various interlinkages and trade-offs that need to be considered in use of water resources are acknowledged in European policy on the water, energy, food, and ecosystems (WEFE) nexus [123], as well as in recent research in this field [124–127]. Both general conflicts in demands concerning use of land and resources, and water scarcity, in particular, affect the arid and semi-arid regions of the MENA region. For these regions, land management must pay greater attention to how soil health and quality affects water retention. Degraded soils have poor water retention capacity, demand more fertilizer, and are less able to contribute to carbon sequestration. A more holistic view of land and soil management can also mitigate effects of stress caused by heat, extreme weather events and increased climate variability.

7. Transition issues

Conservation agriculture can lead to yield benefits, but improvements may not be noticeable in the initial years [94]. In a Swedish context, examining various sites over a period of 54 years, Droste et al. [77] find that increasing SOC leads to long-term yield stability and resilience, which is important in view of accelerating climate change. However, adopting sustainable management practices can come at the cost of short-term productivity. Policy changes to support the transition are therefore recommended [77, 128]. To minimise initial economic impacts for farmers of conversion, Yigezu et al. [46] and Tu et al. [129] recommend transition strategies that involve gradually reducing conventional inputs.

Sustainable agricultural practices achieve control of pests and pathogens without damaging the environment, but these practices are also largely dependent on healthy soil biota and rich ecosystems in the agricultural landscape. Agricultural soils have been affected by numerous sources of pollution [130]. Soil management practices and use of chemicals will have negative effects on many soil invertebrates and microbes [131, 132] but will favour others. The net effect is therefore not only loss of important strains of soil biota or total mass, but the creation of imbalances in microbial communities that can have detrimental effects for plant health and crop yields.

Since soil health and ecosystems have been damaged by prior unsustainable practices, including use of synthetic fertilizers and pesticides, restoring health takes time, and processes of remediation and restoration are therefore crucial [59, 77, 132–134]. The ability of new cultivars to benefit from plant-microbial symbiosis has been affected by selection of cultivars for other traits, and by reduced dependence on this symbiosis through the use of synthetic fertilizers [93]. Transition to sustainable farming with organic fertilizers should therefore also consider the choice of suitable cultivars and heritage varieties that retain the ability to fully benefit from improved soil health.

8. Smallholder farming and sustainable agriculture

It is difficult to evaluate the magnitude of smallholder and subsistence farming world-wide, since it is frequently undertaken in regions with limited statistics, on fragmented or mixed-use plots where land-use can be difficult to identify from satellite images. In many contexts, it is not necessarily the primary occupation of the farmer. Despite its marginal position in debates on agricultural productivity, smallholder farming plays a vital role for biodiversity, food security, human health, equity and climate resilience, since value is not lost in the distribution chain but stays with producers and their communities. Locally sourced food reduces community vulnerability to disruptions in the food supply chain, due to disasters, logistics failures, financial crises, or armed conflict. The latter consideration is significant for the MENA region, where several countries are affected by conflict or volatility [33]. Food systems worldwide are exposed to numerous disruptions, which will increase as a result of climate change and environmental degradation [69]. Smallholder farmers are particularly vulnerable to such shocks and have difficulties making adequate choices in the face of uncertainty [21, 22, 31]. To address such challenges, Kim et al. [70] suggest a land-water-nutrient nexus (LWNN) approach (see also Jat et al. [96] for strategies from an Indian context). Crop diversification can be a strategy to meet the double uncertainty of price fluctuations and crop failures [135], and polycultures also have environmental benefits. However, food processing industries and international markets tend to be oriented towards monocultures, and smallholder farmers can be obligated by contracts to produce particular crops.

Low-input smallholder production systems are one of the dominant food production systems globally [136]. In an Ethiopian case, Baudron et al. [136] observe that complex agricultural landscapes that incorporate trees offer better overall livelihoods for farmers, lead to better carbon balances, as well as being more resilient both to fluctuation in input prices and to climate stress. They further underline that low-input farming with resource-saving practices can increase profitability for farmers more than yield optimization, while yield stability is another important consideration for smallholders.

Baudron et al. [136] therefore argue for an increased attention to agricultural practices that support synergies between agriculture and biodiversity, rather than presenting the situation as an irreducible choice between 'land sparing'—aiming to reduce demand for land through intensification— and 'land sharing', assuming loss in yields, as a consequence of practices that are more favourable to wildlife and biodiversity. Baudron et al. emphasize the reliance of low-input smallholder agricultural production on ecosystem services provided by biodiverse ecosystems, and further point to the crucial role of ecosystem services to maintain soil fertility, pollination, and for pest and disease control [136, 137].

Despite the benefits that low-input farming can bring [138], barriers include lack of locally relevant expertise, and the time needed to rehabilitate soils degraded by use of synthetic fertilizers and pesticides. Subsidy systems may support heavily mechanised and chemical-intensive agriculture [3, 14], with questionable benefits for smallholder farmers. Further barriers in transitioning to sustainable agricultural practices are access to markets, and global food systems structured to favour monoculture of particular crops and cultivars.

9. Conclusions

In view of the numerous factors that influence outcomes for the use of organic fertilizers, locally tailored strategies that combine approaches to enhance soil health and sustainable land management would be recommended. However, sufficiently detailed data is still lacking on how different management practices affect yields and environmental impacts depending on local conditions, particularly in the global South. Citizen science has the potential to offer a better evidence base for farmers' choices, but the structure of many citizen science projects rarely supports longer term collaboration and dialogue with smallholder farmers in the global South [139, 140]. In addition, smallholder farmers may not be able to afford individualised consulting, and agronomists may lack expertise applicable to low-input agriculture. Transitioning to sustainable practices is knowledge intensive [44], and this is therefore an area where international networking with academic institutions could play a significant role in supporting climate adaptation and mitigation efforts. Exchange of knowledge among farmers [141] and farmers' organizations can also play a role for mobilizing resources and expertise, but such potential contributions will depend on the orientation of the organization [142].

Among other implications of the current climate crisis, a narrow focus on crop yields is not sufficient, since outcomes of fertilizer application are usually estimated under optimal or normal growing conditions. Increased weather variability and the ensuing risk of crop failure, means that greater attention must be devoted to resilience, and the capacity to cultivate under unpredictable and less than optimal conditions. This in turn means, for instance, that effects on root growth, the capacity of root systems to absorb water and nutrients under extreme conditions, as well as the capacity of the soil to retain water and nutrients over longer periods of time all become critical factors. Also, rather than considering fertilizer application merely from the view of inputs and short-term yields, and besides measures such as C:N ratios, we need to take on a more holistic view, looking at how choice of fertilizer relates to nutrient absorption efficiency, drought resistance of root systems [143], soil health, land degradation, water management and ecological intensification. Future shortages of P [144–146], loss of arable land [37], decline in soil carbon [147], as well as widespread decline in soil fertility driven by industrial practices in agriculture, point to the important role of organic fertilizers. However, availability of organic material is constrained by competing demands on biomass and land for industrial and carbon sequestration purposes, while contamination of organic waste and wastewater [10, 118, 148] poses an issue for possible circular approaches. To generalise the use of organic fertilizers, redesign of food systems and policy changes are therefore required, adopting a more comprehensive approach to the complex interlinkages that are involved.

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