

Review

Soil and Crop Management Strategies to Ensure Higher Crop Productivity within Sustainable Environments

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Abstract: The rising population and reduction in the amount of land and some other resources have created tremendous pressure on current agricultural producers to meet the increasing food demands. To cope with this challenge, certain key inputs, such as fertilizers and other chemicals, are overused, which are worsening the surroundings. This intensive agricultural production without adherence to ecological sustainability has led to declining soil health, land degradation, and severe environmental problems. So, future efforts to feed the growing population should aim for greater agricultural production within sustainable environments. In this regard, innovative steps are needed, as business-as-usual policies lack the potential to cope with these challenges. The concept of agricultural sustainability and various soil and crop management strategies (SCMS) that have been designed to optimize crop yield under sustainable environmental conditions are discussed, including nutrient management, site specific nutrient management (SSNM), integrated nutrient management (INM), integrated soil fertility management (ISFM), integrated soil-crop system management (ISSM), ridge-furrow mulching systems (RFMS), sustainable water management (SWM), conservation agriculture (CA), sustainable land management (SLM), vertical/sky farming, and integrated crop management, and breeding strategies as well as other approaches combined with technological and behavioural changes. The present review suggests that a sustainable production system can be developed by combining the multifaceted efforts under SCMS practices with short- and long-term preventive measures. Reducing chemicals' usage, such as that of fertilizers and pesticides, plus improvements in the crop input use efficiency could minimize greenhouse gases emissions while protecting the environment. Sustainable agriculture holds promise for humankind and the planet Earth, and it can be successful if all developed and developing nations stand together to seek 'our common future' to produce more food while generating less environmental pressure.

Keywords: agricultural sustainability; soil tillage; land degradation; soil erosion; greenhouse gas emissions

1. Introduction

Since prehistoric times, agriculture has occupied a pivotal role in the lives of humans, considering their dependency on it for the provision of basic needs, such as food, clothing, and shelter. Cereals, such as wheat, rice, and maize, are the major constituents of our diets that are responsible for fulfilling most of the calories that we need [1]. Due to the vagaries of nature, climatic factors, such as temperature, rainfall, and CO₂, are key components that determine the productivity of a crop [2], and all such climatic factors have consensually been reported to change [3]. The increasing demand for crop production coupled with the high cost of energy based inputs and the decreasing trend in farm

incomes have led to severe economic problems for conventional agriculture [4]. Our agricultural systems are so diverse in terms of the ecology, socio-economic status plus historical and political context that it is imperative to devise flexible and locally adjustable strategies for the resiliency and sustainability of agro-ecosystems of the near future [5].

Modern agricultural science and molecular biology technologies have boosted the production of cereal crops over the past few decades through the development of new germplasm, but there has been evidence of yield plateaus or decreasing yield gain rates in recent years. For instance, CIMMYT (the International Maize and Wheat Improvement Center) estimated that the potential progress in cereal yield has been decreased to approximately 0.5% per year during recent decades, and the rate even stagnated in Europe [1]. China is no exception as the annual growth rates of cereal yields have gradually declined from 4% in the 1970s to 1.9% in the 1990s, and even maize and rice yields have declined or have stagnated in most provinces since the 2000s [6]. Thus, increasing the yield potential through both modern breeding technologies and innovative crop/soil management practices have been regarded as important strategies to overcome the barrier of ensuring higher crop productivity with less environmental impact. The present study aims to review the concept of agricultural sustainability, and the various soil and crop management strategies (SCMS) that have been designed to optimize crop yield under sustainable environmental conditions.

2. Future Food Demands

Questions have been raised over the ability of the agriculture sector to keep pace with the nutritional demands in the near future. Such concerns can be attributed to the fact that agriculture not only fulfils the food demand of approximately 9.5 billion people, but is also responsible for numerous other additional services ranging from purification of water and waste management to the production of fibre, fuel, and chemical products as well as biodiversity conservation and recreation [7,8]. Moreover, the ever-growing human population further exacerbates the problem by additionally increasing the demand for food. To meet the global target of 70% more food by 2050 [9], an average annual increase in production of 43 million Mg is required (Figure 1a). Data regarding cereal production worldwide since 1960 are shown in Figure 1, depicting a constant increase in production. However, it is worth-mentioning that the current increase of 31 million Mg year⁻¹ will not be able to keep pace with the future need of an annual increase of 43 million Mg (an increase of 39%).

The harvested area under cereal crops and their average yields per unit area globally (including the USA and China, both of which are the largest cereal producers) are presented (Figure 2a,b). A dramatic increase in the yield of cereal crops per unit area has been observed throughout the world, including both China and the USA (Table 1). This increase in cereal production can be attributed to the improved per unit area yield instead of the harvested area. It is also evident that future projections of cereal production should come from even further enhancements in per unit area crop yield rather than an increase in harvest area (for which a declining trend has been observed since 1960) (Figure 1; Table 1).

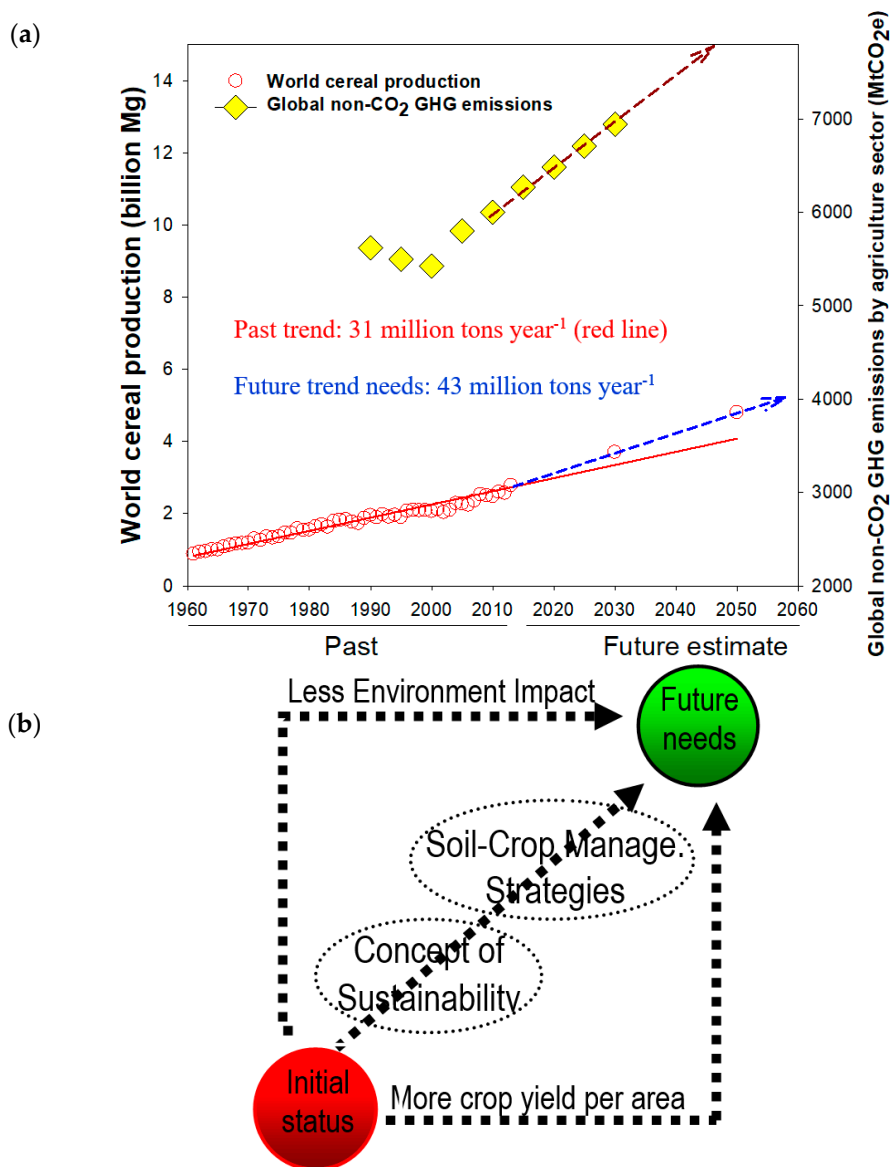


Figure 1. World cereal production targets and global non-CO₂ greenhouse gas emissions (a), and concept model (b) of higher crop productivity and less environmental impact, which can be achieved through the implementation of several soil-crop management strategies originating from the concept of sustainability. To meet the demands predicted by the FAO (2009), cereal production will need to increase to over 4 billion metric Mg by 2050 (blue line). The rate of increase of the cereal yield must move from the red trend line (31 million metric Mg per year) to the red line (43 million metric Mg per year) to meet food demand, an increase of 39%. World cereal production data (billion Mg) are from the FAO: <http://faostat.fao.org/>. The future demand for yield increases will be mostly from countries in the developing world based on FAO (2006) (<http://www.fao.org/docrep/009/a0607e/a0607e00.htm>). The data of global non-CO₂ greenhouse gas emissions are obtained from United States Environmental Protection Agency (<http://www.epa.gov/climatechange/EPAactivities/economics/nonco2projections.html>). Non-CO₂ greenhouse gases indicate methane, nitrous oxide, and fluorinated greenhouse gases, which contribute significantly to climate change. Historical estimates are reported for 1990, 1995, 2000, and 2005, and projections of emissions are provided for 2010 to 2030. Figure 1a is adopted from Wu and Ma (2015).

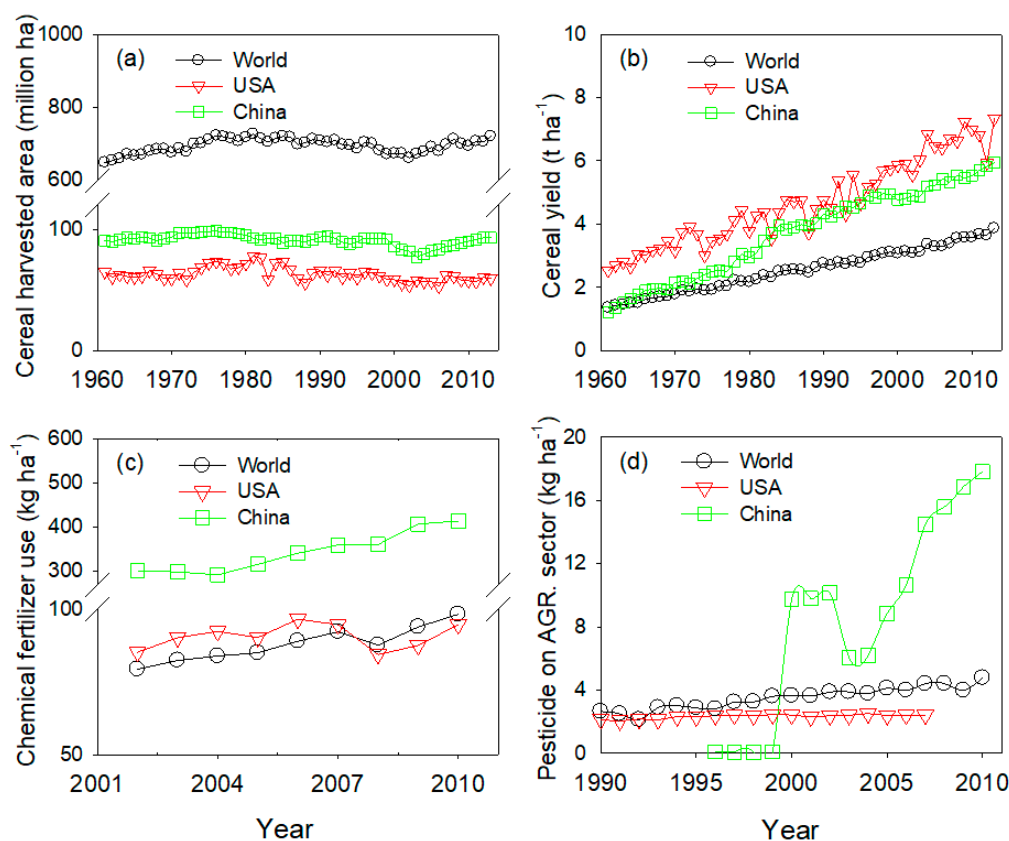


Figure 2. Cereal harvest area since 1960 (a), cereal yield since 1960 (b), chemical fertilizer use since 2002 (c), and pesticide use by the agriculture sector since 1990 (d) for the world, the USA, and China. The pesticide data are the quantity of pesticides applied to crops and seeds in the agriculture sector, which is expressed in “kg” of active ingredients per hectare. Additional information is available at <http://faostat.fao.org/site/424/default.aspx#ancor>. Chemical fertilizer mainly includes nitrogen and phosphate fertilizers on arable and permanently cropped area expressed in kg per ha. The data for the world are the average values across all countries. The data used for these figures are from the FAO (<http://faostat.fao.org/>).

Table 1. Past trends in cereal harvest area, cereal yield, chemical fertilizer use, and pesticide use by the agriculture sector per unit area. The absolute trend for each trait was estimated by linear regression using the equation: $y = ax + b$ (where “y” is the value of the trait; “x” is the year; “a” is the absolute trend; and “b” is the intercept). The relative trend for each trait was then calculated by the equation: relative trend = absolute trend/averaged value.

Trends	World	USA	China
<i>Cereal harvested area</i>			
Mean value (million ha)	693.8	62.9	91.1
Absolute trend (million ha year ⁻¹)	0 ^{ns}	−0.15 ^{**}	−0.17 ^{**}
Relative trend (%)	0 ^{ns}	−0.25 ^{**}	−0.18 ^{**}
<i>Cereal yield per unit area</i>			
Mean value (t ha ⁻¹)	2.53	4.67	3.72
Absolute trend (kg ha ⁻¹ year ⁻¹)	44 ^{**}	84 ^{**}	90 ^{**}
Relative trend (%)	1.74 ^{**}	1.8 ^{**}	2.42 ^{**}

Table 1. Cont.

Trends	World	USA	China
<i>Chemical fertilizers use per unit area</i>			
Mean value (kg ha ⁻¹)	87.9	90.6	342.4
Absolute trend (kg ha ⁻¹ year ⁻¹)	2.08 **	0.31 ^{ns}	15.94 **
Relative trend (%)	2.4 **	0.30 ^{ns}	4.7 **
<i>Pesticide use on AGR sector per unit area</i>			
Mean value (kg ha ⁻¹)	3.49	2.33	8.43
Absolute trend (kg ha ⁻¹ year ⁻¹)	0.11 **	0.02 **	1.27 **
Relative trend (%)	3.07 **	0.82 **	15.1 **

“**” indicates the line regressions between year and trait were significant at $p \leq 0.01$, whereas “ns” indicates non-significant using correlation analyses (Statistix, 2003). Data of cereal harvested area and cereal yield are from 1961 to 2013. Data of chemical fertilizers use are from 2002 to 2010, and pesticide use from 1990 to 2010. All data are originated from FAO (<http://faostat.fao.org/>).

Modern agricultural technologies have made it possible for farmers to utilize ample land, modern machinery, and improved inputs to bring under cultivation even bigger farms, thus further increases in productivity can be realized through better varieties, efficient water utilization, and the investment of capital in addition to the availability of fossil fuel energy and other agricultural related chemicals [10]. However, improvements in the overall performance of the prevailing crop production units must strive for innovative strategies if the objective of these is to deal with the dual challenge of enhancing yield to fulfil the increasing dietary needs and ensure environmental sustainability [11]. Thus, globally concerted efforts are needed to ensure maximum crop productivity with minimum environmental pollution as no single option can entirely satisfy the nutritional needs of the rapidly increasing human population. To accomplish the growing food demands of the rising population through environment friendly and socially acceptable methods, changes are required in the production, storage, processing, and distribution that are as revolutionary as those observed in previous major revolutions, such as the green revolution [1].

3. Environmental Concerns

Further yield improvements pose considerable challenges for researchers because of the unprecedented changes in global warming and its related uncertainty [12]. Currently, it is not only the nutritional demand, but rather various other types of needs, such as energy, water, wood products, and land for urbanization, infrastructure development, and the disposal of urban and industrial wastes, have become imperative [13]. According to Godfray et al. [1], the current objective is much more complex in nature than only maximizing crop production as it urges an adjustment to a much more comprehensive system of crop growth, ecology, and socially acceptable results.

After the IPCC's 2007 report, greenhouse gas (GHG) emissions have increased up to 49.5 billion Mg (gigatons or Gt) of CO₂eq during 2010, which was greater than all earlier reported extremes having an estimated uncertainty of $\pm 10\%$ for the 90% confidence interval [14]. Both China and the USA are two of the largest producers of GHG emissions that together contribute almost 42% of the total value (http://cdiac.ornl.gov/trends/emis/tre_coun.html). Greenhouse gases other than CO₂, such as nitric oxide, methane, and other CH₄ and fluorine containing gases, are major contributors to climatic changes [15], and one of the most significant contributors of these non-CO₂ GHGs is the agriculture sector. This is evident from the fact that in 2005, almost 82% of non-CO₂ GHGs emission was due to the agriculture sector in Central and South America; there, non-CO₂ GHGs have more significant effects on climate change than CO₂ on a per-ton basis. Data regarding global GHGs emissions other than CO₂ by agriculture are presented in Figure 1a; after a minor decrease during the last decade of the 20th century, emissions have increased consistently and are expected to rise even more in the future.

Thus, promising strategies to reduce the GHGs emissions with less environmental impact are needed for the future (Figure 1b). Similarly, the global temperature is expected to increase by 2–4 °C till

the end of the 21st century [14]. Most of these GHGs and even climate change are involved in complex interactions not only with the vegetation, but also with one another, which makes the situation even more serious.

Global urbanization has also disturbed the ratio of agricultural production to the global world food supply. According to Satterthwaite et al. [16], worldwide, the ratio of rural to urban dwellers was 6.7 to 1 in 1900, which was reduced to less than one during 2010, and it is expected that till 2025, this ratio will change to 0.67 for rural versus urban dwellers. The scarcity of available land due to urbanization is putting unprecedented pressure on farmers to produce more food from this depleting resource. Consequently, the use of various inputs, such as synthetic fertilizer, has tremendously increased in the recent past. The overuse of chemical fertilizers and in particular that of nitrogen is significantly contributing to the emission of GHGs, eutrophication, and thus environmental degradation.

A comparison between China and the USA and the rest of the world shows that China uses significantly more chemical fertilizers and pesticides per unit area in agriculture each year (Figure 2c,d; Table 1), and since the last decade or so, the gap between China and the USA has further widened. Using such large amounts of chemicals (both fertilizers and pesticides) is adding to the already high GHG emissions, especially in China. However, even at higher nitrogen and pesticide application rates, the average yield per unit area is lower in China than the USA, suggesting that the fertilizer use efficiency is significantly greater in the USA than in China. Certainly, there is an immense need to search for novel strategies that can ensure better crop productivity on the one hand and on the other also have the potential to guarantee environmental sustainability.

Decreasing chemical inputs through balanced fertilization or integrated nutrient management (INM) can lessen the use of inorganic fertilizers and may reduce the emission of GHGs, as has been reported by many earlier researchers [17–19]. Figure 1b vividly illustrates various approaches to fulfil future needs (increased crop yield and less environmental impact) based on the current status (low crop productivity level) by combining the SCMS strategies with the concept of sustainability.

4. The Concept of Agricultural Sustainability

Agricultural practices are the key determinants of the level of food production and are mainly responsible for the status of our environment [9]. Unfortunately, most of these practices, like using increasing inorganic fertilizers and other chemicals, that guarantee higher yields are not environmental-friendly and sustainable strategies, which is why the gap between the production and consumption of most agricultural commodities has widened at an alarming rate for the last decade and a half (Table 1), and this luxuriant use of farm inputs poses a great threat to our environment. The current scenario not only demands that crop productivity must be increased, but that it should be done in a sustainable way that promises greater social, economic, and environmental security. To achieve such goals, researchers must fully strive for the identification of innovative strategies for sustainable crop productivity, increased efficiency of inputs in addition to the protection of the remaining natural resources and agro-ecosystems [20].

However, a lack of unanimity over the key concepts of agricultural sustainability is a main hurdle towards durable progress based on minimizing the effects of certain agricultural practices on the environment, society, and even the economy [21]. Although, the term, sustainability, has moved from a conceptualization to the improvement of analytical tools, anthropogenic interruptions are leading to increases in growing ecological tremors [22]. Long-term sustainability is one of the ultimate goals that improves the overall performance of agricultural systems and reduces threats to the health of humans and ecosystems [23,24]. According to Godfray et al. [1], the theme of sustainability is based on the phenomenon that resources should not be used at rates higher than the capability of the Earth to substitute them. Similarly, Kesavan and Swaminathan [25] suggested that agricultural sustainability, in its simplest sense, should connote the concept of the maintenance of the quantity and quality of agricultural produce over the long term, without signs of fatigue.

Sustainability in agriculture aims for the obtainment of a multifaceted set of objectives, which are potentially long lasting. In this regard, agricultural sustainability can be defined as the science of producing crops in a way that is best suited to humans' welfare and resource use efficiencies and, at the same time, are environment friendly (Figure 3). Their suitability should not only be limited to the welfare of human beings, but also to all other living organisms [21]. The concept of sustainability is also based on the models of resiliency (the potential of a system to withstand stresses and shocks), persistency (the ability to stay effective for longer periods), and considers a diversified set of socio-economical and environment friendly returns [26]. Based on the definition of Tilman et al. [9], agricultural sustainability comprises the strategies that are responsible for accomplishing dietary and clothing demands under secured environments, along with guaranteeing a better life through an overall enhanced welfare of society while also focusing on an acceptable cost benefit ratio for producers.

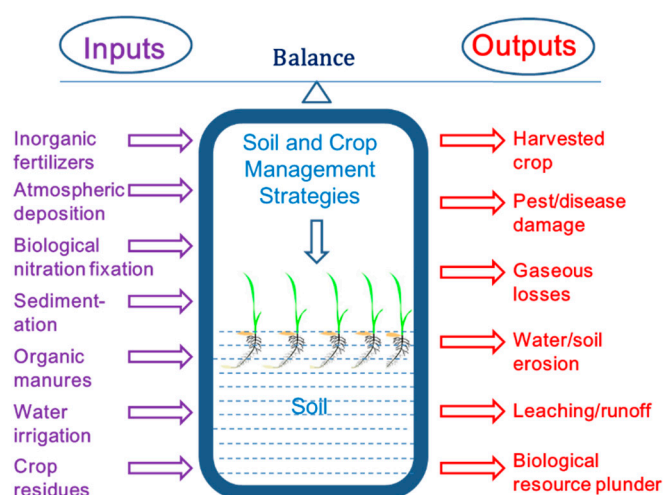


Figure 3. The nutrient budgets between inputs and outputs. This figure is adopted from Gruhn et al. (2000) and Wu and Ma (2015).

The concept of agricultural sustainability needs to be reconsidered in the context of the high demand for increasing crop production in resource poor countries due to their rising populations [13] as follows: (i) Enhancement of the productivity per unit time, area, and key inputs, such as water, fertilizers, and energy; (ii) optimization of the use of off-farm inputs; (iii) maximization of the income of households via increasing production, trading carbon credits, off-farm employment, and value addition of farm produce; (iv) improvement of the quality and quantity of fresh water resources at the farm level; (v) provision of educational opportunities, especially for women; (vi) creation of clean household cooking fuel for rural populations to improve the health of women and children and spare animal dung and crop residues for use as soil amendments; and (vii) addressing the concerns of farming families, especially food security until the next harvest.

A more comprehensive discussion of the concept of agricultural sustainability can be found in Pretty [26], who described the following main aspects of: (i) Integration of ecological and biological processes for instance nutrient cycling, N fixation, soil regeneration, allelopathy, competition, predation, and parasitism into food production processes; (ii) minimization of the use of non-renewable inputs that cause harm to the environment or the health of farmers and consumers; (iii) making productive use of the knowledge and skills of farmers, thus improving their self-reliance and substituting human capital for costly external inputs; and (iv) making productive use of the collective capacity of people to work together to solve common agricultural and natural resource problems, such as pests, watershed, irrigation, and forest and credit management.

Predicting future trends for agricultural systems while considering complex and interlinked environmental and socio-economic factors is an enormous challenge [27]. Due to agro-ecological constraints, it is difficult to achieve long-term global agricultural sustainability, which is faced with

the challenge of sustaining global food security despite a rapidly changing climate. A thorough understanding of the complex dynamics of the occurrence of multiple abiotic stresses and the prevailing strategies by which plants tolerate, avoid, or escape such harsh climatic conditions is thus crucial [28]. To counteract such harsh environmental conditions and the issues of feeding the rapidly growing population, serious attention must be paid by all sections of the community as no single option exists that can fully mitigate this threat.

Another facet of agricultural sustainability that makes it difficult to achieve is that many of its components interact with one another and sometimes are in conflict. Nutrient use efficiency has been recognized as an integral component of agricultural sustainability [29]. However, another aspect that also needs to be considered seriously is that a shift towards sustainable agriculture may incite secondary problems. For instance, if the land is not allowed for grazing for rehabilitation purposes, those lacking feed will be left with no choice but to sell their livestock, and in the case of an increase in cropping intensity if new lands are to be brought under cultivation, then the added workload will most probably fall on women [26].

5. Soil Management for Sustainable Agriculture

It has long been realized by agricultural scientists that soil management practices are not only pivotal for maximizing the production of agricultural commodities, but are important for controlling the increasing environmental pollution [30]. Thus, attention must be paid to not only protecting soil from erosion (which directly leads to land shortages), but also to adapt practices that avoid soil contamination and degradation.

Soil erosion and land degradation represent critical threats to ecosystem services and agricultural productivity, and such a loss of natural capital assets particularly occurs in semi-arid and tropical regions, where agronomic inputs are low and vegetation cover is poor [31,32]. The erosion of soil by water and wind are key processes degrading the surface structure of exposed soil by which topsoil is lost, which impairs soil fertility and results in unsustainable agriculture [31]. Recent investigations have indicated that land degradation will continue due to the great increase in global GDP by 2050 [33], so to achieve future food security, sustainable soil management via efficient management of nutrients and suitable conservation practices for soil are some of the key challenges [34]. Multifaceted investigations are direly needed to circumvent permanent deterioration of soil resources by erosion or pollution since soils are not renewable.

As a fundamental component of terrestrial ecosystems, most living organisms are sustained by soil, which is also the key supplier of their nutritional requirements [33]. Managing soil organic carbon (SOC) is of the greatest importance as soil organic matter is directly related to numerous soil properties that are relevant to ecosystem functioning [30]. Even small changes in this large carbon (C) stock can change the atmospheric CO₂ concentration, which affects the global carbon cycle and even climate change. For instance, the C store within 0–30 cm of the soil surface is estimated to contain approximately 700 Pg organic C, which is equal to twice the quantity of C in the atmosphere as CO₂. This great C stock in soils represents both an opportunity and a threat to the global C cycle and climate change [35]. The challenge is to manage soils to sequester additional C from the atmosphere, which can be achieved by the SCMS practices described below, while sustaining higher crop productivity.

An increase in SOC content indicates an accumulation of atmospheric carbon in the soil, which can be achieved by two routes: (i) Increasing the transformation of photosynthates to soil organic matter by enhancing plants' photosynthetic ability, and (ii) slowing the decomposition of the organic matter within the soil. The SOC content of sub-soils is lower and more stable than that of topsoil [36], which implies that the former has a greater potential for increasing the C store, although the underlying mechanisms are still poorly understood [37]. For instance, the application of biochar to soils has recently begun to attract considerable attention as an innovative soil management practice by scientists and policy makers for its potential role in increasing C sequestration and reducing GHG emissions [38]. Additionally, the development of plants with a well-distributed and deeply penetrating root system

should be exploited to achieve this goal. Thus, a full understanding of root architecture is of critical importance in breeding programmes [2].

The application of molecular biology techniques in studying living microorganisms in the soil and their interactions with roots and soil fertility, such as through second-generation sequencing and associated bioinformatics analysis, is providing a deeper understanding of soil biological processes and soil ecology for novel practical applications [30,39]. For instance, a rapidly increasing body of sequence information for genes encoding biological functions involved with soil processes could provide a powerful tool for recognizing the taxonomic and functional diversity of soil microbes (bacteria, fungi, and archaea) [40].

6. Strategies for Optimizing Crop Yield within Sustainable Environments

To ensure greater resilience of ecosystems to the predicted stresses in the future, a transformation from crisis-driven strategies to long-term mitigation measures is required [41]. Over time, various terminologies have been introduced by agricultural scientists to create awareness within their own community as well as among farmers, who can practically adapt them to achieve their goals. The following sections discuss the most common terms with special emphasis on their impact related to agricultural and environmental sustainability.

6.1. Crop Management and Breeding Strategies

Traditional crop husbandry is considered as both the art and science of raising crops aimed at providing useful agricultural products to the consumer at a reasonable cost along with an adequate amount of profit for the grower [4]. Farmers have to deal with complicated situations and implicate steps based on their understanding of a complex system comprising of a diverse set of social, economic, and technical aspects. Unfortunately, stagnant yield potential is an important obstacle in agricultural sustainability, while rigorous efforts are required to enhance the potential yield of the main food crops [9]. Greater resilience in both management practices and breeding programmes aimed at improving yield potentials are two of the most central areas that can most efficiently mitigate food insecurity and environmental concerns under the 2050 scenario [10]. A complimentary approach for breeding tolerance to multiple stresses in major crops has been recently reviewed in detail [28].

Although still in its infancy, the application of genetic engineering and agricultural biotechnology to current crop plants to enhance their performance under various stressful environments, such as drought, soil acidity, salinity, and temperature stress, is also vital. Fortunately, the new approaches of genetics and crop physiology have made it possible to exploit more directed tactics for selecting across various traits. New varieties of crop species can easily be developed that can produce better yields in challenging environments [1]. Giving due consideration to the concerns of some people (mostly those living in developed nations) regarding their potential to negatively affect public health, transgenic plants can currently be used for non-dietary purposes [42]. Such steps will reduce the load on agricultural land as most of it will be available to grow food crops. On the other hand, this will provide ample time to scientists to comprehensively evaluate the threats posed by these transgenic plants through scientific bio-safety testing protocols if progress is to resume [42].

6.2. Soil and Crop Management Strategies (SCMS)

Various SCMSs or other mitigating options have been identified and practised by scientists to create awareness regarding the optimal use of resource inputs with special emphasis on environmental sustainability. All these SCMSs aim to improve crop productivity and reduce deterioration of land by optimizing various characteristics of soil, such as its biological, physical, chemical, and hydrological properties, through balanced nutrient management [43]. As shown in Figure 3, these SCMSs maintain a strict balance between nutrient inputs and outputs through two key principles: (1) Matching the input quantity with the demand of the crop, and (2) synchronization with crop growth in terms of application timing. These SCMSs not only enhance the yield of crops, but, at the same time, can

preserve soil resources in addition to protecting the environment [17,44]. These SCMSs can employ farmyard manures, natural and mineral fertilizers, farm wastes, remains of crops, agroforestry, soil tillage, intercropping, rotation of crops, fallows, irrigation, and drainage to safeguard the accessible plant nutrients and water [4,45,46]. According to Zhang et al. [47], SCMSs also comprise of innovative approaches, like incorporating fertilizer at depths below the ground surface, adding urease inhibitors, or applying coated urea, which may enhance the uptake of nutrients. These modifications may inspire growers to give more attention to long-term policies, which are also environment friendly, instead of only considering the yield associated returns.

In the context of global environmental pollution, increasing N and phosphorus (P) use efficiencies have emerged as key targets [10]. Without the use of synthetic fertilizers, increases in yield would not have been practically possible. However, a part of the applied N and P fertilizers are not utilized by the crop and are lost to the environment, and such losses significantly contribute to the reduction in the efficiency of fertilizer usage and greater environmental pollution, especially in rapidly developing countries [44]. For instance, the use of N and P fertilizers increased largely, i.e., by 51% annually, during the period from 1996 to 2005 in China, whereas cereal yields increased only by 10% [47]. This large increase in fertilizer inputs without a corresponding increase in yields could lead to a nutrient imbalance and therefore serious environmental pollution concerns [18,44]. A better N and P balance can be achieved without sacrificing crop yields while significantly reducing environmental risk by adopting optimum SCMS practices, controlling the primary N and P loss pathways, and improving the performance of agricultural extension services [48]. A mechanistic relationship between grain yield and GHGs emissions exists that, through modified SCMS practices, can produce a 39% greater yield in wheat plants while reducing the intensity of GHGs emissions by 21% compared to conventional farming systems [17]. Adding organic fertilizers combined with suitable managing strategies, like incorporating plant residues or applying zero-tillage or minimum tillage rather than inorganic fertilizers, can improve soil quality, increase C sequestration, and reduce GHGs emissions while increasing grain yield [4,49].

- Nutrient Management

Managing fertilizer application in the field is one of the greatest challenges since it focuses on maximum efficient utilization of fertilizers to enhance crop yield and ensure environmental safety [19]. Plant nutrient management mainly emphasizes nitrogen and phosphorus as these are the main contaminants that enter and leave fields through fertilizer (both inorganic and organic), or any other major source of plant nutrition entering or leaving the field, including effluent management on dairy farms [50]. Excess nutrients, especially N and P, which are not taken by the plants may move into the water table or other water reservoirs, thus leading to environmental pollution. Delgado and Lemunyon [51] described that nutrient management is the art and science aimed at linking tillage, irrigation, and conservation of soil and water for the optimization of crop fertilizer use efficiency, productivity, quality, and net profit while minimizing the off-site movement of nutrients with less environmental effects.

- Site-Specific Nutrient Management (SSNM)

SSNM can be described as a crop-based approach that provides principles, guidelines, tools, and strategies that allow growers to decide the time and amount of fertilizers to be applied to a crop under actual field conditions at a specific site and season [52,53]. Dobermann et al. [52] defined SSNM as the comprehensive, site-specific nutrient management of a particular cropping season to match the demand and supply of nutrients based on variations in cycling through soil-plant systems. Such types of SSNM try to exploit (1) seasonal and regional variations in environmental yield potential and the demand of a crop for nutrients, (2) variation in the spatial variability of fields in terms of intrinsic nutrient availability, (3) farm-specific within-season dynamics of crop N demand, and (4) site-specific cropping patterns and crop management strategies.

- Integrated Nutrient Management (INM)

INM can be defined as using inorganic and organic fertilizers, bio-fertilizers, crop residues, and other living materials in such a balance that enhances fertilizer use efficiency, thus resulting in increased crop yields while indirectly minimizing the environmental risk through balanced fertilizer application [54]. The primary goal is to combine traditional methods with modern techniques of nutrient application that are environment friendly and economically sound cropping systems, which utilize both organic and inorganic fertilizers in a judicious and effective method [4,47]. All three primary macronutrients, i.e., N, P, and K, and other macro and micronutrient inputs and outputs are managed in INM, with the objective of nutrient cycling with tight synchrony between the demand of the nutrient and its application to soil (Figure 3). Nutrient losses through runoff, leaching, volatilization, and immobilization are reduced in INM, leading to an increase in fertilizer use efficiency. According to Zhang et al. [47] and Wu and Ma [55] the key principles of INM are (1) matching the input quantity with the crop demand, and (2) synchronization in terms of the timing application with crop growth (Figure 3).

- Integrated Soil Fertility Management (ISFM)

ISFM was described as a fertility management strategy of the soil, which emphasizes the sensible usage of chemical fertilizers, organic manures, crop residues, and resilient germplasms coupled with an understanding of the skills to employ such practices to local conditions with the objective of increasing the agronomic use efficiency of the applied fertilizers and enhancing crop yield [56,57]. The recent study by Nhamo et al. [49] showed that both crop residues and FYM (farm-yard manure) are crucial for enhancing the fertility of rice fields under ISFM. Comparatively greater yield benefit has been found for rice crops under organic manure or symbiotic biological N fixation by legumes than inorganic fertilizers. Nhamo et al. [49] also suggested a step-by-step innovative novel tactic to enhance crop production via the inclusion of various approaches of ISFM at various growth phases. Similar results of increasing the cereal productivity and farmers' income by opting for ISFM have also been reported in West Africa [57].

- Integrated Soil–Crop System Management (ISSM)

Introduced by Zhang et al. [18], this approach identifies three key points: (i) Consideration of all available options to enhance the quality of soil; (ii) exploiting the use of all possible nutrient sources and matching the availability of nutrients with crop needs; and (iii) fitting nutrient and soil management strategies with high-yielding cropping systems. Countries where the N balance has already been achieved can also improve crop productivity and fertilizer use efficiency by utilizing new approaches of ISSM, such as growing better varieties, location-specific agricultural practices, slowly releasing nitrogen amendments, efficient irrigation systems, and proper rotation of crops, etc. [11].

- Ridge-Furrow Mulching System (RFMS)

Sustainable agricultural development in arid plus semi-arid regions is primarily restrained by a shortage of water [58]. As an innovative water-saving cultivation technique, the RFMS is also designed to enhance crop productivity under water-scarce rain-fed conditions. This technique involves incorporating plastic film, crop straw, gravel sands, and rocks in the ridges and furrows before or shortly after sowing to cover the topsoil, thus preserving the soil moisture. This practice could be beneficial for channelling water into furrows, reducing soil evaporation, and enhancing the infiltration of soil water deeper into the soil profile, thereby increasing the availability of water to crop plants [59]. For instance, the RFMS practice could increase water use efficiency (WUE) by up to 70% compared with traditional flat or the well-irrigated practice, while it improves N fertilizer productivity and N uptake efficiency by up to 33% and 45%, respectively, under wheat-maize double-cropping systems in northwest China [58]. In addition, through mulching, the emission of GHGs into the atmosphere can be significantly influenced. It is suggested that plastic mulching under RFMS could serve as a physical

barrier to reduce the emission of GHGs and the C footprint of grain crops while increasing grain yield and carbon emission efficiency [59,60]. However, in some other studies, opposite results were also found [61,62].

- Water Management Techniques

Water is the single-most vital reserve for the sustainable development of agriculture, and improvement of the WUE is the main challenge confronting water management in agriculture [63]. Furthermore, increased non-agricultural demands and global warming exert great pressure on the amount of water left for agriculture. The availability of water must be matched with its demand by crops in terms of both the quantity and quality at proper cost and without any negative impacts on the environment [63]. Interest in micro-irrigations, such as drips or sprinklers, has gained more importance with time due to their greater efficiency. For instance, in drip irrigation, water is directly applied to the plant rooting zone, thus minimizing evaporation from the surface and can thus increase the crop productivity and WUE by at least 50% [64]. Further research has suggested that drip irrigation techniques can simultaneously decrease salinization by reducing water evaporation and increasing the WUE [9]. Scientists must keep their eyes on the salinity of our agricultural lands, which is associated with irrigation, since it is a key constraint limiting crop yields.

Irrigation scheduling techniques are greatly diversified in terms of their utilization and performance. Scheduling is planned by exploiting multiple options taking into account the estimation and measurement of the water status in soils and their balance, symptoms of stresses in plants, climatic parameters, and sophisticated models [65]. In areas suffering from water shortages due to increasing municipal plus industrial demands, regulated deficit irrigation (RDI) could be applied as a viable option that keeps a balance between the level of drought and the yield of a crop. RDI could significantly increase the WUE by minimizing the demand for irrigational water, resulting in no or little yield reduction. Thus, the negative impact is much less than the advantage obtained by diverting the water saved for irrigating other fields. In addition, alternate wetting and drying (AWD) and below surface drip irrigation systems are also promising strategies to increase WUE. With adequate incentives and service provision by governments in water deficient regions, water conservation and its utilization in crop production can be enhanced [66].

- Conservation Agriculture (CA)

CA can be defined as “a farming system that thrives for permanent soil cover, reduced disturbance of soil, and diversification of plant species” [67]. It comprises of a farming system suited to the needs of crops and the prevailing conditions of a locality, thus enhancing resource-saving agricultural crop production while concurrently protecting the environment from soil erosion and land degradation. The principles of CA mainly consist of three linked components: (1) Reduced soil disturbance, (2) maintenance of permanent soil covers, and (3) species diversification [68].

Zero tillage, no-till, or reduced tillage are agronomic practices or agricultural techniques that originated from the concept of CA to grow crops each year in such a way that soil is not or minimally disturbed with tillage [68]. Such strategies generally improve water availability and its infiltration into the soil, which then promotes C sequestration through decreased SOC decomposition. They can also be beneficial for eliminating soil erosion and enhancing the biological activity and quality of the soil, particularly in semiarid or arid regions. Cover crops and crop rotation are generally used in zero tillage farming to help control weeds and disease and increase the nutrient and moisture contents of the soil [46]. In addition to a range of other benefits for crop production, zero tillage has been rapidly adopted in many regions of the world, such as South America and northern China.

- Sustainable Land Management (SLM)

Land represents the most important non-renewable resource especially for poor populations who predominantly depend on it for their livelihood. Disturbing this resource can significantly affect crop productivity, intensifies financial crises and tensions, and leaves current biodiversity and the

environment at risk due to the cutting of forests, which leads to the release of carbon [69]. Via SLM, crop productivity can be increased by the effective management of limiting resources, such as land, water, biodiversity, and the environment, while the overall sustainability of an ecosystem is enhanced [32]. SLM is defined as “the adoption of land-use systems that through appropriate management practices enable land users to maximize the economic and social benefits from the land while maintaining or enhancing the ecological support functions of the land resources” [70]. TerrAfrica [70] also provides an overview, guidance, challenges, and the framework of SLM for countries in Africa and associates who are collaborating with them. The importance of SLM is increasingly recognized for the opportunities it provides to reduce poverty and mitigate land degradation worldwide.

- Vertical/Sky Farming (VF)

Vertical or sky farming is a relatively new strategy for growers that exploits innovative technologies, like aeroponics and hydroponics, in which crops are raised in open air/misty environments or mineral nutrient solutions under indoor controlled conditions instead of soil, which enables raising multiple times during a season and avoids losses caused by unfavourable atmospheric conditions [71]. It also increases the area available for agricultural production by many fold as plants can be grown in several layers, thus lessening the pressure on land resources. It is regarded as a promising approach because it is independent of the environment and thus quite immune to changes in environmental conditions [20]. Other benefits of vertical farming are that chances for recycling agricultural wastes are enhanced, and the loss of agrochemicals to the environment, especially water, is reduced. Due to its wider applicability, including in urban areas, it also minimizes the fuel consumed in transporting the produce from rural to urban areas and thus helps protect the environment.

- Technological and Behavioural Changes

At the technical level, a range of agricultural approaches, practices, technologies, and even behavioural changes have the potential to increase crop productivity and improve environmental sustainability. All these technological and behavioural alternatives can be employed in a complementary and integrated fashion to promote crop production under an environmentally sustainable system. The previous model of research, which was an earlier paradigm of science developed at the national or international level and then expanded to the farming community, must be substituted or replaced by a vigorous sharing of knowledge within farmers and the scientific community [9].

Site-specific crop management, precision agriculture (PA), and satellite farming are some of the novel agricultural strategies based on variations within or in-between the fields. The theme of PA is to develop a decision support system for whole farms to search for maximizing returns from farm inputs while minimizing resource consumption and safeguarding the environments [72]. The role of satellite navigation involving modern techniques, such as global positioning systems (GPS) and geographic information systems (GIS), provides promising support for PA that can be regarded as an important component of the modern revolution in agriculture. PA also demonstrates the environmental credentials of agro-ecosystem since it could facilitate the building of a decision support system or biophysical models to monitor and mitigate emissions of GHGs and the leaching of nitrate [73]. It could also be integrated with remote-sensing approaches to monitor soil moisture conditions and nutrient deficiencies as an indicator for the application of irrigation and fertilizers [74].

Multiple stresses, such as high temperature, drought, and elevated CO₂, are expected to occur simultaneously and will directly affect major crops in the near future. Thus, the interactive effects of these stresses need to be studied comprehensively because, based on the existing literature, our knowledge regarding the physiological and agronomic performance of some major cereals under multiple abiotic stresses is lacking [2,28]. Fertilizer industries need to actively contribute to a concerted global struggle to strengthen and facilitate the 4R Nutrient Stewardship initiative, which aims to apply the right nutrient source at the right rate, right time, and at the right place to further maximize NUE

and to reduce the unintended losses of nutrients to the surroundings [75,76]. Moreover, site-specific fine-tuning of the general principles in accordance with the prevailing environmental conditions in a particular area is pivotal for ensuring sustainability. In addition, bio-fertilizers, natural pesticides, crop choice and rotations, inter- and relay cropping, plants with allelopathic effects, agroforestry comprising of fruits, nuts, and timber trees, sowing seed directly in living cover crops or mulching, and the integration of semi-natural landscape elements at the field and farm scale or their management at the landscape scale are some of the agro-ecological practices that need to be properly integrated into our current agricultural systems [77].

Through monetary rewards and other incentives, farmers should be encouraged to adapt the best agricultural practices that ensure greater and sustainable yield and environmental stability [78]. In some less-developed parts of the world, such as Africa, improved varieties, extension training, and increased nutrient inputs can still boost yields as these practices have not been adopted compared with other more-developed regions of the world [79]. Similarly, taxing fertilizers or pesticides or removing subsidies of such inputs would discourage their excessive use [9]. Another long-term viable alternative is to attract qualified and knowledgeable people to farming or enhance the capacity of those involved through various modern technology diffusion systems. It is evident that most farmers, especially in underdeveloped countries, currently lack basic education, which makes the diffusion of any useful innovation difficult for extension workers [80]. Cooperation both nationally and internationally is needed to tighten the coordination within or among different countries. Likewise, cooperation with the IPCC also needs to be enhanced. Similarly, the adaptation of policies developed to cope with environmental pollution is critical.

7. Successful Demonstration

Novel and innovative approaches developed by research organizations need to be widely disseminated to farmers and then adopted in a systematic way. With persistent improvement of existing agro-ecosystem management practices, some countries have already achieved a certain degree of success in solving the issue. Below are some of the motivational examples for other countries to follow.

In Denmark, the amount of surplus N has been reduced from 170 kg N ha⁻¹ yr⁻¹ to less than 100 kg N ha⁻¹ yr⁻¹ during the past 30 years. Conversely, the efficiency of N utilization in the agriculture sector, including both crop and livestock farming, was improved from approximately 20%–30% to 40%–45%. Furthermore, N-leaching from the crop root zone has been reduced to half, while N losses to the atmosphere and aquatic environments have also been reduced significantly [81]. It is claimed that such results were possible due to a combination of approaches and measures (ranging from command and control legislation to market-based regulation and governmental expenditure to information dissemination and voluntary action), with specific strategies addressing the entire N cascade to improve the quality of ground and surface water and reduce deposition in natural terrestrial ecosystems.

Chinese researchers are using optimal approaches by integrating several SCMS practices to enhance crop productivity with less environmental impact and thus offer an extraordinary laboratory for the rest of the world. One project by Zhang et al. [44] involved 16 universities and other institutes of the China Agricultural University, where the performance of wheat, maize, and rice were evaluated during the period from 2008 to 2012 in about 500 experimental fields across 11 provinces. Their findings suggested that both the cereal yield and N use efficiency have simultaneously significantly increased by more than 30%. However, transferring successful technologies or research results into farmers' fields in China overall or to specific regions, which are dominated by smallholder farmers, remains a huge challenge [44]. Interestingly, recent work provided further evidence of the possibility and feasibility of mobilizing millions of smallholder farmers to adopt recommended integrated soil-crop system management to improve crop production while simultaneously protecting the environment [82]. From 2005 to 2015, this great effort involved a complementary network of

more than a 1000 researchers, extension agents, and agribusiness personnel in collaboration with 20.9 million farmers who implemented the improved management technologies in their local fields across 452 counties in China over a total cropped area of 37 million hectares. The mean grain yields of three major cereals, including rice, maize, and wheat, were enhanced by approximately 11%, while the N application rate, estimated losses of reactive N, and emission of GHGs were reduced by 16.5%, 25.8%, and 19.6%, respectively. Developing nations, like India or Bangladesh, that are dominated by smallholder farming similar to China might seek to emulate this viable solution for ensuring higher crop productivity while reducing environmental pollution.

8. Conclusions

It can be concluded that current agricultural practices could previously meet the demands of the population, but future needs are increasing much more rapidly than in the past due to the growing population. Analyses reveal that constantly rising temperatures, higher GHGs emissions, and rapid increases in environmental pollution have made current agro-ecosystems much more susceptible than ever before. The overwhelming evidence that underdeveloped nations are especially vulnerable to such perils further exacerbates the pressure to enhance their poor economic status and food security. Fortunately, a wide range of mitigation strategies exist that, if exploited sensibly, have the potential to mitigate the threats to some extent, if not fully. Through multifaceted efforts involving SCMSs practices, plus short- and long-term preventive measures, a sustainable production system can be developed. Minimizing the application of chemicals, especially as fertilizers and for controlling insects/pests, plus improvements in the input use efficiencies of crops will help minimize GHGs emissions while protecting the environment. Sustainable agriculture holds promise for humankind and the planet Earth, and it can be successful if all developed and developing nations stand together to produce more food with less environmental pressures and thus seek “our common future” [25].

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