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Review

Managing Land Carrying Capacity: Key to Achieving Sustainable Production Systems for Food Security

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Abstract: Many previous studies have estimated the carrying capacity and feasible planetary boundaries for humankind. However, less attention has been given to how we will sustainably feed 9 billion people in 2050 and beyond. Here, we review the major natural resources that limit food production and discuss possible options, measures, and strategies to sustainably feed a human population of 9 billion in 2050 and beyond. Currently, food production greatly depends on external inputs, e.g., irrigation water and fertilizers, but these approaches are not sustainable. Due to the unbalanced distribution of global natural resources and large regional differences, urbanization expansion causes important areas to face more serious arable land resource shortages. Hence, sustainably feeding 9 billion people in 2050 and beyond remains an immense challenge for humankind, and this challenge requires novel planning and better decision-making tools. Importantly, the measures and strategies employed must be region-/country-specific because of the significant differences in the socioeconomic characteristics and natural environmental carrying capacity in different parts of the world. Considering the impact of unexpected extreme events (e.g., a global pandemic and war) in the future, the food trade and translocation of goods will also face challenges, and the strategies and decision-making processes employed must consider the possible influences at both regional and global scales.

Keywords: water resources; crop production; land resources; fertilizer

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1. Introduction

To feed the billions of people living on the planet, the production of high-yield and high-quality foods is a challenge that must be met. Estimates show that global food production will have to increase by 70% by 2050, which will increase the pressure imposed on land, water, labor, nutrients, and energy. Today, 820 million people, mainly from developing countries, are still suffering from hunger and malnutrition [1,2]. Currently, food production greatly depends on external inputs, such as irrigation water and agrichemical products. Considering the remarkable magnitude and speed of global population changes, it is likely that food production will further undermine the natural ecosystem and environment. Meanwhile, food production will be constrained by the expansion of urbanization, land degradation (e.g., erosion and salinization), nonfood uses of crops and farmland (e.g., bioenergy, construction of transportation lines, and recreational activities), and climate change. Previous studies have mostly focused on promoting food production while protecting the environment. Regarding food security and the environment, interdisciplinary research should lead to increased productivity while exercising environmental conservation, but alone, these suggestions are unlikely to keep the environment healthy with the continuous increase in the global population. With the continuous growth in population, water availability, arable land area, soil degradation, soil erosion, climate change caused by fossil fuel consumption, the eutrophication of inland and coastal marine waters, and losses in biodiversity have become major environmental problems worldwide. MIT modelers calculated that the known world copper reserves will be entirely depleted in 36 years (i.e., by 2006), lead in 26 years, mercury in 13 years, natural gas in 38 years, petroleum in 31 years, silver in 16 years, tin in 17 years, tungsten in 40 years, zinc in 23 years and that all natural gas reserves would be exhausted by 2020 [3]. However, the current situation is so complex, reflecting to a large extent the multiplicities of human activities, that it is unlikely that a simple combination of technical, economic or legal measures and instruments will bring about substantial improvements [4]. Thus, the theoretical bearing capacity limit of the environment should be considered a leading topic in food security.

Harmony between humans and nature is needed to feed 9 billion people in 2050 and beyond by optimizing our own interests and promoting the sustainable use of natural resources. To achieve a sustainable food supply for 9 billion people, humans should focus on the relationship between the ultimate bearing capacity of the natural environment and food production. This means that we need to break the traditional thinking of "input and output" and, rather, consider "input under and reasonable output under the ultimate environmental bearing capacity".

The capacity of nature is limited (e.g., climate change, land system change, freshwater use, biogeochemical flows, biosphere integrity, and atmospheric aerosol loading), and its input and output are not perfectly proportional to each other. Natural conditions have limited the ability of food production to continuously increase. For example, climate change (e.g., extreme events) could lead to maize and winter wheat grain yield losses in Europe; additionally, based on predicted future drought and heat extreme events, average yield losses range from 3% to 17% depending on the severity of the conditions [5]. Over the past 40 years, barley yields have increased by over 60% in Europe [6]. A review of barley in Norway showed a 70% yield increase over 1946–2008, with 48% of the yield increase being attributed to the introduction of new varieties [7]. Additionally, this study showed an accelerating trend of increased yields due to new varieties, with the 1946–1960 period showing a 29% yield increase due to new varieties, 43% in the period 1960–1980 and 78% in the period 1980–2008 [7]. Increasing trends in agricultural and ecological droughts have been observed on all continents [8]. It overestimates global mean drought-affected areas by 60%, drought intensity by 65%, and drought duration by 35% on average over the globe, and tends to overestimate drying trends in areas that are drying and underestimate wetting trends in areas that are becoming wetter [9]. So, leaving aside other reasons for the increase in crop yields over the past 40 years, a decline in crop yields is inevitable due to predicted droughts and temperature changes.

The excessive pursuit of high-yield crops can generate high levels of greenhouse gas emissions and nutrient losses and other environmental problems. A relatively high yield based on the ultimate environmental bearing capacity limit should be the goal, and it is better to reduce the environmental cost on this basis to solve the problem of food security. However, agriculture still faces an even greater challenge today, as the growth in global food production is exacerbated by climate change, and environmental quality and natural resources must be protected. This challenge puts greater pressure on developing countries with higher population densities. While many developing countries with larger populations have made significant gains in addressing food security, these gains are heavily dependent on continued fertilizer use increases.

Over the past century, the pursuit of higher yields has been accompanied by an overuse of water and fertilizers, which has led to serious environmental problems, such as eutrophication, greenhouse gas emissions and soil acidification. There is an urgent need to develop a rational food production plan and focus on sustainable food production and the efficient use of natural resources.

Until recently, agricultural production practices in many countries have focused on increasing yields by using greater inputs of resources, especially through the excessive exploitation of groundwater and excessive use of chemical fertilizers, which have had great impacts on the environment. Many agroecological and environmental protection measures have improved water and fertilizer use efficiency by reducing inputs, but little has been done to stabilize and improve crop yields. The efficient use of intensive agricultural resources, especially land, water, energy, and nutrients, should be considered in efforts to increase food production. The environment should also be protected, including reducing greenhouse gas emissions and reducing the water pollution caused by pesticides and excessive fertilization. These goals can be achieved through the highly efficient utilization of agricultural resources and reasonable field management practices, which are important for agricultural sustainability and of food security risk reduction. Due to the low planting density, unsuitable planting dates, short growing periods of various crops, early harvest and other reasons, the utilization efficiency of light energy and heat energy in agricultural production is low [10]. Situations in which the irrigation and fertilizer are either too high or too low or those where the timing is not appropriate will cause low water and fertilizer use efficiency. The exploration of these potential factors has helped us solve the problem of food security. However, food production is primarily constrained by the availability and accessibility of key global resources.

This review summarizes the main natural resources that affect crop productivity and seeks to determine the critical points for food security and the ultimate environmental bearing capacity. In this review, we present the agricultural production boundary theory for the first time. At the same time, this review puts forward the main measures to solve food production, mainly including the use of molecular technology, the efficient use of water and fertilizer technology, and plant breeding.

2. Major Resources That Affect Food Production

2.1. Water Resources

Water is an integral part of most living organisms. It plays an important role in the world's ecological environments and food security. Therefore, access to adequate agricultural water supplies is essential for human food security. Water is a naturally circulating resource, and it forms closed hydrologic cycles. The total amount of water resources will not decrease over a relatively short geological time scale, at least in theory. When considering the length of the hydrological cycle, the bearing capacity limit of water resources should be considered. Because some groundwater aquifers recharge slowly, the mean recharge time might take hundreds, thousands or even millions of years [11].

At the human scale, it will take a long time to return to the initial storage level after groundwater is extracted from an aquifer with a slow recharge rate [12]. That is, water resources are limited, and water is exhausted once it has been overexploited because the accumulation rate is slow. In addition, one view is that the total amount of water on Earth lost into space is related to the amount of water present on ancient Mars, which is inferred from the present global deuterium to hydrogen ratio [13]. It is very important to seek the upper limits of water resource exploitation, as it is one of the most effective measures to maintain sustainable agriculture production and environmental friendliness worldwide.

Nearly 80% (4.8 billion) of the world's population (for 2000) live in areas where either incident human water security or biodiversity threat exceeds the 75th percentile [14]. Widespread groundwater level declines have become a reality in recent decades, which are primarily shown by rapidly falling groundwater levels as measured locally in wells; more recently, these declines have been proven at the basin scale by gravity recovery and climate experiment (GRACE) satellites in many regions [15]. There are two views on the decline of the groundwater level: one is that this problem is caused by the overexploitation of groundwater resources by people, which means that extraction rates are greater than the natural recharge rate; the other is that the loss of water is caused by natural runoff, which means that the flowing water leaves land as runoff that reaches the sea. This is all based on global hydrological models and GRACE data, which vary from 90 to 510 km^3 $year^{-1}$ for recent years [16]. The estimates of groundwater usage vary widely due to difficulties in collecting data. In one study, about 38% of global consumptive irrigation water demand is claimed to be met by groundwater [17]. Groundwater abstraction accounted for 33% of the total withdrawals globally and provides water for agricultural (42%), domestic (36%), and for industrial requirements (27%) [18]. However, in some countries, such as the US, groundwater use for agriculture is more than 80% of total usage [19]. In this context, it is important to realize that 6–20% of the wells they sampled are at risk of being unable to provide water at the same levels in the future [20]. However, even with their extensive survey, they were unable to document wells and groundwater in about 50% of the countries of the world.

None of these comments are made to deny that there are serious issues with groundwater depletion in many locations, with a significant portion of that driven by food and agriculture. It is estimated that more than half the world's mega cities (those with populations over 10 million) are groundwater dependent for drinking/domestic water. India is a country under high pressure as it has only 4% of total global land, but hosts 24% of the world's population, and accounts for more than 30% of the irrigated land in the world [21,22]. A new study reviewing the situation in India notes that groundwater irrigation is used "to produce staple grain crops that provide over half of the calories consumed by its over 1.3 billion people" [23]. While groundwater use has allowed India to greatly increase agricultural production (by permitting multiple annual crop growth), largely preventing widespread predictions of famine for India's growing population, "in-situ and satellite-based observations indicate a rapid decline in groundwater storage in north India" [24]. Nevertheless, it is also important to observe that some northern regions in India and many more in South India are showing increases in groundwater rather than depletion (due chiefly in the south to increased rainfall). Thus, it is important to look at regional/local details rather than to overgeneralize at a global or even a national level.

Electric pumps are the main instruments of groundwater pumping for irrigation in the majority of states of India. Much of the energy used to run the electric pumps is subsidized, and there is evidence that cheap electricity has encouraged farmers to grow water-intensive crops that have led to a rapid decline in groundwater in India [25]. These subsidies can be huge in India (where an estimated USD10 billion was spent in 2005 alone on agricultural electricity subsidies), and these subsidies comprise the largest expenditure in many state budgets [26]. An increase in fixed monthly electricity bills would reduce the likelihood of groundwater exploitation along the margins and overexploitation of groundwater [27].

Groundwater, in particular, contributes more to results and has fewer feedback mechanisms than other agricultural inputs. Water governance is a complex issue, and groundwater governance has a number of unique aspects (being largely out of sight). However, governance may be a key instrument to tackle issues of water security and scarcity, which often seem to be the "result of, and expression of, poor governance in the first place, rather than a physical condition" [28]. Groundwater has many of the issues commonly comprising "governance of the commons" [29], where many have access to the resource, pay little cost to access it, having no ownership rights, and have little incentive to conserve the asset. Economic pricing plays a key role in determining the utilization of assets and resources and encouraging adaptation. However, like other parts of the world where groundwater use has boomed, India is now facing a severe crisis of groundwater depletion, with widespread declines in water tables occurring in some of its most agriculturally productive regions [30]. Although irrigation alone consumes nearly 89% of groundwater use in India [31], it also should be noted that a high percentage of that country's urban drinking water and as much as 85% of rural drinking water are from groundwater sources [32]. While agriculture can be relocated, drinking water is essential for any population, so it is always prioritized, even though the usage levels are almost always much lower than water for agriculture.

The proportion of households in South East Asia and 10 South East Asian and Pacific countries that rely on groundwater as their primary source of drinking water, with an average of 66% of households in urban areas (range of 17–93% for individual countries) and 60% of households in rural areas (range of 22–95%) relying on groundwater for drinking water. Together, these people represent 79% of the total population of the case study countries [33]. The potential limits of water on the carrying capacity of earth and reported calculations of 4 billion up to 157 billion, and the variation, not the aggregate, of freshwater supplies poses the chief obstacle to meeting people's water needs [34]. Finally, it is important to know that most estimates of the requirement to achieve a 50% increase in agricultural production over the next 30 years would only require a 15% increase water usage (McNabb, 2019). Given that 50% of water used for open irrigation is essentially wasted, there are a number of ways to address the additional strain on water supplies.

The rising sea levels are strong evidence of the latter opinion, and different studies have found that groundwater depletion has accelerated the rate of sea-level rise, and the contribution of groundwater depletion to sea level might reach 31 mm by 2050 [35]. Some researchers consider climate variability to be the main reason for the sea-level rise, and the continuous rise in global temperatures has made an important contribution to sea-level rise and may contribute to a sea-level rise greater than one meter by 2100 [36]. Globally, the decline in groundwater levels is an important issue, and groundwater level declines are limited to certain regions, specifically those where local and large-scale aquifers are overexploited. In irrigated areas, the response to annual variations in groundwater levels in deep wells may mirror exploitation-induced pumping changeability. Understanding how human activities in response to drought lead to changes in deep groundwater by over pumping water and the massive construction of high buildings is vital to managing the effects of climate change on the nation's freshwater resources over the course of a decade and beyond.

The good news is that the current exploitation of water is within the bearing capacity limit of natural water resources, and if water use is managed properly, renewable freshwater resources can meet human needs far into the future. Agriculture is the world's largest consumer of freshwater globally, and approximately 70% of the fresh water used by humans is diverted for agricultural production [37]. Additionally, there is global concern regarding regulating the water resources for agriculture in a way that meets the demand for food production and considers the safety and reliability of the water used for agricultural production. However, global food production still has significant inequalities in terms of geographical distribution and water consumption, and the natural environment has been acknowledged as being greatly threatened regarding its ability to provide vital ecosystem services. The North China Plain is one of the largest aquifer systems in China, and it is an important area in China's food production. The groundwater spatial distribution indicates a major reduction in the groundwater level due mainly to over-pumping for irrigation [38].

Overexploitation is beneficial for agricultural production, but the sustainability of high-yield agriculture appears to be threatened by a large-scale decline in the groundwater level [39]. In addition, the significantly increased evapotranspiration and crop water consumption due to the intensive cropping system is the main reason for the imbalanced groundwater budget. The irrigated areas of the northern High Plains and California Central Valley account for half of the groundwater depletion by aquifer overexploitation in the United States; in particular, the southern High Plains have led to a concentrated depletion of 330 km^3 of fossil groundwater, which has mostly been replenished over the past 13,000 years [40]. Global groundwater depletion for irrigation increased mostly due to a 22% increase in irrigation that occurred over ten years, and most groundwater depletion is centered in a small region that depends on aquifer overexploitation for growing crops [41]. Globally, crops contribute most to groundwater depletion through transfer, with values of 29% in rice, 12% in wheat, 11% in cotton, 4% in maize and 3% in soybeans [42].

2.2. Arable Land Resources

Human action has played a vital role in the dramatic change in land resources. In recent years, with economic development, the understanding of how arable land area affects agricultural productivity in various countries has obviously improved. Food security has drawn wide attention around the world for a long time due to the challenges of contending with a large population and limited arable land. Under the condition of rapid urbanization, the food situation has changed and China's very large population is facing a major challenge [43]. In recent years, rural residents in developing countries have been attracted to urban areas due to their superior infrastructure, public services, cultural facilities, life convenience and job opportunities.

A large number of rural laborers left the countryside and entered cities, which resulted in the expansion of the city scale. China's urbanization rate increased from 17.91% in 1978 to 57.35% in 2016, which is twice the world average for the same period [44]. This urbanization has the following two effects on arable land: one is that urban expansion has taken up a large amount of arable land, and the other is that the rural population size has decreased, resulting in a loss of cultivated land. As urbanization expands, there will be increased competition for land, water and energy, which will affect food production and lead to food security issues. Due to the unbalanced distribution of global natural resources and large regional differences, urbanization expansion causes important areas to face more serious arable land resource shortages.

Over the past four decades, urban land expansion rates have been higher than or equal to urban population growth rates worldwide [45]. China and India together account for more than 35% of the world's population, and the expansion of urbanization has taken up much of the land available for agriculture [46]. Across all regions and for all three decades, urban land expansion rates are higher than or equal to urban population growth rates, suggesting that urban growth is becoming more expansive than compact [47]. Population growth contributed more to urban expansion in North America than in Europe, and the global urban land cover area will increase by 4.3×10^5 km^2 to 1.26×10^7 km^2 by 2030 [48].

The rapid expansion of urbanization leads directly to the utilization of large areas of farmland. On the one hand, urban expansion has been associated with the high construction rates of high-rise buildings and their supporting facilities, such as water conservancy projects and transportation projects in arable land, and these buildings and facilities consume a large amount of farmland. On the other hand, urbanization expansion will result in a large rural population moving to cities, which will lead to a decline in the agricultural production of small farmers (without being taken over by other farmers). In turn, the rapidly growing urban population will have to demand more food from other agricultural land, while intensive water use and greenhouse gas emissions will occur simultaneously.

Globally, urban expansion will result in a 1.8–2.4% loss of global croplands by 2030, potentially leading to losses that are responsible for 3–4% of the worldwide crop production [49]. The effect of agricultural land value remains somewhat undocumented or controversial, with several studies implying those urban developments are hindered by highly productive or profitable agricultural land [50]. Thus, the contribution of urbanization to land-use change has become an important sustainability issue. Urban expansion will take place in some of the world's most productive farmland regions, especially in the megacities of Asia and Africa [49]. This dynamic will put pressure on potentially strained food systems in the future and threaten livelihoods in vulnerable areas.

2.3. Soil Quality

There is an urgent need to adapt food production to world population growth by defining sustainable land management strategies. In solving food security problems, attention should be given to the soils where crops grow and the environment where organisms live. Now, it is clear that the sustainability of arable land is becoming increasingly important for agricultural productivity. Agricultural productivity has significantly affected food security through soil degradation, causing the soil quality and productivity to decline. Many "degraded, desertification or soil-depleted" lands can be restored through appropriate reforestation [51]. Serious soil degradation can be prevented or reversed by changing farming practices [52], especially on smallholder farms [53].

Recent estimates suggest that between 5 and 10 million hectares of arable land is irreversibly lost globally each year due to soil erosion, salinization, biodiversity decline, compaction, acidification, and other degradation processes. In terms of agricultural productivity, land degradation is caused by the mismatch between land quality and land use. Land degradation indicates a temporary or permanent long-term decline in ecosystem function and production capacity due to factors such as soil erosion, deforestation, waste disposal, excessive grazing, the conversion of agricultural land to nonagricultural use and inappropriate land management practices. Agriculture is one of the major causes of land degradation.

Globally, more than 20% of the world's arable land, 30% of its forests and 10% of its grasslands suffer from the threat of soil degradation, which affects approximately 1.53×10^9 people and could be the result of several factors, including human activities such as unsustainable land management practices and climate change [54]. The degraded land performance reveals general declines in soil fertility and soil structure, degraded irrigated land and reduced biological biodiversity, which ultimately lead to a reduction in the biological production potential of the affected land to sustain life.

The soil degradation due to human activities is mainly manifested through agricultural mismanagement and deforestation. Chemical soil degradation is pollution caused by a loss in nutrients and/or organic matter, salinization, acidification or industrial activities, such as the excessive use of fertilizers, pesticide mining and the use of other chemicals. Biological soil degradation is related to the reduction in or depletion of soil organic matter, the continuous negative balance of soil nutrients and the imbalance of fertilizer application. The causes of soil degradation include deforestation, land-use conversion, and other activities, such as the overexploitation of minerals and oil, overgrazing, and overcultivation.

Soil degradation leads to a decrease in soil quality and productivity. In the soil degradation process (soil structure decline, compaction, salinization, soil biodiversity decline, and acidification), soil erosion is the most critical form of soil degradation. Soil erosion is one of the most important factors affecting soil fertility and productivity because it removes organic matter and important nutrients, hinders vegetation growth and negatively affects the overall biodiversity. Globally, 33% of the Earth's surface is affected by some type of soil degradation [55]. Soil erosion changes the physical, chemical, and biological properties of the soil, causing a decline in agricultural productivity.

It is precisely in these conditions that properly implemented conservation agriculture can reverse soil degradation, restore soil quality, enhance productivity, and advance food security [56]. It is estimated that the global area of soil erosion is approximately 16.43 million km^2, accounting for 10.95% of the total surface area of the Earth [57]. It is estimated that approximately 0.43% of crop productivity is lost each year due to the severe soil erosion affecting 12 million hectares of agricultural areas in the European Union (EU) [58]. The average annual soil erosion in India accounts for 5.76% (14.917 t ha^{-1} year^{-1}) of the country's total area and directly affects 0.66% of its crop productivity [59]. In contrast, approximately 2% of crop productivity in China is affected by soil erosion, although the population density indicates a decrease in soil erosion estimates; furthermore, soil erosion is increasing significantly in South America and Africa [60,61].

Since the world receives more than 99.7% of its food (calories) from land and less than 0.3% from oceans and aquatic ecosystems, protecting farmland and maintaining soil fertility should be a top priority for human welfare [62]. Soil erosion is one of the most serious threats to world food production, particularly in countries with fragile soils, harsh climates and limited technical inputs. Rojas et al. [63] reported that soil erosion could reduce global food production by 15%. While a fully reliable picture of soil degradation and its implications in developing countries does not exist as yet, and the effects of demographic and economic trends on future patterns of degradation cannot be predicted with certainty, the evidence is sufficient to warrant serious attention by the policy community [64]. The early, high estimates of soil degradation have not been substantiated. Degradation appears not to threaten the aggregate global food supply by 2020. Every year, 7.2% of the total agricultural land in the EU suffers from severe soil erosion, and approximately 3×10^9 kg of wheat and 6×10^9 kg of maize are lost to severe erosion [58]. Soil erosion affects soil health by reducing the thickness of topsoil, altering the soil properties and consuming soil organic matter and nutrients. A direct implication of the imbalance between agricultural soil loss and erosion in native vegetation and geological time is that, over time, sustained soil loss will become a key issue affecting global agricultural production under traditional dryland farming practices.

2.4. Energy

Energy is used in agriculture to increase crop productivity in response to population growth and limited arable land availability. Modern crop production is characterized by high-input fossil energy consumed as "direct energy" (fuel and electricity used on the farm) and "indirect energy" (energy outside the farm for the production of fertilizers, plant protectants, and machinery). Solar, wind and other energy sources are categorized as "supporting energy" [65]. Agriculture is both a producer and a consumer of energy. It uses large quantities of locally available noncommercial energy sources, such as seeds, manures and animate energy, and it also uses commercial energy sources directly and indirectly in the forms of diesel, electricity, fertilizers, pesticides, chemicals, irrigation water and machinery.

Globally, the amount of supportive energy input required for crop production varies widely. In some low-input farming systems, such as in large areas of Africa, the energy input to arable land is less than 1 GJ ha^{-1}, while in some modern high-input farming systems in Western Europe, this input can exceed 30 GJ ha^{-1} [66]. A high energy input in agricultural production is characterized by the extensive use of chemical fertilizers, pesticides, and labor-saving high-power machinery. The introduction of these high-energy technologies in agriculture has significantly increased investment in fossil energy resources. Over the past several decades, energy-intensive agricultural systems have been crucial to maintaining food security. To maintain the sustainability of energy for agricultural production, the direct relationship between the energy input limit and environmental carrying capacity must be balanced. In agricultural production, energy input should be of concern to researchers because energy use can be very costly.

In many cropping systems, mineral fertilizers account for the largest share of the energy budget. Fertilizer accounts for approximately 70% of energy use in corn production in eastern Canada [67]. Nearly 90% of the energy used to produce mineral fertilizers is nitrogen. Nitrogen fertilizer and N_2O emissions accounted for the majority of the differences between crop energy use and greenhouse gas emissions. Synthetic nitrogen is the largest type of energy input, accounting for 51%, 53% and 19% of the total energy budget for standard, no-till, and no-till mulched maize production scenarios, respectively [68].

The agricultural sector is already a major contributor to global energy use and greenhouse gas emissions, and as our population grows to nine billion and needs more protein and calories, the environmental impact of agriculture is likely to increase. Furthermore, the agricultural sector accounted for 6.3% of US emissions in 2009, equivalent to 413 terabytes of carbon dioxide [69]; these numbers are worrisome. Nitrogen-related greenhouse gas emissions account for approximately 7% of China's total greenhouse gas emissions, which is several times higher than the soil carbon benefit from using nitrogen fertilizer [70]. For high yields on the North China Plain, the greenhouse nitrogen surplus was 4328 kg ha^{-1} year^{-1} and that of wheat–maize was 346 kg ha^{-1} year^{-1}, resulting in an average cadmium concentration in greenhouse soil that was 2.8 times higher than that of wheat–maize rotation [71]. Atafar et al. [72] showed that the concentrations of lead, arsenic and cadmium in soil increased with increasing fertilization, and the concentrations of lead and arsenic were significantly higher than that of cadmium, which was related to the overuse of fertilizers and pesticides.

Although fertilizers play an important role in maintaining soil fertility, increasing yields and improving harvest quality, the fertilizer losses caused by excessive fertilization, increased agricultural costs, wasted energy and environmental pollution pose challenges to the sustainable development of modern agriculture. Excess nitrogen is added to the soil primarily through plant assimilation, absorption by the substrate, and other losses, including the volatilization of ammonia during simultaneous nitrification and emissions of N_2O and N_2 and denitrification. The increased use of chemical fertilizers for food production reduces the transition of ecosystems to farmland; however, excessive fertilization causes an increase in the greenhouse gas nitrous oxide and nitrate leaching into the ground and surface waters. Jankowski et al. [73] proposed that when the threshold value of nitrogen fertilizer applied to maize planting was 80 kg N ha^{-1} $year^{-1}$, the risk of affecting gas emissions and groundwater was small.

The application of inorganic fertilizer not only significantly increased the triethylenetetramine abundance in soil but also changed the whole bacterial community abundance in soil. Triethylenetetramine is used industrially for floatation and the collection of nickel ore, and slag from those mineral processing operations can be contaminated with residual amounts of triethylenetetramine. The importance of the soil and plant microbiomes to agriculture and food sustainability are well overviewed in recent surveys [74,75]. Additionally, the impact of other soil organisms and impacts on soil and plant health are increasingly being studied, but, as noted by FAO, the "majority of soil biodiversity remains undescribed, and information on the functional abilities and ecology of most soil taxa is far from being complete" [76]. Discovering and managing these additional biological strata are likely to have significant impacts. Fertilizers and pesticides tend to stay in the soil for a long time; thus, they inevitably affect the soil microbial community, which affects soil health. The excessive use of indirect energy (fertilizers, pesticides, etc.) in agriculture indirectly leads to changes in the dynamics of the soil microbial population, which directly changes the soil toxicity and soil matrix utilization. Although the present soil situation is still good, even with the long-term and excessive application of fertilizer, the long-term effect will significantly affect the structural and functional diversity of the soil microbial community and the dominant species in soil.

3. Carrying Capacity of These Resources

3.1. Water Limits Food Production

Freshwater use has been identified as one of the nine planetary boundaries, highlighting its key role in global sustainability. The water used for food production is mainly fresh water, which is a limited resource, accounting for only a small fraction of the world's water (0.008%) and covering approximately 0.8% of the Earth's surface [77]. In the natural process, water moves constantly through the hydrological cycle of evaporation, evapotranspiration, precipitation, condensation, and runoff, and the whole cycle is mostly driven by solar radiation energy (Figure 1A).

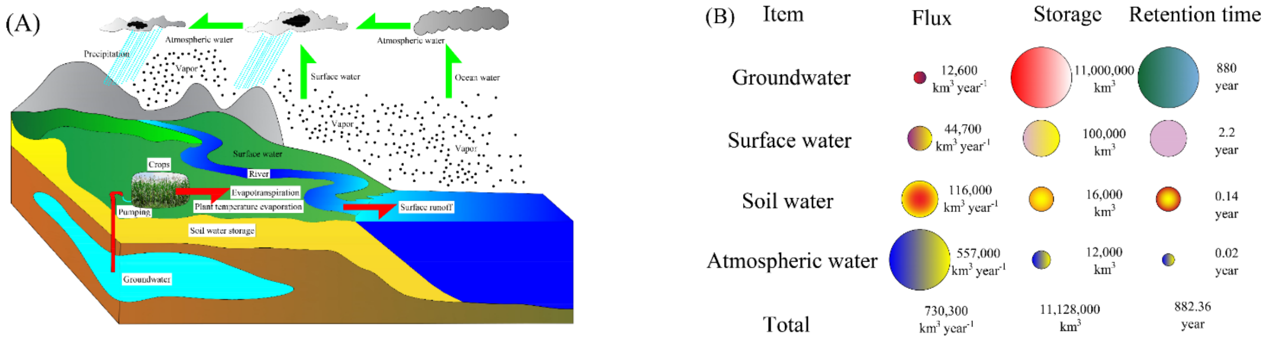

Figure 1. (**A**) A schematic of the global water cycle shows the main pools and fluxes associated with the applications discussed here. (**B**) Global average annual input fluxes, total storage and residence times for groundwater, surface water, soil water and atmospheric water. The scope of the circle is based on an assessment of the world's water resources and groundwater supply. The circles are colored according to the classification of green water (soil water available to plants), blue water (surface water and groundwater), and dark-blue water (nonrenewable groundwater). Groundwater is an active part of the hydrological cycle and is usually closely related to surface water features such as rivers, lakes or wetlands. Even in areas where surface water is abundant, groundwater is often an important source of drinking water. It is more readily available than surface water and less prone to quality degradation and drought [78].

It is widely recognized that water is an important and fragile resource, and groundwater plays a key role in this complex system. Groundwater flows slowly through the pore space of permeable geological units called aquifers and is an active part of the hydrological cycle. Groundwater is usually closely related to surface water features such as rivers, lakes or wetlands; however, its flux, storage and residence time are significantly different from other parts of the hydrological cycle. Groundwater, as the largest unfrozen reservoir of fresh water on the planet, is more accessible than surface water and is less susceptible to degradation and drought. There is no general "shortage" of fresh water but only localized mismatches between availability and demand based on current use patterns [79]. Localized solutions are needed to ensure proper governance and pricing, efficient use, waste reduction and food sourcing patterns. Pressures in one location generally do not influence another location unless aquafers are linked.

In 1900, the world's population was less than 1.7 billion, but it more than quadrupled during the 20th century and now exceeds 7 billion. To sustain the rising demand for food and rising living standards, global water use has increased by nearly six-fold, from ~500 km^3 year^{-1} in 1900 to ~3000 km^3 year^{-1} in 2000, and approximately 70% of the global water use is for agriculture [80]. Of this, approximately 90% of water consumption in agriculture (water intake from evaporation during use) is used for irrigation [81]. In arid and semiarid regions of the world, groundwater is often the only available water resource to support or expand agricultural production. Since irrigated agriculture accounts for approximately 40% of global food production, pumping groundwater for irrigation has contributed significantly to the expansion of the global food supply [82]. At the same time, it has led to the depletion of groundwater in many parts of the world, resulting in a permanent decrease in the amount of water stored in aquifers. In recent years, groundwater depletion has become a global problem.

As stated, groundwater depletion is a global problem, the extent of which was not known until recently. The current global groundwater footprint is approximately 3.5 times the actual size of an aquifer, and approximately 1.7 billion people live in areas where groundwater resources and/or groundwater ecosystems are threatened. That is, 80% of aquifers have a groundwater footprint smaller than their area, meaning that the global net value is driven by a few heavily overexploited aquifers [83]. According to the global groundwater extraction volume (12,600 km^3 year^{-1}) and the total global groundwater reserves (~11,000,000 km^3 year^{-1}) (Figure 1B), there is a relatively small amount of groundwater [11,84], and a theoretical calculation estimates that groundwater can be mined for nearly 900 years. It seems that the global water consumption is manageable in the total range, and there is still plenty of fresh water for us to use without considering replenishment. However, water scarcity is a local problem or regional phenomenon, meaning that global boundaries must be spatially narrowed to reflect the differences in water availability. In many areas, the depletion of aquifers is a reality that is mainly manifested in the rapid decline of local groundwater levels measured at well locations.

Currently, most of the world's fresh water is extracted in areas with water stress, which suggests that spatial patterns of water use rather than absolute water scarcity require further assessment to reduce human-imposed pressure on fresh water. Fresh water consumption around the world is mainly used for crop irrigation, and it is necessary to establish boundaries between food security and fresh water. It is therefore necessary to set targets for food production within the narrowed waterside boundary of the Earth. The historic granaries moved from the water-rich south to the arid north from 1980 to 2015, increasing the water-scarcity footprint by 40% [85].

This result indicates that when grain production in China's water-scarcity regions declines to 80%, the loss in national grain production is only 8% and can be compensated for by closing the yield gaps in other regions [86]. The world's per capita freshwater intake is 552.1 m^3 year^{-1}, of which approximately 70% is for agriculture [87]. Therefore, the amount of irrigation water used for agriculture per capita is 386.47 m^3 year^{-1}. The global per capita agricultural land is only approximately 0.7 ha, accounting for 37.9% of the world's per capita land area [88]. Based on these data, we can determine that the maximum irrigation amount should be 552.1 m^3 ha^{-1} year^{-1}. Around the world, approximately 55–70% of arable land needs irrigation for successful production [89]. The percentage of land using irrigation worldwide is shown in Figure 2.

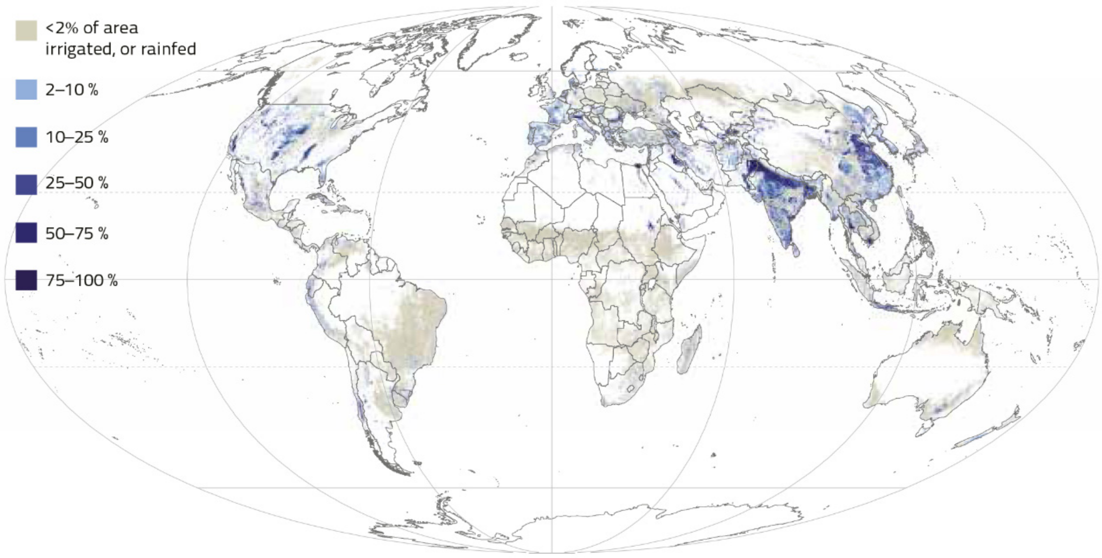

Figure 2. The percentage of land using irrigation worldwide in 2015. In the last 50 years, water resources and agriculture have made remarkable progress. The large-scale development of the water infrastructure makes water serve the people. Although the world's population has increased from 2.5 billion in 1950 to 6.5 billion today, the irrigated area has doubled, and the amount of water extracted has tripled. Agricultural productivity has increased thanks to new crop varieties and fertilizers, as well as extra water for irrigation. In 2003, 850 million people in the world were food insecure, with 60% living in South Asia and sub-Saharan Africa and 70% of the poor living in rural areas. In sub-Saharan Africa, the number of food-insecure people increased from 125 million in 1980 to 200 million in 2000.

Irrigation management aims to increase food production, contribute to economic development, reduce poverty through improved performance, and irrigate agriculture to promote the productivity and sustainability of irrigation systems. Therefore, in consideration of the sustainable use of fresh water, the upper limit of irrigation should be controlled at 1003.82 m^3 ha^{-1} $year^{-1}$. According to this calculation, the world's consumption of fresh water for agricultural production is approximately 4900 km^{-3} $year^{-1}$. This irrigation limit applies to areas where groundwater is extracted for irrigation, and there are particular areas where groundwater is overdrawn, causing a reduction of 80% (803.06 m^3 ha^{-1} $year^{-1}$).

3.2. Land Resources Limit Food Production

Different factors determine the availability of food for the largest number of inhabitants on Earth. Appropriate soil, energy and fresh water are the most fundamental factors determining food security since agriculture provides the largest part of our food supply. Land is an important resource because it is a source of food and contributes to the global biogeochemical cycle. Land resources also provide agricultural production and support many other human needs and services.

Many studies have investigated the carrying capacity of humans on Earth. Sustainable food production for a rapidly growing global population is an important test of the land carrying capacity. The current challenge is how to increase food production without making a marked increase in arable land. To meet the demand for food production, an additional 2.7 to 4.9 million hectares will be needed for agricultural production [90]. One-third of arable land has been polluted, and the use of polluted land will be an important challenge to overcome in modern agriculture. In addition, food security is becoming increasingly difficult in the context of climate change and its impacts on crop growth, yields and disease susceptibility.

The use of existing land also faces other challenges and is crucial to ensuring the safety and sustainability of the production systems involved. Approximately 25% of the world's land resources are highly degraded, 44% are moderately degraded, and pollution levels are steadily rising [91]. Land degradation is an umbrella term that includes a variety of land conditions, such as desertification, salinization, erosion, compaction, or the establishment of alien invasive species. In recent years, there has been a growing belief that land degradation can be defined as a natural or man-made activity that reduces the productivity of land or soil.

Many researchers believe that land degradation is primarily soil-nutrient constrained, leading to reduced productivity, which leads to reduced benefits or economically unviable practices, or to constraints due to problems such as erosion, wetland development and soil salinization that make the land unsuitable for growing crops. The use of technical means to overcome severe soil degradation has resulted in considerable crop production in the short term, but the sustainable use of land resources is the primary consideration in the long term. Therefore, increasing the area of farmland without causing ecological damage is an urgent problem at the global level and requires more attention.

It is generally recognized that the increase in cultivated land area has caused great disturbance and damage to nature. However, there are two main strategies for meeting the growing global demand for food, i.e., maximizing the existing agricultural land or increasing crop yields. Many people believe that increasing the amount of fertilizer and pesticides is the most effective and direct way to increase food production. However, the excessive use of pesticides, herbicides and fertilizers has caused widespread collateral damage to the wider environment [92].

The excessive use of fertilizers also leads to biodiversity loss and pesticide resistance, as well as to the emergence of new pests and pollution, reduced freshwater supplies, soil degradation and erosion, and direct health hazards. Fertilizers and pesticides can linger in the soil for a long time and can affect soil microbes or interfere with soil health. The soil fertilizers and pesticides of the amendment strongly affect various functions and properties of soil, such as rhizome deposition, the nutrient contents of massive and rhizosphere soil, soil organic carbon, pH, water, and soil enzyme activity. Therefore, we should find the food production peak, which in turn determines the artificial measures necessary, such as fertilization and pesticides.

We collected data on the yields of 1516 major food crops, including rice, wheat, maize, and potatoes (Figure 3). We recommend the control of yield limits for major food crops, of which rice, wheat, maize, and potato yields should not exceed 6920.41 kg ha^{-1}, 4345.05 kg ha^{-1}, 5348.43 kg ha^{-1}, and 38,928.5 kg ha^{-1}, respectively. Using data from thousands of field trials around the world, we found that rice, wheat, and maize yields increased with increasing nitrogen application rates at levels less than 240 kg ha^{-1}. The yield of rice and wheat is highest when N is applied at 180–240 kg ha^{-1}, but decreases when N is applied above this range. When food production reaches its technical peak, the shortage of arable land will become a key factor restricting food production. As the world's existing land area, a generally favorable climate and deep soil provide the conditions for stable food yields, further controlled cropland expansion is needed to realize the potential for increased agricultural output.

The great expansion of arable land has contributed significantly to food security in recent decades, resulting in a 28% increase in grain production [93,94]. This 28% increase in grain production was due to a 2.4% increase in the cropland area [95]. Bruinsma [96] indicates that 78% of the increase in the crop yield between 1961 and 1999 was due to the increase in yield, and 22% was due to the increase in harvesting area. Approximately 3 billion hectares of the world's 13.4 billion hectares are suitable for crop production, approximately half of which are already cultivated (1.4 billion hectares in 2008) [93,96]. Increasing the area of reclaimable farmland is an effective means to improve crop production.

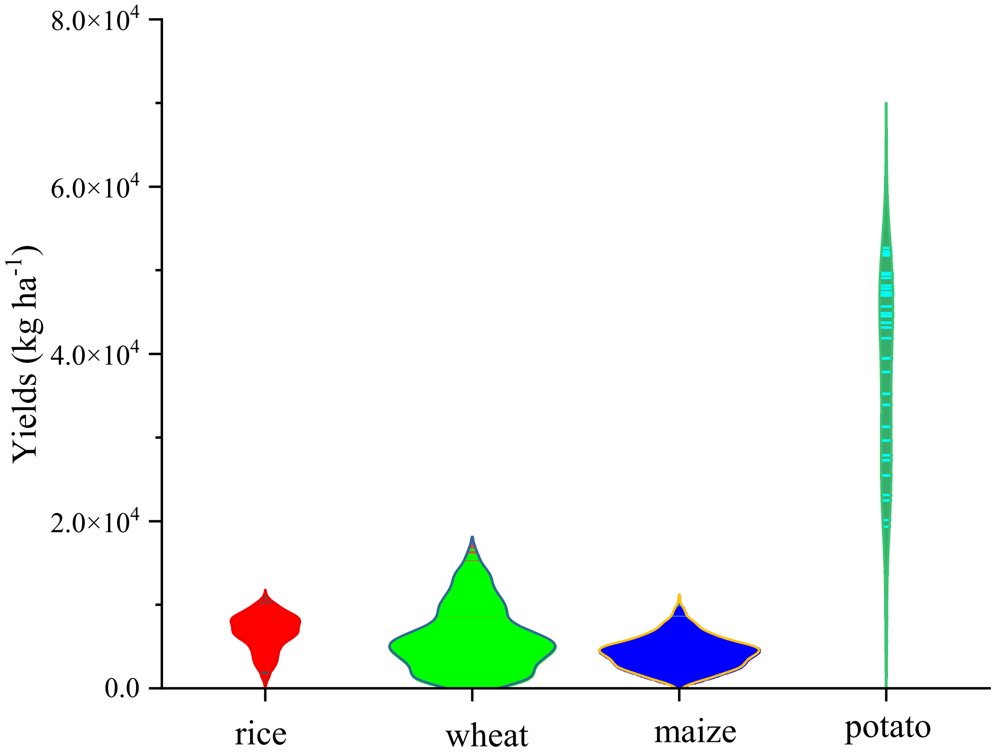

Figure 3. Rice (n = 264), wheat (n = 615), maize (n = 637), and potato (n = 52) yields corresponding to different field management techniques. The solid line in the middle of the box represents the median value. The box boundary represents the upper quartile and the lower quartile. The whisker caps indicate the 90th and 10th percentiles.

However, according to researchers, much of the land that can be cultivated is ecological forests, which would be highly undesirable for large-scale agricultural use because of the impact on biodiversity conservation, greenhouse gas emissions, regional climate and hydrological changes, and the high cost of providing the necessary infrastructure [97–99]. It is difficult to balance the contradiction between expanding cropland area and ecological protection. The proportion of global cropland area in the total land area has continued to increase, from 10.32% in 1961 to 11.97% in 2017 [100]. We expect the proportion of global cropland area in the total land area to reach 12.72% by 2050 and 13.73% by 2100.

4. Impact on Food Security

A key step in promoting sustainable agriculture is to assess the productivity of different agricultural systems around the world. Historically, the agricultural strategy was assessed based on a narrow range of standards, such as profitability or yield. In the future, the evaluation of agricultural systems should be based on environmental sustainability and the stability of food production. The stability of food production may be at risk under climate and environmental changes, as climate and the environment could be important determinants of future food production, food security and food prices [101].

Sustainable food production is closely related to the ultimate environmental carrying capacity [102]. All measures to increase food production should fall below environmental carrying capacity limits. For example, irrigation is an effective way to increase crop yields, but the ultimate carrying capacity of irrigated water resources will affect the sustainability of food production [103]. Fertilization is another important field management measure used to improve grain yield, but the long-term damage of excessive fertilization to soil in the pursuit of high yields and stable yields will affect the sustainability of food production [104,105].

These processes are relevant to national and local development. Understanding such linkages or connectivity is therefore crucial to restoring soil quality and mitigating degradation. Various activities can be considered as conservation practices as they maintain or improve soil fertility or reduce soil erosion, runoff, and pesticides. These activities include management measures such as conservation tillage, soil conservation crop rotation and land improvement.

The current agricultural research results and future research direction should be clearer; that is, we must establish the environmental boundary theory of food safety production, and the critical point of "food security-environmental carrying capacity" should not be broken. It is necessary to immediately stop the overextraction of groundwater in pursuit of high yields. A "soft solution" to water shortages focuses on improving overall water productivity in agriculture [106]. Innovative irrigation practices can improve water use efficiency, gain economic advantages and reduce environmental burdens [107]. Drip irrigation is one of the most effective irrigation techniques worldwide [108]. Sprinkler irrigation also significantly affects crop yield under the interaction of irrigation frequency and irrigation time [109].

According to crop water demand physiology and soil conditions, precision irrigation, including irrigation amount, irrigation time, irrigation frequency, and irrigation times, can be used. However, the difficulty in implementing widespread precision irrigation is encouraging farmers to accept higher water prices due to improved equipment systems. The application on a large scale requires farmers to gain more knowledge about the wider environmental benefits and economic advantages of precision irrigation. Farmers generally lack the incentives and means to understand crop water use, actual irrigation applications and crop responses to different water management practices, all of which affect the current level of water efficiency on their farms. The water use efficiency of agricultural water management will remain unknown, and farmers will have little incentive to adopt more effective practices. Sustained knowledge exchange is necessary so that all stakeholders share a greater share of the responsibility for addressing the critical points of crop production and the ultimate carrying capacity of water resources.

Precise fertilization techniques should be applied in agriculture. The system of fertilization is determined according to the nutrient physiology of crops and soil conditions, such as the time, amount, proportion, times and quantity of fertilization [110]. The processes of watering and fertilization should be coupled. The target yield is determined according to the growth status of crops and the yield of the previous season. According to crop nutrition theory data, the fertilization formula is formulated. The formula should be adjusted according to soil conditions. The ratio between the amount of fertilizer absorbed and the amount of fertilizer applied under drip irrigation can be used to calculate the amount of fertilizer applied under drip irrigation.

The use of mulch and other mulch materials can retain soil moisture, reduce soil evaporation, inhibit weed growth, affect soil microorganisms, control soil structure and temperature, and provide aesthetic benefits. The selection of suitable mulch materials should be combined with effective fertilizer management strategies. In addition, crop types, crop management methods and climatic conditions are important factors affecting suitable mulching materials and nitrogen management strategies. Reducing pests and weeds is essential for crop management in the field and can further improve fertilizer use efficiency. A better understanding of the interactions between major nutrients and other nutrients, as well as mulching, may help to understand the importance of a balanced supply of fertilizers, thereby improving plant growth, water use efficiency, fertilizer use efficiency and yield.

Biotechnological methods have the potential to increase crop yields under different environmental pressures. Molecular breeding, genetic engineering, and their combination with conventional breeding make crops better able to withstand changes in salinity, drought, temperature and solar radiation [111,112]. With current and emerging technologies such as rapid RNAi (rapid gene recognition), target gene replacement cycles, marker-assisted selection, chromosome engineering, genome-wide selection and nano-biological technology, designers are developing and improving the functions of crops that can be used for natural resources, such as water, soil nutrients, carbon and nitrogen in the atmosphere, more efficiently than ever before [113,114]. The benefit of crop improvement brings more benefits than improving grain production, which can reduce the value of the environmental bearing capacity limit. Farmers supported by low-yield land will receive unexpected benefits, including economic benefits, social welfare, and ecological benefits. In addition, the production of crops can be improved by the indirect manipulation of the quantitative trait locus (QTL) to control the genetic variation in the characteristics and physiological mechanisms of biomass production and its distribution.

To ensure global food security, a new green revolution in agricultural productivity is needed to dramatically increase crop yields and the supply of food. This goal requires an integrated, multifaceted, and sustainable approach that will increase production per unit area and optimize the resource use efficiency of crops. The successful and acceptable application of biotechnology to crop breeding will be essential to provide the required stepwise increases in production.

Diversified cropping systems (farmland biodiversity and ecosystem services) are an effective way to balance food production and environmental impacts. In the future, agricultural research and innovation need to focus on resource efficiency, production stability, minimizing environmental impacts, buffering extreme events and adapting to local conditions.

Reliable food production and distribution determine the availability of food, and both are key factors in achieving food security. A major problem is the worldwide distribution of food; for example, poverty-stricken areas have major food shortages, while other areas have an increasingly obese population. A partial solution would be the achievement of an equitable distribution of food resources.

The environment for agricultural production, trade and consumption is more dynamic and unpredictable. Knowledge, information, and technology are increasingly generated, disseminated and applied through the private sector. There are changes in the ability to utilize knowledge developed elsewhere or for other purposes. The knowledge structure of the agricultural sector is undergoing major changes in many countries. Agricultural development increasingly takes place in the context of globalization. Based on a historical view of the assumptions of environmental constraints on food production over the past few decades and looking into the future, we analyze the types of interdisciplinary research required to improve productivity.

Past experience in using global generalizations of the state of the planet and future trajectories have proven unsatisfactory. The sustainability paradigm is suffering a general insufficiency of problem-solving power [115]. Those analysts go on to state they are seeing an accumulation of anomalies (problems that resist solution under the sustainability paradigm) and in their commentary they sound an alarm to warn the scientific community about the possibility of a paradigm crisis in sustainability science. We also presented empirical, quantitative data that might be interpreted as demonstrating that the scientific community is losing trust in the paradigm.

There are real problems that are faced by individuals and societies around the world which stem from population numbers in specific locations, resource utilization, and current imperfect technologies and policies. Nevertheless, despite the challenges, food production is growing as fast as population demand, life expectancy is increasing around the world and the planet is getting greener [116,117] and many new technological advances in agriculture are developing rapidly [118], including gene editing [119] and new laser biotechnology [120]. This is not to say that broad metrics cannot be useful and there are some interesting new approaches [121] but they need to demonstrate real-world applicability and usefulness.

We need to integrate the environmental carrying capacity boundary theory into the agenda, as we look for all the strategies to feed 9 billion people by 2050 and beyond. This approach calls for the establishment of more effective cooperative institutions around the world to further explore the limits of the natural environmental carrying capacity. The achievement of an increased food supply with environmental protection requires research that combines engineering, technology, science, policy, and action.

5. Conclusions

Solutions to ensure maximum food safety and water resources could include the following methods: First, less water can be used for irrigation, such as by using drip irrigation with film mulch, irrigating only in the critical period of crop physiological water demand or using underground drip irrigation with special crops. Second, more drought-resistant crops can be grown in areas with groundwater depletion, and drought-resistant crop varieties can be bred all over the world; additionally, targeted measures, such as metering and the regulation of groundwater pumping, can be implemented. Third, food production can be coordinated and managed domestically and globally, such as by adjusting the main production grain regions to alleviate the intensification of groundwater depletion for irrigation, optimizing high-water-consumption crops in humid and semihumid areas, planting drought-resistant crops in arid and semiarid regions, and exporting the grain yield to countries with less food.

Increasing food production with limited land resources with environmentally sustainable development is an even greater challenge. It is therefore necessary to assess the impact of urbanization on farmland expansion at the global, national, and subnational levels to identify potential conflict areas and conflict-forming strategies to identify more sustainable forms of urban expansion.

To achieve sustainable development, it is necessary to plan effective agricultural production systems, taking into account resource management and respecting natural services. Energy input–output analysis is often used to evaluate the relationship between the efficiency of production systems and environmental impacts, but the bearing capacity of the environment is often neglected. Some researchers have used environmental assessment approaches, such as ecological footprint, material flow analysis, ecological network analysis, life cycle analysis, and energy and renewable energy, to assess environmental performance at different scales, focusing on sustainability analysis.

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