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Review

Soil Degradation, Land Scarcity and Food Security: Reviewing a Complex Challenge

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Abstract: Soil health, along with water supply, is the most valuable resource for humans, as human life depends on the soil's generosity. Soil degradation, therefore, poses a threat to food security, as it reduces yield, forces farmers to use more inputs, and may eventually lead to soil abandonment. Unfortunately, the importance of preserving soil health appears to be overlooked by policy makers. In this paper, I first briefly introduce the present situation concerning agricultural production, natural resources, soil degradation, land use and the challenge ahead, to show how these issues are strictly interwoven. Then, I define soil degradation and present a review of its typologies and estimates at a global level. I discuss the importance of preserving soil capital, and its relationship to human civilization and food security. Trends concerning the availability of arable agricultural land, different scenarios, and their limitations, are analyzed and discussed. The possible relation between an increase in a country's GNP, population and future availability of arable land is also analyzed, using the World Bank's database. I argue that because of the many sources of uncertainty in the data, and the high risks at stake, a precautionary approach should be adopted when drawing scenarios. The paper ends with a discussion on the key role of preserving soil organic matter, and the need to adopt more sustainable agricultural practices. I also argue that both our relation with nature and natural resources and our lifestyle need to be reconsidered.

Keywords: soil degradation; land degradation; soil conservation; scenario analysis; agriculture; organic agriculture; food production; food security; climate change; ecosystem services; precautionary approach

1. Introduction: The Key Priority Represented by Soil Conservation

The 68th UN General Assembly declared 2015 the International Year of Soils (IYS) [1]. The UN stated that "... *soils constitute the foundation for agricultural development, essential ecosystem functions and food security and hence are key to sustaining life on Earth*" [1] (p. 1). In the same document, the UN declares:

- the sustainability of soils is key to addressing the pressures of a growing population,
- the sustainable management of soils can contribute to healthy soils and thus to a food-secure world and to stable and sustainably used ecosystems,
- good land management is of economic and social significance, and this includes soil management, particularly for its contribution towards economic growth, biodiversity, sustainable agriculture and food security, which in turn are key to eradicating poverty and allowing women's empowerment,
- it is urgent to address issues such as climate change, water availability, desertification, land degradation and drought, as they pose global challenges,

- there is an urgent need at all levels to raise awareness and to promote sustainable use of our limited soil resources using the best available scientific information and building on all dimensions of sustainable development.

José Graziano da Silva, FAO Director-General, declared that "*The multiple roles of soils often go unnoticed. Soils don't have a voice, and few people speak out for them. They are our silent ally in food production.*" [2]. We have to praise the UN and FAO for this much-needed initiative aimed at reminding us about how our life is inescapably dependent on soil and natural resources. This is a fact that urbanized people often tend to forget as they live, culturally and physically, far away from the land, the soil and the food system.

Unfortunately, soil has always been associated with "dirt", whereas "culture", emphasizing knowledge and appreciation of literature, arts, philosophy, and the development of humanist ideas, has been perceived to be superior to the provision of food, feed, fiber, and fuel to sustain the very existence of humankind. Consequently, our dependence on natural resources has been overlooked by intellectuals and cultured people, as well as by our economists, and in turn by society. It is unfortunate that neo-classical economics, which we trust in making decisions about our future, simply excludes natural resources (the biophysical side of our economies) from its theories, considering them as nearly free and infinite, therefore not a matter of concern. In the last decades, people's environmental concern has begun to spread. Issues such as pollution and climate change have gathered widespread attention, as have energy, water and the conservation of biodiversity, pushing policy-makers to take action. Concern about soil conservation has been raised by soil scholars and works have been produced to raise awareness among farmers, policy makers and society e.g., [3–10]. Since the 1990s, the concept of soil quality has become popular in the field (for the USA see, for example, [8]). Nevertheless, the importance of soil conservation has not yet gained the attention it deserves, and the topic is not as popular as other issues within the environmental discourse and people's awareness [9,11,12]. For example, in Europe, the Joint Research Centre (JRC), highlights that there is little public awareness of the importance of soil protection [11], and an "European Network on Soil Awareness" has been created, "*To establish an action plan for the development of measures/programmes/initiatives to raise awareness of the importance of soil across European society (*i.e., *policy makers, general public, universities, schools, industry,* etc.*)*" [13].

Within the activities undertaken in relation to the International Year of Soils, FAO and the Intergovernmental Technical Panel on Soils (ITPS) released an important report on the status of soils and related issues [14]. This is the first such report on this topic, and aims at raising awareness amongst both policy makers and lay people.

Agriculture, the domestication of plants, animals, ecosystems and soils, is the practice by which we have produced our food and fueled our civilizations for more than ten thousand years. It is of crucial importance to realize that soil health and water supply are the cornerstones agriculture is based upon. So much so, that there cannot be agriculture without water, and we cannot have vegetation and agriculture without soil. Soil health, therefore, is tightly linked to land use, food production and to people's health, as well as to the use of inputs, and to many other environmental and socioeconomic issues. The optimism of the 1970s and 1980s, following the great achievements associated with the green revolution, namely the rise in productivity in Mexico and India, had to face the problems associated with the increasing pressure the "revolution" created on finite soil, water, and other natural resources [15–19].

1.1. The Great Achievement of Agriculture Since the "Green Revolution"

With the so-called "green revolution", the productivity of the main agricultural crops has more than doubled, on average, with some cereals reaching a staggering 4- to 5-fold increase [15,20–25]. This has helped meet world food demand and save hundreds of millions of people from starvation. Asia, for example, which was threatened by hunger and mass starvation as late as the mid-1960s, became self-sufficient in staple foods within 20 years, even though its population more than doubled [24,26]. Of the productivity increase, it has been estimated that about 70% is due to the intensification of agriculture (e.g., new varieties, irrigation, use of inputs), and the remaining 30% is a result of new land being brought into production [24,27,28]. It must be highlighted that the doubling of global food production during the past decades has been accompanied by a massive increase in the use of inputs, such as synthetic nitrogen, phosphorus, pesticide applications and extensive use of irrigation and energy [15,16,22,29–31]. The intensification of agriculture has also led to the degradation and exhaustion of soil and land, which is one of two topics this paper addresses. Along with increased food supply and improved health conditions, world population has risen from 3 billion in 1960 to about 7–7.5 billion (2015 estimates); it is expected to reach 8.5 billion in 2030 and 10 billion in 2050 [23,24,32–34]. Agricultural land has become one of the largest terrestrial biomes on the planet, occupying an estimated 40% of the land surface [20,30,35]. Agriculture also accounts for 70% of all water withdrawn from aquifers, streams and lakes [36,37]. Since the 1990s, however, there has been a slowdown in the growth of world agricultural production. World cereal output stagnated and fluctuated widely [21,24,25,27,32,38]. Food imports played an important role in allowing those countries that could afford it to meet the internal food demand and actually increase food consumption [27]. Experts warn us that addressing the stagnating yields of our most important croplands is of paramount importance; failure to identify and alleviate the causes of yield stagnation, or reduction, will have a major impact on the future of global food security. Many issues, including yield reduction, have coalesced to determine agricultural trends in recent decades (e.g., population pressure, water supply, markets, policies, climate) [21,23–27,32,39].

A recent work by Grassini *et al.* [38], nevertheless, seems to indicate that some physical limits to yield productivity may have already been reached for rice, wheat and maize, and that further attempts to increase productivity may result in a decreasing marginal return on investment (see also [21]). The authors explain, " . . . *as farmers' yields move up towards the yield potential threshold, it becomes more difficult to sustain further yield gain because it requires fine tuning of many different facets of management in the production system*" [38] (p.8). Alexandratos [27] warns us that while in some cases food insecurity can be imputable to social issues, such as distribution, access and entitlement, focusing just on this issue " . . . *can be misleading if it induces us to ignore the stark reality that it is often failures to develop agriculture and increase food production locally that lie at the heart of the local food insecurity problem*" [27] (p. 5910). While we can fully agree with such a statement, one should also consider that such a failure might also have been induced by external forces, such as markets and international policies. The dumping of highly subsidized agricultural commodities from developed countries has greatly harmed farmers in developing countries [40,41]. For decades, the World Bank has actively discouraged African countries from investing in rural development [40–44], to the point of dismantling the work carried out by Norman Bourlaug for the African green revolution [41]. Nor should we ignore some other major issues that prevent the agriculture of poor countries from developing: local conflicts, widespread corruption, lack of infrastructure, poor education, and lack of scientific support, lack of credit and land concentration [44–48].

1.2. The Pressure on the Land and the Appropriation of the Net Primary Productivity of Nature

Out of a global land mass of 13.2 billion ha, 12% (1.6 billion ha) is currently in use for the cultivation of agricultural crops, 35% (4.6 billion ha) comprises grasslands and woodland ecosystems, and 28% (3.7 billion ha) is forested [37]. According to Ramankutty *et al.* [49], in the year 2000, there was about 12% (1.5 billion ha) cropland and 22% (about 2.8 billion) pasture. The authors argue that the assessments are complicated by misunderstanding and confusion regarding the definitions of cropland and pasture. Data from the Global Land Cover Share-database, which represents the major land cover classes defined by the FAO, provide the following figures for land cover: 13.0% croplands, 13.0% grasslands (including both natural grasslands and managed grazing lands); 28% "tree-covered areas" (including both natural and managed forests); 9.5% shrub-covered areas; and 1% artificial surfaces (including urbanized areas) [50]. It has been argued that land degradation affect all types of land cover [50].

Over the past 50 years, the world's net cultivated area has grown by 12%, mostly at the expense of forest, wetlands and grassland habitats. At the same time, the global irrigated area has doubled [37]. Tropical forests were the primary source of new agricultural land in the 1980s and 1990s, representing about 30% of new agricultural land; 55% is represented by intact forest and 25% by disturbed forest [28]. By 2050, the demand for new agricultural land (due to population pressure, diet change and demand for biofuels) is expected to increase by about 50%. It is very probable that tropical forests will account for that land; therefore, further deforestation is to be expected, together with an exacerbation of soil degradation [28,51].

The future expansion of cropland will inevitably affect remaining ecosystems, their biodiversity and the services they provide. It has been estimated that Human Appropriation of Net Primary Productivity (HANPP) may have reached about 40%–50% of the net primary production of potential vegetation [16]. According to the Global Footprint Network [52], at present humanity uses the equivalent of 1.6 planets to provide the resources we use and to absorb our waste, an underestimate according to some environmental experts (e.g., [16,53–55]). Water supply is also expected to become a major problem in the future almost everywhere on the globe [36,56,57].

1.3. Is There Enough Land to Meet Future Needs?

Since the 1990s, a discussion has been going on among the experts on whether there is sufficient land to meet the future demand for food and fiber for the increasing population. Due to the increase in consumption as expected from population growth and the changes in food consumption patterns, it has been estimated that global agricultural production levels for 2005 would need to increase by 70%–110% to meet demand in 2050 [32,58,59]. Over the coming decades, further annual yield increases of 1% to 1.5% are needed to meet the projected demand for wheat, rice and maize [60]. Some experts (e.g., [23,58,60]) argue that this is a challenge, because with the present yield trends, just meeting current demand already appears difficult. According to FAO [61], the arable area in developing countries will have to increase by almost 13%, or 120 million ha, over the years from 1997–1999 to 2030 to meet the food demand (about double the area of France, 64 million ha). More recent estimates (e.g., [62]) suggest that, by 2030, an additional 81 to 147 million ha of cropland will be needed compared to the 2000 baseline. The authors argue that due to rapid urbanization, bioenergy policy mandates, forest plantations, and new protected areas, which are competing for land access, the total additional land demand is likely to range from 285 to 792 million ha between 2000 and 2030 (the latter figure equals the contiguous surface of the USA—800 million ha—without Alaska or other non-contiguous, overseas, states/territories).

Unfortunately, people have been building and expanding their cities on the most fertile soils, thereby squandering such a valuable resource [4,9,63]. This pattern is unlikely to change in the future. Continued urbanization will pose a further threat to agriculture production [63,64], along with the changing patterns of food consumption by the growing urban population [32].

1.4. Soil Degradation: A Threat to Future Food Security

Along with assessing the quantity of new land, soil quality is also a matter of concern. Soil degradation has been defined as a "global pandemic" [18], as it is a world problem.

Land and soil degradation includes loss of soil cover, soil erosion, salinification, acidification and compaction. The gravity of soil degradation, and the possibility to remedy it, depend on the type of degradation process, with soil erosion and salinification being very serious as they can drive farmers to abandon the land, or face the very high management costs to keep cropping it. Soil degradation has become a very serious problem in densely inhabited agricultural regions. India supports 18% of the world's human population and 15% of the world's livestock population, but has only 2.4% of the world's land area [65]. Soil degradation is causing a decline in crop productivity and huge economic loss, putting the food security and livelihood of farmers at risk [65]. In sub-Saharan Africa (SSA), soil degradation (nutrient depletion is the primary form of soil degradation in SSA), is leading to a decline in crop productivity, and has been linked to hunger and poverty [66]. With regard to South America, Wingeyer *et al.* [67] point out that, although newly introduced extensive monoculture have brought some economic benefits, nevertheless, the current agricultural practices, even with the adoption of the No-Tillage system, result detrimental to long-term soil conservation. Indeed, monocultures, in combination with a general lack of biodiversity, cause soil degradation through wind and water erosion, SOM depletion and nutrient loss.

Soil degradation forces farmers to look for new land. Nevertheless, most new land would be represented by marginal land, or (more probably) by the land now covered by the tropical forests in Latin America and Africa. Such soils are not very suitable for agriculture production and require high investments to become productive [3,4,6,7,62,66,68–70]. The assessment of the quality of land presently cropped is also an issue, as its level of degradation will affect demand for inputs, productivity, and eventually for new and more fertile land [6,14,24,32,62,68].

FAO models estimate about 25% of land to be highly degraded [37,71] (Figure 1). Estimates of soil degradation are highly variable (I will discuss this point in detail in Sections 2 and 4). The overall effects of soil degradation pose a major threat to food security especially in poor regions. FAO [37] highlights that there is a strong relation between land degradation and poverty. It is urgent, therefore, to act to halt soil degradation and adopt practices to improve soil health.

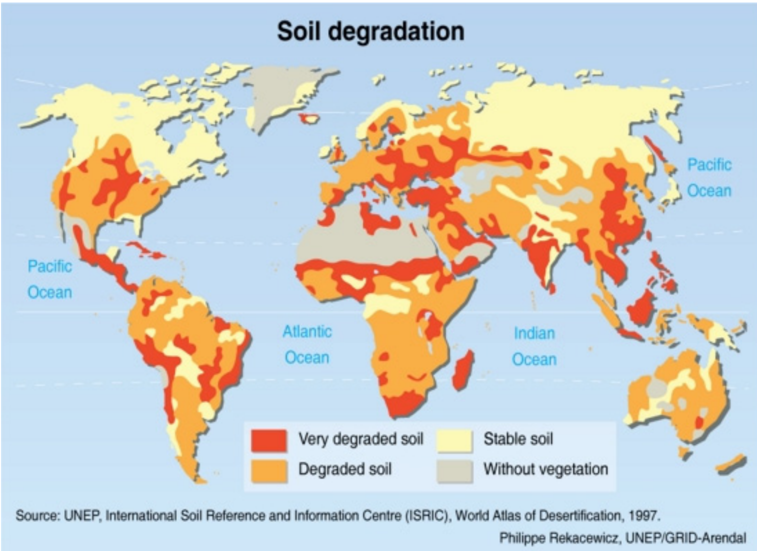


Figure 1. Estimates of the level of soil degradation at a global level (source: [72], public domain for non-market purposes).

Concerning the future, we must take into account the potential effects of climate change on soils and agriculture. Although some regions may benefit from global warming, and increase their agricultural output, (where water is not an issue), many other areas of the globe, especially the more populated ones, may experience a reduction in agricultural productivity [23,32,55,56]. Nizeyimana *et al.* [63] argue that we need to develop models able to link gradual changes in soil quality, or the risk of crossing a soil threshold, to changes in human welfare in real time. However, as Lambin and Meyfroidt, [73] observe, the high complexity of the globalized world makes predictions of expected land use impact of national policies highly uncertain. The authors argue that in a more interconnected world, agricultural intensification may cause more rather than less cropland expansion. They observe that regulations on land use to protect natural ecosystems in some regions may result in displacing ecosystems elsewhere by increasing imports. For example, mitigating climate change by mandating the use of biofuels in one place may increase global greenhouse gas emissions due to indirect land use changes in remote locations. Again, a decrease in rural population due to migration may increase land conversion through remittances being invested in land use.

Soil and water are the basic resources for human survival. In the past, civilizations rose due to their high-quality soils and abundant water supply. Civilizations, conversely, then fell because they had exhausted their soils and mismanaged their water. Poor knowledge of soil ecology and inadequate technology may excuse them for their mistakes. However, today, lack of experience, poor knowledge and poor technology are not valid reasons that can excuse us for spoiling our soils. We are going through what is possibly a very critical time. Population pressure will pose major global challenges both on natural resources and on the social fabric of our societies. Preserving soil health and the water supply are, more than ever, a matter of survival, while we are going through a transition period towards a possibly more balanced co-existence with the planet.

Estimates of the future availability of agricultural land and soil quality are highly uncertain. The complexity of multiple pressures induced by the globalization process, the potential effect of climate change and climate extremes, and the critical issues regarding future energy and water supplies add to our level of uncertainty. There are so many elements at play, and so many more that we do not even know to be at play (because we ignore their existence) that we may not be able to predict how the world will be in 2050. Such uncertainty and high stakes require an effort toward increasing our knowledge, enhancing awareness concerning the importance of preserving natural resources, and adopting management practices to preserve those resources (our real capital). Furthermore and above all, we need to adopt a precautionary approach to reduce the margins for mistakes that we cannot afford to make. Eventually, a more ethical approach towards our relationship with nature should be promoted.

The paper is organized as follows. In Section 2, I define soil degradation and present a review of its estimates at a global level. In Section 3, I discuss the importance of preserving soil capital, as there is no substitute for it to support human life. Civilizations rose thanks to their soil and declined upon its exhaustion. I argue that the mainstream economic approach may fail to gain a proper comprehension of the issue, as it tends to confuse numerical abstraction with the real meaning behind the figures. Similarly, it fails to recognize the true economic importance of the food system in society. Since the beginning of the assessment exercises (late 1980s), experts have been debating about the problems and limitations of different scenarios (e.g., large uncertainties in the data, different methodologies), as well as the role that soil degradation may play in potential future agricultural land use and in food security. In Section 4, I analyze different scenarios and their limitations. Relying on the World Bank database, I provide further analysis concerning arable agricultural land trends, and discuss their possible relation to an increase in GNP and population and to future trends at a country level. I argue that a precautionary approach must be embraced in the assessment of soil degradation, and that it is urgent to work towards restoring soil health and preventing future soil degradation, also in view of enhancing soil resilience to climate extremes and other potential stressor events. In Section 5, I discuss the key role of preserving soil organic matter and the need to adopt more sustainable agricultural practices. I point out that before introducing new practices and policies, the specific biophysical and socioeconomic characteristics of the context must be properly understood (*i.e.*, what may work in one context may not work in another); local stakeholders should be fully involved in the process of that change. In Section 6, I argue that we may need to reconsider our relation with nature and natural resources, and our lifestyle as well. A novel ethic in relation to the natural world may be needed to raise awareness of our strict dependence on nature, an awareness that our urbanized civilization seems to have lost.

2. Soil Degradation: Definition, Typologies and Estimates of the Problem

How we define soil has been changing over time, and the definitions differ slightly from one discipline to another, or according to the expertise of different scholars. FAO [74] provides a general definition of soil: "*In its traditional meaning, soil is the natural medium for the growth of plants. Soil has also been defined as a natural body consisting of layers (soil horizons) that are composed of weathered mineral materials, organic material, air and water. Soil is the end product of the combined influence of climate, topography, organisms (flora, fauna and human) on parent materials (original rocks and minerals) over time*". The depth of soil is related to the layer in which bio-chemical activity is still present and works to alter the bedrock or sediment.

Soil degradation represents a major threat to food production and environment conservation, especially in tropical and sub-tropical regions (where most of the future population growth will take place). The threat to sustainable development caused by land degradation was explicitly recognized at the 1992 Earth Summit and the 2002 World Summit on Sustainable Development. A unique UN Convention to Combat Desertification was created in 1994 to specifically coordinate efforts to reduce land degradation in dry lands and promote sustainable development [75].

2.1. Defining Soil Degradation

FAO [56] defines soil degradation " … *as a change in the soil health status resulting in a diminished capacity of the ecosystem to provide goods and services for its beneficiaries. Degraded soils have a health status such, that they do not provide the normal goods and services of the particular soil in its ecosystem*".

"Ecosystem goods" refer to the absolute quantities of land products having an economic or social value for present and future generations. They include animal and vegetal production, land availability and soil health, and water quality and quantity. "Ecosystem services" concern more qualitative characteristics and their impact on beneficiaries and the environment include such factors as biodiversity and maintaining hydrological and nutrient cycles. None of these can be measured or valued in a simple way. The land degradation definition includes an explicit reference to a time over which degradation is assessed. Georeferenced data on economic goods produced rarely go back more than 50 years [76]. Oldeman *et al.* [76] in "The Global Assessment of Soil Degradation" (GLASOD) describe soil degradation as "a human-induced phenomenon", and point out that in a general sense soil degradation could be described as the deterioration of soil quality: the partial or entire loss of one or more soil functions.

Soil degradation, therefore, refers to a broad spectrum of changes in soil characteristics because of natural or anthropogenic factors that alter their structure and quality, including deforestation and the removal of natural vegetation, agricultural activities, overgrazing, overexploitation of vegetation for domestic use, and industrial activities [7,14,18,19,76,77]. Oldeman *et al.* [76] (p. 7) distinguish two categories of human-induced soil degradation processes: "*The first category deals with soil degradation by displacement of soil material. The two major types of soil degradation in this category are water erosion and wind erosion. The second category of soil degradation deals with internal soil physical and chemical deterioration. In this category only on-site effects are recognized of soil that has been abandoned or is forced into less intensive usages*". Such alterations result in reducing the soil's capability to function and its resilience (the capacity to recover from stressor events), that is, the soil's ability to provide actual or potential productivity or utility (to produce economic goods and services) and to perform environmental regulatory functions [3,7,14,70,78,79].

Soil degradation can occur through the following processes: physical (*i.e.*, erosion, compaction), chemical (*i.e.*, acidification, salinization) and biological (*i.e.*, loss of soil organic matter, loss of biodiversity). The factors that determine the kind of degradation are as follows: soil inherent properties (*i.e.*, physical, chemical), climate (*i.e.*, precipitation, temperature), the characteristics of the terrain (*i.e.*, slope, drainage) and the vegetation (*i.e.*, biomass, biodiversity) [7,77]. The causes that lead to soil degradation are complex and can be of a different nature: biophysical (*i.e.*, land use, cropping system, farming practices, deforestation), socioeconomic (*i.e.*, institutions, markets, poverty), and political (*i.e.*, policies, political instability, conflicts) [3,6,7,14,18,70,76,80,81]. Actually, Blaikie and Brookfield [3] (p.1) point out that "*Land degradation should by definition be a social problem. Purely environmental processes such as leaching and erosion occur with or without human interference, but for these processes to be described* *as "degradation" implies social criteria which relate land to its actual or possible use*". According to [3], land degradation should be a matter of "political ecology", a discipline that combines ecology with political economy.

2.2. Estimates of Soil Degradation

The assessment of the amount of degraded soil and land is a difficult task. There are large differences among the different models concerning the estimates of the extent and intensity of soil degradation [14,71,82,83]. Different definitions of degradation are used by different scholars, models depart from different assumptions and adopt different boundaries, and there are some inherent limits and errors in the information, data and instruments used (e.g., [6,62,68,71,75,76,82–84]).

Although a distinction is made between "soil degradation" and "land degradation", at times these are not properly distinguished in the assessment exercises [14,71,82,83]. FAO [37] explains that "land degradation" is a broader concept than "soil degradation" (or water pollution), as it includes the assessment of the interrelated components of the ecosystem and of the trade-offs that may exist between them: loss of biodiversity, for example, matched against improvements in economic services under intensive farming (see also [75]).

Estimates for agricultural land degradation have been highly variable. During the last two decades, the figures provided by different assessments range from 15 to 80% of global agricultural land [37,71,76,83,85–87]. Later assessments [37,71,85], estimate 25% of the present agricultural land to be highly degraded, about 44% to be slightly-moderately degraded , and about 10% to be recovering from degradation.

Estimates provided by the FAO-UNDP project Land Degradation Assessment in Drylands suggest that the global land status can be categorized (in order of importance) as follows: 25% "High degradation trend or highly degraded lands", 36% "Moderate degradation trend in slightly or moderately degraded land", 8% "Moderate degradation in slightly or moderately degraded land", 8% "Improving lands", 18% "Bare areas" (the remaining 2% is represented by water) [37,71]. Reynolds *et al.* [88], pointed out that dry land prone to degradation, covers about 40% of the earth's land surface and is linked to the subsistence of 2.5 billion people. In such areas, agricultural management plays a key role in guaranteeing soil fertility conservation.

2.3. Soil Erosion and Other Typologies of Soil Degradation

Erosion is a process of soil degradation that occurs when soil is left exposed to rain or wind energy. Poor management of agricultural land induces soil erosion that leads to reduced productivity (which must be compensated with the addition of fertilizers), or, in extreme cases, to the abandonment of the land. Intensive conventional agriculture makes soils highly prone to water and wind erosion, which worsen when situated on a slope. Under natural conditions, annual rates are of the order of 0.0045 $t \cdot ha^{-1}$ for areas of moderate relief and 0.45 $t \cdot ha^{-1}$ for steep relief. In comparison, rates from agricultural land are in the range of 45–450 $t \cdot ha^{-1}$ [69].

Pimentel and Burgess [86], report mild to severe soil erosion possibly affecting about 80% of global agricultural land. Soil erosion has been estimated to reduce yields on about 16% of agricultural land, especially cropland in Africa and Central America and pasture in Africa [89]. On the plot and field scale, erosion can cause yield reductions of 30%–90%. Yield reductions of 20%–40% have been measured for row crops in the USA Corn Belt [69]. Extreme events may be significant in worsening erosion, especially if ground conditions already make the soil prone to erosion, and can produce landscape features that are both dramatic and long lasting. Morgan [69] reports that in nine small catchments under a four year rotation of maize–wheat–grass–grass in Ohio, three of the largest storms, all with return periods of 100 years or more, accounted for 52% of the erosion; 92% of the soil loss occurred in the years when the land was planted with maize.

Salt-affected soils occupy an estimated 950 million ha of land in arid and semi-arid regions, *i.e.*, nearly 33% of the potentially arable land area of the world [7]. Soil acidity and the resultant toxicity caused by high concentrations of aluminium and manganese in the root zone are serious problems in sub-humid and humid regions. Lal [7] reports that soil compaction is a worldwide problem and can reduce crop yield by 20%–55%. Nutrient depletion is another significant process of soil degradation, with severe economic impact on a global scale. To cover the losses, more land would have to be converted to agriculture and more inputs used to replace the reduced soil fertility.

3. The Importance of Preserving Soil as Capital: A Call for a Precautionary Approach

In this section, I present a brief overview of the role of soil in the history of human civilizations, and its key role in their rise and fall. I also present some recent cases of the dramatic effects of soil mismanagement, and discuss the complex chain of locks-in that may perversely drive the conventional agricultural system towards its own collapse. I argue that, while our ancestors might not have had the proper means to be aware of the process of soil degradation, today a lack of knowledge and experience is not an excuse we can use to justify inaction. Presently, economics is the leading discipline to which our society turns to determine the best actions. While economics is surely a useful and necessary discipline (not an exact science though), it is not able to deal with complex issues on its own (as is evident from its poor forecasting accuracy in economic matters alone). In order to deal with soil conservation, we need to embrace a more complex approach and integrate the knowledge from different disciplines and diverse social actors/stakeholders. We must also raise social awareness about our strict dependence on natural resources, such as water, soil, energy and biodiversity.

3.1. Humans and Soil: Is History Always Repeating Itself?

Historically, warnings about the state of the soil have been a constant. Early Greek scholars such as Plato (428/427 or 424/423–348/347 BC) and Aristotle (384–322 BC), and Roman authors such as Lucretius (99 BC–*c.* 55 BC), Livy (64 or 59 BC–AD 17), and Pliny the Elder (AD 23–AD 79) warned their compatriots (without much success) about the detrimental effects of improper agricultural practice and soil over-exploitation [4,9,90]. Lucretius, already in 60 BC, wrote about the soil exhaustion of the Roman countryside, observing how agricultural productivity was declining, and that farmers had to farm more land and work harder than their ancestors to support themselves did. The Roman historian Pliny the Elder attributed the decline of agricultural productivity to the negligence and greed of the urbanized landlords, whose focus was on extracting maximum profit from their land which led to the neglection of practices that could preserve soil health. Pliny the Elder was keen in forecasting that such a state of affairs would eventually lead to a decline of the empire. The collapse of the Roman Empire was probably due to a variety of interwoven events and processes: decreasing marginal returns from expansion, climatic events, plagues that repeatedly ravaged the late empire and may have caused the death of about 30% of its population, widespread greed and corruption, the appearance of powerful enemies, and so on. Along with these problems, however, soil exhaustion played an important role too [4,90–93].

Dale and Carter [90] point out that historians recognize land scarcity as the main trigger to war and colonization; however, it is often overlooked that the conquerors or colonizers ruined their own land before undertaking their expansive actions. The authors also relate the rise and fall of the wealth of early civilizations to the conditions of their soil. Soil exhaustion, loss of soil fertility and salinization, in fact, greatly contributed to the collapse of many early civilizations (e.g., Middle East, Greece, Roman Empire) [4,9,90]. Notwithstanding the list of cases, it seems that the importance of our relation/dependence on the soil is still neglected, or at best undervalued. Montgomery [9] (p. 3) states that "*Soil is our most underappreciated, least valued, and yet essential natural resource*." Hillel [4] (p. 9) pointed out that "*Obviously, we cannot protect what we do not understand*". Scientific advances have greatly increased our understanding of the soil. While in the early history of agriculture, farmers did not know much about the complexity of soil ecology, the influence of the climate, *etc.*, at present we do (even if soil is still the most mysterious living system on earth). What is surprising is that we seem not to really care about soil conservation. Churchman and Landa [94] argue that much has been done for the conservation of biodiversity and famous animals, but the soil on which life strictly and directly depends seems outside our view: "*Underfoot... Unseen... Ignored*." As some scholars observe, the problem is probably that soil degradation is just too slow to be noticed [9,78]: " . . . *the 'quiet crisis' which nevertheless erodes the basis of civilization*" [3] (p.1). While we are ready to act in the case of an extreme event, slow changes tend to escape our perception, or do not cause us to worry much. The fact that something happens at a slow pace may lead us to believe that we have time to take action—in the future, when the problem will be more serious and really worthy of attention. While this strategy may work for some human issues, food is a very different matter (and the cases of hunger and famine are recent reminders even for wealthy countries to take notice). Concerning the present agricultural practices and their effects on the fate of soil, Foley *et al.* [35] (pp. 570–571) concluded that "*In short, modern agricultural land use practices may be trading short-term increases in food production for long-term losses in ecosystem services, including many that are important to agriculture*".

The great achievements of technology may make us feel confident that we will be able to find a techno-fix to overcome any possible problem (e.g., geo/planetary-engineering to halt climate change, GMOs for life-science engineering). However, we should not rely on the belief that human ingenuity will overcome any boundary [4,9,78]. As Montgomery [9] (p. 6) argues, "*Modern society fosters the notion that technology will provide solutions to just any problem. But no matter how fervently we believe in its power to improve our lives, technology simply cannot solve the problem of consuming a resource faster than we generate it: someday we will run out of it*". Hillel [4] makes the case of Rome, which was able to develop grand and highly ingenious technology while failing to prevent soil erosion, to distinguish technology from science. He argues that while technology aims at achieving a utilitarian goal, science aims at acquiring a fundamental understating of the processes and relationships operating in the natural world. While the Romans excelled in practical technology, they disregarded much of science. As the early Roman writers argued, the wealthy city-dweller landlords were more interested in extracting the maximum profit from their rural estates than in caring for the long-term sustainability of their farms' soils [4,90,92].

The Dust Bowl that hit the US plains (Figure 2) in the mid-1930s is considered one of the worst man-made agricultural, ecological and socioeconomic disasters in history. It affected about 20 million ha of land, mainly in Colorado, New Mexico, Nebraska, Kansas, Oklahoma and Texas, forcing about 2.5 million people to migrate (mainly to the West Coast and California). Such an unfortunate event is a telling example of how poor knowledge of the nature and functioning of ecosystems, improper use of technology and the blind search for maximum profit can perversely come together, leading to the total devastation of the environment and the disintegration of human society [4,9,95].

(**a**) (**b**)

Figure 2. The Dust Bowl in the US southern plains during the mid-1930s. (**a**) Dust storm approaches Stratford, Texas in 1935 (photo from NOAA George E. Marsh Album [96], public domain for non-market purposes); (**b**) Texas County, Oklahoma, homestead and field struck by the 1930s Dust Bowl (photo from USDA archives, Farm Service Agency, USDA-Farm Service Agency [97], public domain for non-market purposes).

Historian Daniel Worster, in his detailed account of the Dust Bowl [95], quotes Georg Borgström (a world authority on hunger; 1912–1990) in saying that the Dust Bowl was one of the three worst ecological blunders in history (along with the deforestation of China's uplands around 3000 B.C. and the destruction of Mediterranean vegetation during the Ancient Greek and Roman times). According to Worster [95] (p. 4), the Dust Bowl was " . . . *the inevitable outcome of a culture that deliberately, self-consciously, set itself the task of dominating and exploiting land for all it was worth*." The pure capitalist approach to land use (aiming at extracting the maximum profit), along with the adoption of a specialized one-crop farming system and the mechanization of agriculture, was a recipe for disaster. The industrialization of agriculture set into motion a perverse treadmill. High investments led farmers into debt, forcing them to farm their land more extensively and intensively (the soil capital was spent to service the loans for machinery and fertilizers). Their overproduction drove prices down, forcing many farmers to sell their land to large landowners and speculators who exploited the land even further [4,9,95].

We have come to learn that there are complex relations among ecology, soil, management practices, socio-economic issues, culture, *etc.*, and that perverse traps may be generated and dangerously self-perpetuated [3,37,79,81,89,95,98–101] (Figure 3). That calls for the necessity to adopt a broad, holistic approach to the analysis of the problem of soil degradation and rural development.

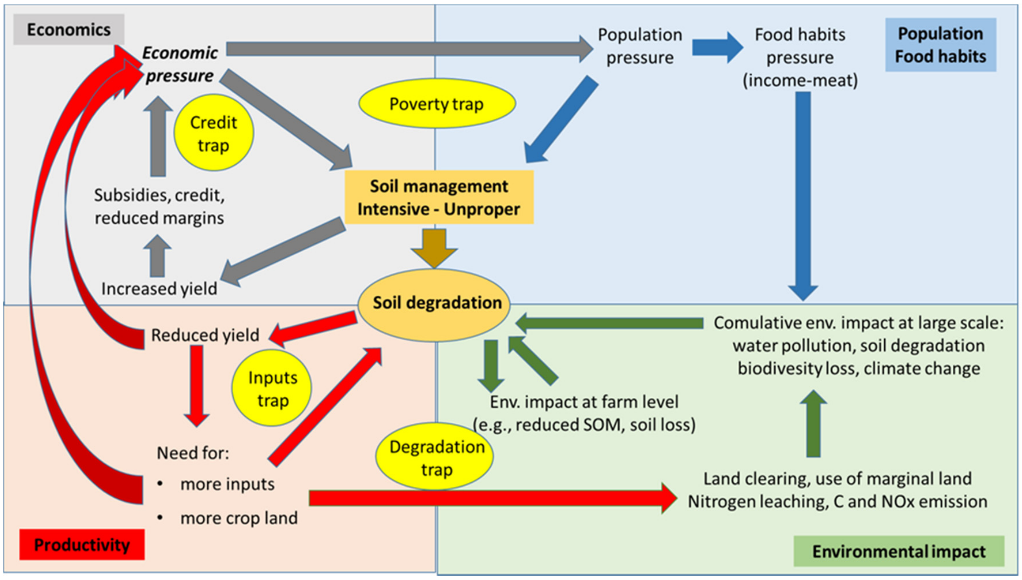


Figure 3. A basic sketch of the complex relations among the different dimensions of the farming system in relation to soil degradation.

In some cases, the farmers can try (and succeed) to reverse some of these trends. Nevertheless, often farmers have no control over forces at play. Population growth and environmental degradation, for example, may be too slow to be perceived by people, and action may be postponed in favour of needs that are more urgent. Chronic poverty and soil degradation can generate self-reinforcing feedbacks that cause poverty to persist and worsen, along with soil degradation, as farmers may lack the capital to adopt soil conservation practices (see [81], for a review of some of these complex feedbacks).

Economic pressures may force farmers to adopt unsustainable practices, as they rarely have enough power to deal with the conditions posed by larger companies that dictate prices and banks that control the credit; these and other organisations have the power to influence the decisions of consumers and policy-makers from other continents. For this reason, agricultural policies have to be taken at a national (or supranational) level to support farmers and guarantee that they are not forced to spoil the very resource that offers them (and us) a living.

Our society's obsessive focus on GDP growth seems doomed to repeat the old paths. In industrial countries, the reduced importance of agricultural GDP leads us to overlook the relevance of agriculture (and thus of soil). Measuring our wealth in terms of GDP, together with the disconnection that the majority of citizens and consumers have to the natural world, has made us blind to the fact that agriculture and soil stand at the very basis of human life. As agriculture represents just a few percentage points of the GDP of industrialized societies (at a global level), we tend to dismiss it as an unimportant affair. The "power of the market" eventually solves any problem of food scarcity by importing food from somewhere else (so the Romans trusted), or by fostering new fix-it-all technologies (so we now trust).

3.2. Economics and the Soil: Are We Doomed to Perpetuate the Spoiling of Our Most Important Capital?

The influential economist Herman Daly provides a telling example of the dangerous drift taken by mainstream economics [102–104]; he reports the following example concerning some notable economists: Nordhaus from Yale (in [105]), Schelling from Harvard [106], and Beckerman from Oxford [107]. To dismiss the importance of climate change, these scholars used the following line of reasoning: (a) climate change will mainly affect agricultural activities; (b) as agriculture represents a mere 3% of the USA GNP, even if 50% is lost that would just mean a mere 1.5% of the USA's GNP; (c) such a figure may easily be compensated by the growth of the GNP in another sector of the economy. Daly states that it is "*True, agriculture accounts for only 3% of GNP, but it is precisely the specific 3% on which the other 97% is based! It is not an indifferently fungible 3%. That is why agriculture is classed as primary production*." [102] (p. 2). He highlights "*Yet some economists confuse fungibility of money with fungibility of real wealth, and proclaim publicly that they don't care if we produce computer chips or potato chips, as long as the dollar value is the same*." [102] (p.2). It is true that US$10 + US1$ = 1US$ + 10US$; nevertheless, 10 kg of wheat + 1 kg of gadgetry ≠ 10 kg of gadgetry + 1 kg of wheat. The problem is that economists seem to miss the importance of the unit of measure; the question should always be "US$ of what?" Mistakenly, they assume that anything can be calculated in US$. According to Daly, the problem is that mainstream economists are thinking within the paradigm of economic growth. Such a paradigm so strongly pervades their way of thinking that they tend to convert any problem to a problem of growth, thus viewing economic growth as the solution to any problem.

A further important problem with economics is that the discipline has developed in a direction that is increasingly delinked from natural resources, which are assumed to always be perfectly substitutable commodities [3,108–113]. In the last decades, bioeconomics [108–110] or, as it is known at present, "ecological economics", has been developed to integrate economics with the ecological foundations of our socioeconomic system [110–113].

Ecological economists have broadened the definition of capital to include the means of production provided by nature. They define capital as a stock that yields a flow of goods and services into the future. Ecological economics distinguishes human-made capital (*i.e.*, human artefacts, social structures) and natural capital as a stock that yields a flow of natural services and tangible natural resources (*i.e.*, solar energy, land, minerals and fossil fuels, water, biodiversity, and the services provided by the interactions of all of these elements in ecological systems) [113].

Such undervaluation of agriculture is surprising as it is a well-known fact that development cannot be achieved without a considerable increase in productivity of the agricultural sector [15,100,114]. Timmer [114] argues that, from an economic point of view, we face the paradox of seemingly living in a world without agriculture. However, " ... *despite the decline in relative importance of the agricultural sector, leading to the "world without agriculture" in rich societies, the process of economic growth and structural transformation requires major investments in the agricultural sector itself*." [114] (p. 61). With such a state of affairs, it is no surprise that the problem of soil goes unnoticed by our policy-makers. The soil simply represents too small a figure in the GNP to be worth their attention, and economists assure them that this is as it should be. The statement by Hillel [4] (p. 280) that "*Our detachment from nature, itself a perversion, serves to further pervert our reality*" should raise the alarm.

I would like to add that such reasoning suffers from further major flaws in its actual economic estimates. It is true that agriculture accounts for a mere 3% of the US GNP, but this figure represents just the value of the production at the farm gate. Agriculture, for example, moves a large amount of money in the form of machinery, agrochemicals, fuels, jobs, the value of the land, *etc.* In 2013, in the USA, agriculture and agriculture-related industries contributed $789 billion (4.7%) to GDP [115]. A 50% reduction in agricultural activities may mean a loss of about 2.5% of GDP, which is not a negligible figure. The 4.7% figure, however, is a conservative estimate. As the USDA [115] points out "*The overall contribution of the agriculture sector to GDP is larger than this because sectors related to agriculture . . . rely on agricultural inputs in order to contribute added value to the economy*". A reduction in farm productivity would thus cause a major fall in the price of land, which would further affect the economy and GDP. Eventually, the collapse of agriculture (which a 50% reduction would entail) would result in food prices skyrocketing and, in turn, in a fall in consumption (food accounts for 13% of American household expenditures: the third in order of importance). The increase in food prices may lead to social unrest and serious socio-economic problems that may undermine the very social fabric of the country. Of course, as damage and defence costs are added to the GDP, a major social disaster may well result in an "increase in the wealth" of the nation.

3.3. The Importance of Preserving True Capital: Soil Health

The various perspectives from which different scholars look at and understand natural resources, especially soil, directly translate into a variety of approaches to the problem of soil degradation. Some narratives focus on food security and rural development (e.g., [6,32,70,73]), whilst others address socio-political (e.g., [3,47,95]) and economic issues (e.g., [116]. Some scholars explore the ethical dimension of soil and the task of environmental conservation [e.g., [117–119]). Other approaches tackle technical issues aiming at preserving soil quality (e.g., [8,70]), including the adoption of different farming practices, such as agroecology (e.g., [120,121]), organic farming (e.g., [122–125]) and precision agriculture (e.g., [60,126]). The use of alternative crops, such as perennials, has also been proposed as a sustainable practice to preserve soil and reduce inputs (e.g., [127–130]).

According to Eswaran *et al.* [131], two main schools of thought exist concerning the way to approach soil degradation and its impact. One school believes that soil degradation is a serious global threat, posing a major challenge to humans in terms of its adverse impact on biomass productivity and environmental quality. This school includes ecologists, soil scientists, and many agronomists. A different school believes that land degradation should not be considered a very serious issue; however, if it were, market forces would take care of it. Such school is comprised primarily of economists. They argue that because land managers (e.g., farmers) have direct interest in maintaining the productivity of their land, they will not let it degrade to the point that it would be detrimental to their profits. Therefore, the very same market forces assure land conservation. Furthermore, we can distinguish two approaches to the remediation processes. One approach is more focused on responding with ad hoc technical solutions, while the other focuses on the importance of soil as an entity integrated in a complex ecological and social context (e.g., [3,6,9]).

In the late 1970s, in the field of environmental economics, it became popular to price ecosystem services in order to increase public interest in environmental conservation [132]. Economic estimates about the value of soil have already been carried out for decades (e.g., in the USA by [5]. Estimating soil "value" is, however, a difficult task, as the inherent value of soil is such that it allows food production and consequently to sustain human life. Furthermore, soil provides many fundament ecological services. Soil ecosystems are still poorly known. It is, therefore, difficult to carry out proper estimates. Assessing the environmental services of agriculture is also popular (e.g., [116,133–136]). Critics, nevertheless, point out that the approach suffers from the usual theoretical and practical problems that affect neo-classical economics, and may actually produce detrimental effects when applied to resource conservation (e.g., [6,117–119,137–139]). By such approach, in practice, value is given to nature when some services for humans are identified as providing a direct or indirect economic benefit (although a number of different typologies of value have been identified, for example, "existence value", usually the economic aspect tends to overcome the others [139]. Eventually, the fate of natural resources continues to be calculated with the usual cost-benefit analysis, thus having to withstand the "*tyranny of discounting*" [6].

Concerning this cost-benefit methodology, Aldo Leopold [119] also warned about the problems arising from a conservation system based on economic self-interest: "*One basic weakness in a conservation system based wholly on economic motives is that most of the members of the land community have no economic value*" [119] (p. 210). Such an approach, he maintained, would eventually lead to dismissing as unimportant those elements and functions from which we do not see direct benefits, while they are, on the contrary, of benefit to the system, " ... *assuming that the economic parts of the biotic clock will function without the uneconomic parts*" [119] (p. 214).

Adams [139] lists a number of challenges posed by the economic evaluation of ecosystem services and argues that there may be cases where, paradoxically, the assessment of ecosystem services may provide a justification for a drastic alteration of ecosystems. The author also warns that the process of assessment is also an act of power, with some stakeholders imposing their evaluations over others. Eventually, Adams [139] argues that the ecosystem service approach is not in itself a conservation measure, and that a more complex approach should be undertaken. He concludes that, ultimately, conservation is a political choice, and ecosystem service values are just one argument for the conservation of nature.

Concerning the tyranny of discounting, we can agree with [20] (p. 676), that "*The goal of sustainable agriculture is to maximize the net benefits that society receives from agricultural production of food and fibre and from ecosystem services*." Nevertheless, we should ask how long do we wish to sustain such an intensive production of food and fiber and related ecosystem services. As Montgomery [9] (p. 5) points out, "*Soil is an intergenerational resource, natural capital that can be used conservatively or squandered*." Preserving soil is a crucial issue in the preservation of our life supporting systems for future generations. Young [6] makes a detailed analysis of the failure and danger of discounting in the case of soil. He argues that the choice of discount rate is arbitrary. The higher the discount rate applied to a resource, the lesser is the present value of net future benefits (discounting can be considered in some ways as the reverse of interest rate). Therefore, if we choose to apply a high discount rate, we tend to exploit a given resource as fast as possible, as its benefits are going to decrease in the future. Young [6] argues that cost-benefit originated to compare alternative investments in business and industry, and cannot be applied to complex systems, such as soil, which concerns multiple services, the whole community, and the present and future generations at the same time. Furthermore, Young [6] also stresses that in the cost-benefit exercise, soil quality is an issue that is greatly misreported, resulting in damaging the long-term economies of local communities.

A different approach to conservation has been taken by scholars such as Leopold [119] and Sagoff [117,118]. Sagoff [117] strongly criticizes the fact that the environmentalists/ecologists (and ecological economists) were eager to embrace the "service approach" as developed by economists, believing that by doing so they could gain scientific legitimacy, as they could show the truth numerically. He argues that by doing so, they dismissed the idea of fighting on ethical grounds, questioning some fundamental issues on their moral basis. Along with Leopold, Sagoff [117] stresses the point that most organisms do not have a value for us (at least one that we can assess); however, they still deserve to be protected on ethical and moral grounds (the principles on which we identify as a society). In doing so, Sagoff argues that, as the environmental movement has its roots in ethics rather than science, it has betrayed its origins, thus doing a disservice to the conservation of nature (for ethical reasons).

In the late 1950s (writing after the Dust Bowl), Aldo Leopold, in his A Sand County Almanac, individuates two major obstacles to the evolution of a land ethic [119] (p. 226). The first is " ... *the fact that our educational and economic system is headed away from, rather than toward, an intense consciousness of land*". The second is the " ... *attitude of the farmer for whom the land is still an adversary, or a taskmaster that keeps him in slavery*". We should overcome the first obstacle by heading our educational and economic systems towards an intense knowledge of the land. That would not be a difficult matter, if our educational system made a little effort. The second obstacle is much more complex to overcome, as it clearly needs to be worked out by society. Farmers should be recognised as playing a key role in our society, a role that we fail to recognise, and value only to the extent allowed by the usual economic assessment (by which both farmers and agriculture itself just disappear from view).

4. Soil Degradation and the Scenarios of Agricultural Land: Optimism *vs.* Concern

A number of assessments conclude that in order to meet food demand in 2050, global agricultural production would have to increase by 70%–110% [32,57,59,98]. According to the review by Eitelberg *et al.* [84], estimates of potential cropland range from 1552 million ha to 5131 million ha, which includes 1550 million ha that is already cropland. Hence, the lowest estimate indicates that there is almost no room for cropland expansion, while the highest estimate indicates that cropland could potentially expand to over three times its current area. The differences can largely be attributed to institutional assumptions, *i.e.*, which land covers/uses (e.g., forests or grasslands) are socially or governmentally allowed to be converted to cropland; there is little variation in biophysical assumptions. Estimates based on comparable assumptions show a variation of up to 84%, which originates mainly from different underlying data sources.

Although soil degradation is surely a controversial topic (as is evident from the UN declaration of 2015 as the Year of the Soil), concern about the importance of soil degradation for the future of agriculture and food security differs among scholars. Some experts maintain that soil degradation should be of major concern; as it represents a global threat to future food production [6,9,24,28,62,68,83,131,140]. They argue that, at a global level, there is not much room for the further expansion of agricultural activities and that many densely populated countries are already facing serious problems of land scarcity. They claim that most of the best agricultural land is already cropped. What is left is mostly forested land, where soil may not be very productive (actually, once deforested such areas are highly prone to soil erosion).

Nevertheless, other experts (e.g., [32,57,59,98,141–143]), although concerned about the need to preserve soil health, are more optimistic about the availability of land that can be further cropped to guarantee the necessary food supply for the present and future world population.

In this section, I provide an overview of the two schools of thought. Eventually, I argue that we need to also take into account other crucial aspects of food production, which are still missing in the present assessments.

4.1. The Optimistic View: Agricultural Land is Still Potentially Abundant

Experts from renowned international institutions, such as the International Food Policy Research Institute and FAO (e.g., [32,37,59,61,98,141]), believe that a large amount of land can still be put into production. FAO's scenario for 2030–2050 [32] is based on the exogenous assumption that world GDP will be 2.5-fold the present one, and per capita income will be 1.8-fold. FAO assessments are characterized for being rather optimistic concerning the possibility of meeting future land use needs.

The report by FAO [61] (p. 41) stated that "*There is widespread concern that the world may be running out of agricultural land. . . . Despite these losses, there is little evidence to suggest that global land scarcities lie ahead. Between the early 1960s and the late 1990s, world cropland grew by only 11 percent, while world population almost doubled. As a result, cropland per person fell by 40 percent, from 0.43 ha to only 0.26 ha. Yet, over this same period, nutrition levels improved considerably and the real price of food declined. The explanation for this paradox is that productivity growth reduced the amount of land needed to produce a given amount of food by around 56 percent over this same period. This reduction, made possible by increases in yields and cropping intensities, more than matched the decline in area per person, allowing food production to increase*". However, the report recognized that land scarcity exists at country and local levels and may affect food security, and that action should be taken. Concerning land degradation, the report points out that the area of degraded land is not known with much precision, as its assessment is usually based on the opinion of experts. In the case of India, for example, estimates by different public authorities vary from 53 million ha right up to 239 million ha. Furthermore, FAO [60], argues that the impact of degradation on productivity is difficult to assess, as "Its seriousness varies widely from site to site over even small distances, and at the same site according to local weather, vegetation and farming techniques" [61] (p. 42). Although FAO reports the principal types of land degradation, it does not consider land degradation in its models: "*Because it is difficult to quantify, the future progress of land degradation was not taken into account in the projections made for this study*" [61] (p. 42).

In a successive FAO publication edited by Bruinsma [98] (p. 136), it is stated that "*Concerning the future, a number of projection studies have addressed and largely answered in the positive the issue as to whether the resource base of world agriculture, including its land component, can continue to evolve in a flexible and adaptable manner as it did in the past, and also whether it can continue to exert downward pressure on the real price of food … The largely positive answers mean essentially that for the world as a whole there is enough, or more than enough, food production potential to meet the growth of effective demand, i.e., the demand for food of those who can afford to pay farmers to produce it*". Recent FAO reports [32,58] still provide a rather optimistic assessment of the potential agricultural land that can be put into production, although the authors are very aware of the complexity of the food system. They argue that the capacity of the world as a whole to produce food is only one aspect of food security and, actually, not even the most relevant one. They [32] (p.10) state that "*there are sufficient spare food production resources in certain parts of the world, waiting to be employed if only economic and institutional frameworks would so dictate*". According to Alexandratos and Bruinsma [32], there are some 1.4 billion ha of prime land (classed as very suitable) and good land (classed as suitable and moderately suitable) that could be cultivated in case of need. More specifically, the scenario indicates that the following classes of land are available: 350 million ha are very suitable, 600 million ha are suitable, 450 million ha moderately suitable, 560 million ha marginally suitable and 920 million ha very marginally suitable (Table 1). An expansion of agricultural activities in the latter classes of land, however, may come at the expense of pastures, requiring considerable development investments (e.g., infrastructures).

Table 1. Land and potential land use, figures in million ha (from [32], modified; see also [144], from the original data).

	Total Land	Potential	VS + S	MS	PS	NS
Total land *	13295	4495	3502	993	3731	6061
of which in agricultural use (1999/2001)	*1559*	*1260*	*1058*	*201*	*425*	*75*
Gross balance of rain-fed potential		3236	2444	792	3306	
Under forest	3736	1601	1307	293	1165	1263
Strictly protected land	638	107	80	27	125	423
Built-up land	152	116	102	14	36	15
Net balance of land with rain-fed potential		1412 (VS + S + MS)	955	458	1979	

(*) Crops considered: cereals, roots and tubers, sugar crops, pulses and oil-bearing crops; VS: Very Suitable; S: Suitable; MS: Moderately suitable; PS: Poorly suitable (this class includes the classes "marginally suitable" and "very marginally suitable" in the original work); NS: Not Suitable.

Alexandratos and Bruinsma [32] warn about the difficulties of knowing the actual land in use, as data for crops and historical data for arable land for many countries are particularly unreliable. Furthermore, data on cropping intensities for most countries are non-existent; for this study, the authors derived them by comparing data on harvested land, aggregated over all crops, with data on arable land, an issue already discussed in detail by Alexandratos [145]. Alexandratos and Bruinsma [32], however, point out that production constraints are and will continue to be important determinants of food security. Furthermore, they argue that increasing productivity may spur population growth resulting in reducing progress and locking the system into a poverty trap. In their report, the authors also stress the fact that, notwithstanding the availability of potential suitable land for the future expansion of agriculture, such land is far from being evenly distributed among the different regions (Figure 4). Very highly densely inhabited regions of the globe, such as East and South Asia, the Near

East and North Africa, have less of a margin for manoeuvring, considering that the future population growth will take away further land, lost to urbanization and infrastructure development. According to Gerland *et al.* [33], the human fertility rate may not slow down as expected, especially for Africa, where culturally families still wish to have a high number of children (4.6 on average), and policies for family planning and women's education and empowerment are still limited.

Some authors [32,37] also warn that the economic growth of developing countries (e.g., China and Brazil) will prospectively increase meat consumption. This in turn will exert a further pressure on agricultural resources. Biofuels may also become a serious competitor for agricultural land. Some experts believe that in many regions of the world productivity is still very low and can be substantially increased [32,37,58,142,143]. According to scenarios from Mauser *et al.* [143], improving crop growth management through better technology and knowledge may result in a 39% increase in estimated global production potential, while a further 30% can be achieved by the spatial reallocation of crops to profit-maximizing locations. According to the authors, the expected increase in yield will make cropland expansion redundant, nor will it be necessary to rely on GM crops. It is easy to agree that with even minimal investments the average crop yield in many developing countries may rise. The proposed scenario, however, relies on the very optimistic assumption that better technology and knowledge will be available everywhere. However, better technology and knowledge come at a cost: at present, for many developing countries such investments are out of reach (in many cases, small farmers cannot even afford to buy improved varieties or minimal inputs).

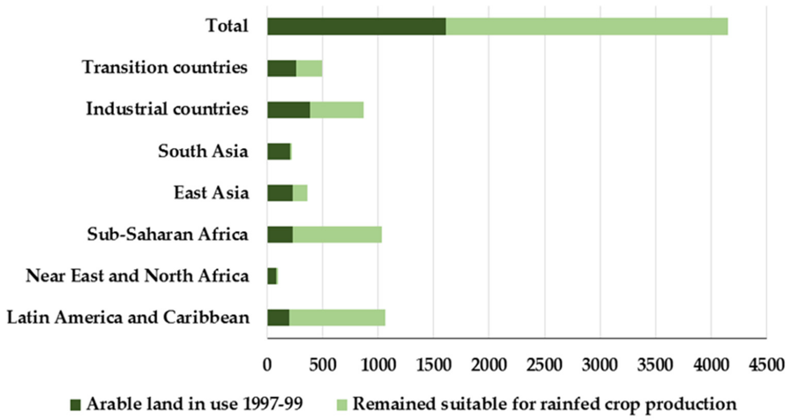


Figure 4. Regional distribution of land presently in use and of potentially suitable land for crop production (data in [144], as reported in [32]).

4.2. The Concerned View: Soil Quality and Soil Degradation Greatly Affect Agriculture Productivity

The limited expansion of cultivated land, notwithstanding the doubling in population, led FAO to suggest that land scarcity may not be a serious problem. Nevertheless, the conclusions of other experts (e.g., as summarized by [24]) are different and address the fact that there is not much suitable land left for further expansion.

It has been estimated that 70% to 80% of the Earth's land area is unsuitable for agriculture owing to poor soils, steep topography, or adverse climate [146]. About 50% of the remaining area is already being cropped, and a large proportion of the other half is presently covered by tropical forests, which beneficially take up CO_2 [146]. According to estimates by Ramankutty *et al.* [146], the total global extent of suitable cropland in the current climate is 4.1 billion ha, which is roughly 120% larger than the 1992 global cropland area of 1.8 billion ha. The greatest potential for croplands in the current climate exists in tropical Africa (560 million ha) and northern South America (470 million ha), which has also been pointed out by other authors. However, displacing tropical forest will cause dramatic problems concerning CO_2 emission and biodiversity loss. Furthermore, tropical soils will lose fertility rapidly once the forest cover is replaced with a crop, and will require expensive inputs to maintain the soil nutrients and conserve soil organic matter (SOM).

A number of experts challenge the optimistic findings by FAO and other authors, on the basis that the data are affected by high uncertainty and some key issues, such as soil degradation, which are not considered (e.g., [6,15,24,28,62,68,71,83,86,147]). Problems with the present models are of both a technical (due to the inherent limits of the process of mensuration) and methodological nature (related to the choice of what to measure, assumptions, and boundaries). Many such limitations have also been recognized by the authors of the scenarios themselves [32,37,56,59,98]. We concede that some of those limitations are inherently very difficult to overcome (e.g., lack of data at a small scale, proper and reliable assessment of soil degradation; great difficulties can be met just obtaining reliable data on crop productivity for many regions).

Conway [24] points out that the fact that in the past 50 years the population has grown by 110% and cropland by only 10% may be telling figures pointing to the fact that there is not much land that can be easily cropped. The expansion of soybean (300%) and palm oil (700%) is presumably due to the clearing of the Cerrado in Brazil and the rain forests in many tropical countries [24,28,83]. Young [6,68] warned that the very same statistics about yields might be unreliable, as in many developing countries there is not a real measure of the areas harvested, of yield or production. Figures may then be affected by assumptions (or even conditioned by speculative forces) rather than respond to realistic measurements (an issue also recognized by [32].

Already in the late 1990s, Young [6,68] and Smil [15] pointed out that in many poor countries the amount of land under cultivation is more than reported in the official statistics submitted by those countries to FAO. Therefore, data used by FAO may greatly overestimate the amount of "free land" (in some regions potential agricultural land is virtually non-existent), with the true remaining balance of cultivable land being much smaller than what is reported by these scenarios. A recent work by Lambin *et al.* [62], based on a bottom-up approach (using direct expert knowledge), supports the claims by Young [6,68]. The experts considered land availability, specific constraints and trade-offs. Their figures about the potential agricultural land for a number of regions considered are just 15% to 65% of those provided by the previous FAO assessments (only for the case of Amazonia were their estimates higher: 168%). Lambin *et al.* [62], argue that a bottom-up approach is better able to consider more fine-grained, up-to-date, and locally relevant criteria to estimate agro-ecological suitability, current land use/cover, and the constraints and trade-offs associated with land conversion. By adopting such an approach, it is possible to provide more realistic figures compared to the global datasets. The authors point out that the drawback of the bottom-up approach is a lack of consistency in the criteria used to define the potentially available cropland, as each expert provides a judgement based on available data, current land use dynamics, and the social and political context of the region. As a result, the costs and benefits of land conversion are not strictly comparable across regions.

Bindraban *et al.* [71] point out that although experts tend to agree on the fact that about 25% of the global land area is degraded, there are large differences concerning the estimates of the intensity and extent of soil degradation. This is due to the different definitions, methodologies applied and lack of on-the-ground validation. Furthermore, the authors argue that the large-scale assessment of the impact of degradation on plant production is also inaccurate, as it suffers from the specific opinion of the experts, or is based on statistical procedures that do not allow extrapolation in time or space.

The physical availability of arable land is only part of the story; the human role in the decision-making process has to be fully taken into account [3,6,18,62,71,75,80,83]. This was a point that other authors also made for related fields such as farming system analyses and rural development (e.g., [45,148–150]).

The critics maintain that soil degradation reduces both actual and potential yields. In some cases, soils are already so degraded that they cannot be cropped and have to be used for pasture instead. Concerning further land expansion, critics point out that irrigation would be needed in order to achieve high productivity of the new land; however, water availability is instead becoming scarce (irrigation will also increase the operating costs of farming). Soil degradation is indeed a relevant issue because it affects land productivity directly, by reducing yields, and indirectly by increasing management costs (e.g., fertilizers, irrigation). For small and poor farmers, economic investments are coupled with indebtedness (Figure 3). Limiting loans to a minimum is actually part of a strategy actively pursued by farmers in poor countries to reduce risks of indebtedness [6,45,148]. This will play against farmers undertaking large investments to provide more inputs for their fields. Agricultural intensification (and the increased use of inputs), in many cases may actually indicate that farmers cannot move on new fertile land, and have to cope with soil degradation instead [6,68].

It has to be pointed out that the African continent, where the largest share of the demographic growth is expected to take place, is also the most fragile in terms of soil composition [4,6,147]. More than half the global population growth between now and 2050 is expected to occur in Africa. The continent is growing at a pace of 2.5% annually (in 2010–2015 figures), the highest rate of population growth among the continents [34].The soils of Africa are derived mostly from parental materials that have been long exposed, hence are highly weathered and leached, and are characterized by inherently low productivity. The soils of Africa, therefore, may also be those most vulnerable to drought and other stressor such as those induced by intensive agriculture. Young [6] warns that the vision of converting the Amazon and Zaire basins into Asian-type rice-lands stems from a misunderstanding of the different biophysical soil characteristics of the former in comparison with the latter.

4.3. Trends for Arable Land 1980–2010: The Complex Relation between Land, Population and Economic Growth

Arable land is regarded as the best and most productive land available; it is generally cropped with cereals or highly profitable crops. Therefore, a reduction in arable land on a per capita basis may affect food production and, most importantly for the poor countries, food security. A reduction in arable land per capita generally forces a country to increase land productivity (increasing the inputs), expand the land used for production (possible marginal land, or converting forests) and/or rely on imports.

In this section, using the data from the World Bank (WB) database [151], I explore how the change in arable land, for the period 1980–2010 (Figure 5), correlates with changes in GDP per capita and with population growth (Figures 6–8). I eliminated from the country dataset a few micro countries, whose socioeconomic peculiarities made them unrepresentative. I used the data starting from 1980, to be able to include data for 111 countries of the WB database, and to be able to consider a relatively large time frame. It would have been possible to include a few more countries by taking the year 1990 or 1995 as a reference point, but that would have reduced the time frame, thus affecting the perceived level of the land change. I wish to point out that the goal of this exercise is not to provide any definitive evidence, but rather to highlight the fact that land, population and economic growth are interwoven in a complex way.

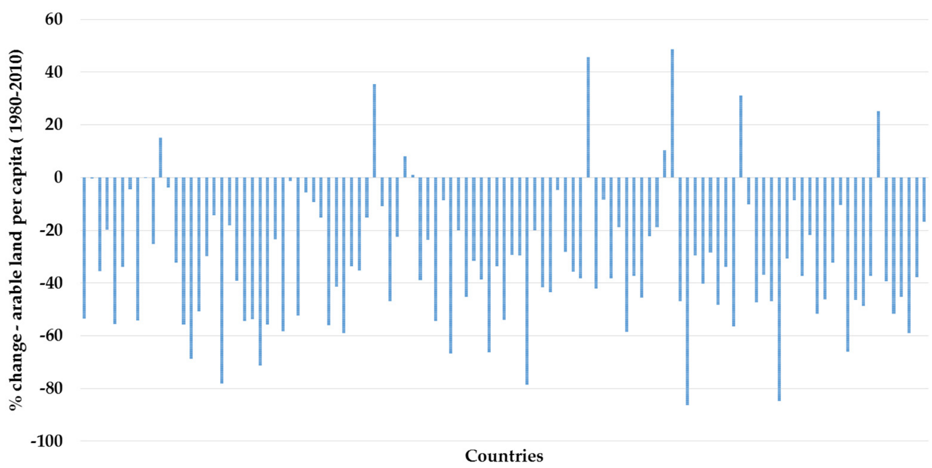


Figure 5. Change in arable land per capita from 1980–2010 (in percentage), for a dataset of 111 countries (data from the World Bank database—[151]).

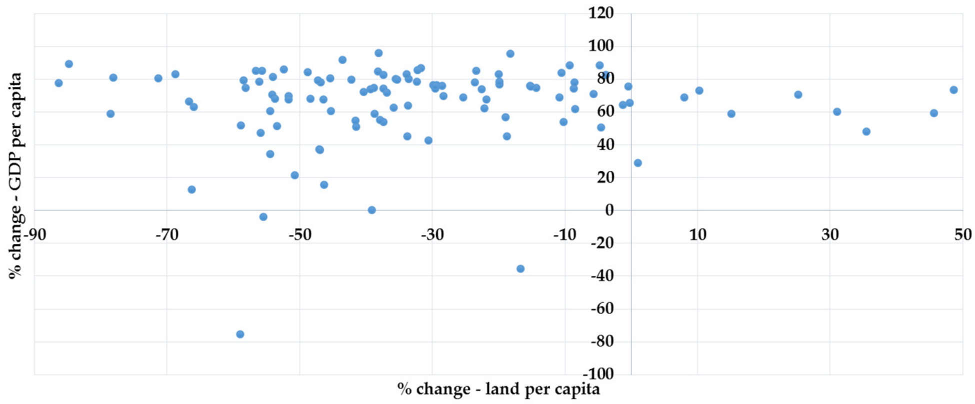
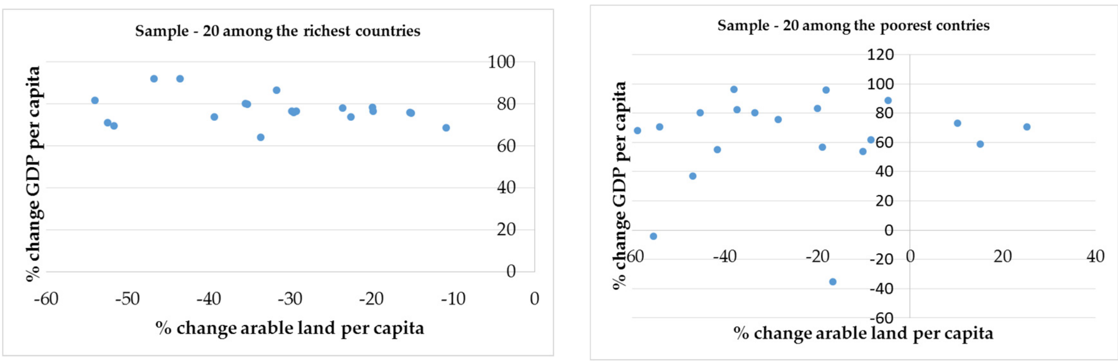


Figure 6. Change in arable land per capita *vs.* change in GDP per capita, from 1980–2010 (in percentage), for a dataset of 111 countries (data from the World Bank database—[151]).



(**a**) (**b**)

Figure 7. Change in arable land per capita *vs.* change in GDP per capita, from 1980–2010 (in percentage), for two datasets of countries: (**a**) A sample of 20 of the richest countries; (**b**) A sample of 20 of the poorest countries (data from the World Bank database—[151]).

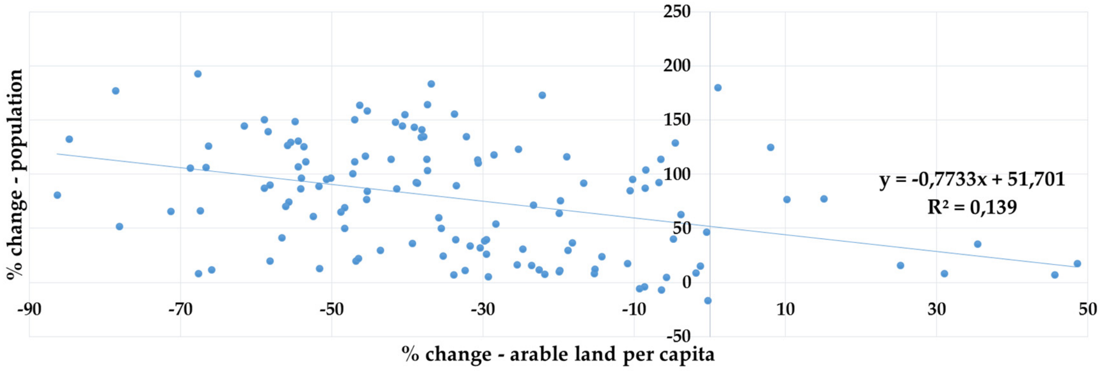


Figure 8. Change in arable land per capita *vs.* change in population, from 1980–2010 (in percentage), for a dataset of 111 countries (data from the World Bank database—[151]).

The data plotted in Figure 6 seem to indicate that the loss of arable land per capita is not related to the increase in GDP per capita. Land loss (−20% to −60% of arable land per capita) affected countries whose GDP per capita increased from five to ten times from 1980 to 2010. The loss of arable land is directly related to both demographic pressures (need for food and urbanization) and economic pressures (urbanization, industrialization, complex infrastructures, financial speculation). Therefore, while the increasing GDP per capita is usually linked to reduced demographic pressure, there was increased land use change because of the new socio-economic forces taking place (e.g., urbanization, industrial settlements, and speculation).

In the early 1990s, some environmental economics scholars suggested the existence of an environmental Kuznets curve (EKC), *i.e.*, that some environmental degradation indicators tend to worsen as modern economic growth progresses, until average income reaches a certain point over the course of development, after which they tend to improve. EKCs have been found for some environmental pollutants (e.g., sulphur emissions), but not for others (e.g., energy, biodiversity). The existence of EKCs has been challenged by some recent empirical work, and also on theoretical grounds (for a discussion and criticisms see [152–155]). If these criticisms were correct, we would expect that those countries that most increased their GDP per capita would present a lower loss of arable land per capita. Nevertheless, the application of this concept to land is somewhat complicated, as the reduction in the rate of land conversion may depend much more on the fact that very little land is left to be converted, or that what is left is of very poor quality and very costly to convert (decreasing the marginal return on the conversion process).

Figure 7 reports the change in arable land per capita and the change in the growth of GDP per capita for the years 1980–2010 for twenty of the richest countries of the database (Figure 7a), and for twenty of the poorest countries of the database (Figure 7b). There are no notable differences between samples.

The data plotted in Figure 8 present the relation between the change in total arable land per capita and the change in the population. From Figure 8, it seems that there is no relation between the reduction in arable land per capita and population growth. A reduction in arable land per capita is evident both where population pressure increased as well as where it was more contained.

As has been argued by many authors (e.g., [3,27,32,62,80,83,95,98,101,156]), land use change is a complex matter and cannot be simplistically attributed to a specific factor, be it population pressure or poverty. Van Vliet *et al.* [156] made the point that scholars tend to generalize, and assume a unidirectional relationship between land use change and its impact. Nevertheless, as humans promote (and adapt to) changes in land use, a variety of consequences are possible, and the issues have to be understood within the specific environmental and socioeconomic context.

The data plotted in Figure 9 seem to indicate that there is a relation between the reduction in arable land per capita and the increase in total arable land. As previously reported, it has been estimated that about 30% of the increase in agriculture production comes from the expansion of cropping land. Of course, there is an increase in demographic pressure in some contexts (e.g., where low income makes it difficult to pay for the inputs need to intensify production, or where there are policies that support land conversion).

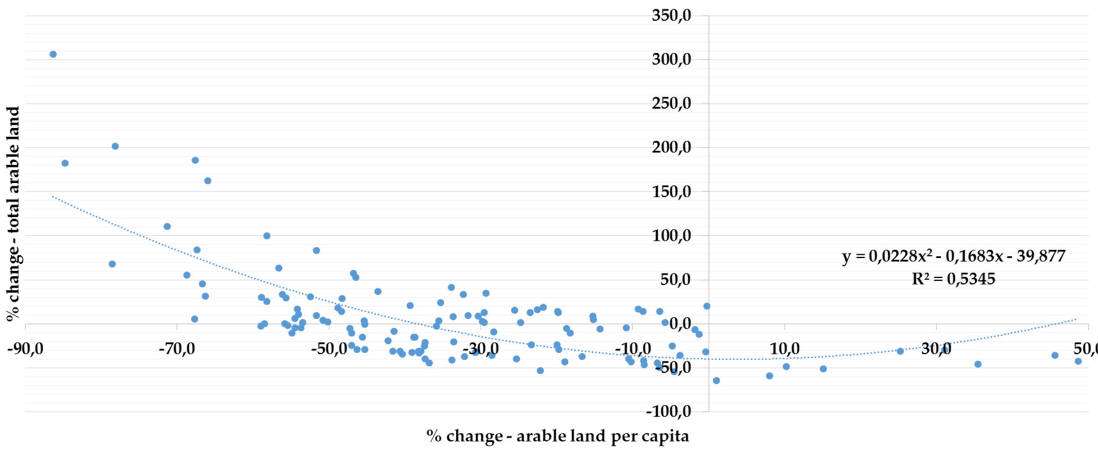


Figure 9. Change in arable land per capita *vs.* change in the total arable land, from 1980–2010 for a dataset of 111 countries (data from the World Bank database—[151]).

Countries from the dataset that lost more arable land per capita from 1980 to 2010 are (ranked in order of quantity): Nepal (−86%), Senegal (−85%), Jordan (−79%), Chile (−78%), Colombia (−71%), Botswana (−69%), Yemen (−68%), Honduras (−67%), Lebanon (−67%), Iraq (−66%), and Tonga (−66%). Countries from the sample that increased their arable land per capita from 1980 to 2010 are (ranked in order of quantity): The Netherlands (49%), Macedonia (46%), Fiji (35%), Portugal (31%), Uruguay (25%), Bolivia (15%), Nicaragua (10%), Ghana (8), and Gambia (1%).

For many low-producing countries, there may still be large margins for increasing crop productivity; nevertheless, this would require farmers to conduct a large economic investment in high quality seeds, agrochemical inputs, and possibly irrigation, which would be a difficult challenge to meet. Eventually, soil exhaustion and soil degradation may also affect those countries that cannot afford to use a large quantity of inputs. Notwithstanding such potential margins, the increasing demographic pressure in most countries will present some great challenges (see for instance the different contexts that characterize countries such as Bangladesh and the Middle East, where the expansion of agriculture is no longer an option, and countries such as Brazil and Nigeria, which can still convert their forests to agriculture or pasture land). Table 2 reports on the pressure on arable land and future demographic trends for the 10 most populous countries. As can be seen from Table 2, all these countries have experienced a reduction in arable land per capita in 1980–2010. It can be noted that the poorest and most populous countries are also those that are already experiencing a shortage of arable land (0.2<) and a high rate of population growth.

Table 2. Trends for population and arable land per capita for the world's 10 most populated countries (percentage of arable land per capita calculated on WB data on arable land and population).

Top 10 Most Populated Countries	Pop. Year 2014 WB (M)	% World Pop. (7260 M)	% Arable Land/Capita 1980–2010	Arable Land ha/capita (Year 2013)	Pop. Growth (Annual %) (2011–2015)	Pop. Year 2030 (est.) UN	Pop. Year 2050 (est.) UN
China	1.364	18.8	−18	0.08	0.5	1.415	1.348
India	1.295	17.8	−45	0.12	1.2	1.527	1.705
USA	319	4.4	−39	0.48	0.7	356	389
Indonesia	254	3.5	−20	0.09	1.3	295	322
Brazil	206	2.8	−4	0.37	0.9	229	238
Pakistan	185	2.5	−28	0.17	2.1	244	309
Nigeria	177	2.4	−19	0.20	2.7	262	398
Bangladesh	159	2.2	−54	0.04	1.2	186	202
Russian Fed.	144	2.0	−8 *	0.85	0.2	139	127
Japan	127	1.7	−20	0.03	−0.2	120	107
Total	*4.231*	*58*				*4.773*	*5.145*

(WB): data from [151]; (*): from 1992 to 2010 (The World Bank began to report statistical data for the Russian Federation in 1992); (UN): Estimates from UN [34].

As has been previously discussed, the figures in Table 2 may actually present an underestimate of the situation. Although we usually associate population pressure, lack of land and poor yields with poverty and hunger, paradoxically there are cases where a large part of the population can experience hunger in a country with high arable land per capita, top yields and the most advanced technology, and the highest GDP per capita in the world. The USA is a striking example of this seemingly inexplicable paradox. The USA has as much as 0.5 ha of arable land per capita, one of the highest value in the world. USA agriculture is the most advanced and productive on the planet. Large subsidies and cheap energy (compared to the EU, for instance) guarantee the lowest cost of inputs. Surplus has to be disposed of. Most farmers, in their rush to boost productivity, eventually become worse off, with only large farmers benefiting from the economies of scale and huge amount of agricultural subsidies granted by the government [40,157–159]. The historian of US agriculture, Willard W. Cochrane [157] talks about a continuous problem of surplus for US agriculture since the XVIII century. A surplus that brought little benefits to farmers (most of which went out of the market, indebted and unemployed), and forced government to continually intervene with policies aiming at surplus removal. Douglas

R. Hurt, another renowned scholar on US agriculture, in his history of US agriculture [158], tells of a continuous "problem of plenty"; since the 1930s, the main agricultural issue that all governments have been faced with is how to get rid of the surplus. The subsidies-surplus treadmill, typical of US agriculture, has grown so large to affect agriculture and the food system on a global level [40,159].

Burning the surplus, producing "green fuels", seems the final solution. Nearly half of USA maize production ends up generating ethanol [160]. Biofuels have a low Energy Return On Investment (EROI) when compared to fossil fuels (about 10 to 30 time lower) [29,161–167], and, what is more important, a very low power density (W.m^{-2}, about 1,000 to 10,000 times lower) [29,166–169]. These characteristics render biofuels an energy carrier that is highly demanding in term of investments and labor. In turn, they have to be highly subsidised to be sold in the market at an affordable price for consumers [40,169–173]. Koplow and Steenblik, [171], estimate that in 2008, in the USA, total support towards ethanol production ranged between 9.0 and 11.0 billion US$. These figures are likely to be an underestimate, given the many faces economic support can take (from tax exemption to price premiums), making precise subsidy assessment a difficult task [171–174] (see for instance the long list of State and Federal Laws and Incentives to support biodiesels and ethanol: U.S. Department of Energy [175,176]. According to Reboredo *et al.* [177], the present low price of oil will require " . . . *a massive public/state subsidy flow* . . . " to sustain biofuels [177] (p. 5). Concerning Genetically modified crops, which, it is claimed, should solve the problem of world hunger, according to the USDA [178], in 2013, U.S. farmers used herbicide tolerant (HT) soybeans on 93% of all planted soybean acres, HT corn accounted for 85% of corn acreage and HT cotton constituted 82% of cotton acreage. Bt corn (which controls the European corn borer, the corn rootworm, and the corn earworm), was planted on 76% of corn acres. Other GE crops commercially grown in the United States are HT canola, HT sugar beets, HT alfalfa, virus-resistant papaya, and virus-resistant squash [178]. According to GMO compass [179], in 2013, HT sugar beets accounted for 95% of the acreage, HT canola for 93% and HT alfalfa for 30%. In total, in 2013, GM crops accounted for about 70% of cultivated land. Yet, notwithstanding the high-yielding strategies listed above, the USDA reports that in 2012, 14.5% of households (about 45 million people) were food insecure, meaning they had difficulty at some time during the year obtaining enough food due to a lack of resources [180]. On the other hand, more than one-third (34.9% or 78.6 million) of U.S. adults are obese, and 68.5% of adults are overweight or obese. The future looks even darker as 16.9% of children are already obese, and 31.8% of children and adolescents are overweight or obese [181]. Nevertheless, in the USA, when agriculture is discussed, social issues (e.g., the huge wealth inequality, the power of corporations) are never addressed. Agricultural productivity seems to be the only problem worth attention. Given the incredible performance of USA agriculture, and the vast amount of waste created by the USA food system, we may be tempted to conclude that focusing the problem on the need to produce more food serves to hide more important social issues, which are taboo, as they concern the system of power. We cannot but agree with Daly [102–104] that the "growth paradigm" has come to be viewed as a solution in itself: whatever the problem, "growth" is thought to be the solution. Probably the fact that "growth" is seen as an easy solution to very complex problems (along with our natural attitude to take the easiest path) keeps our thinking locked in such a paradigm, preventing us from exploring different solutions.

4.4. Energy: A Key Constraint for the Future of Agriculture

Although the scenarios previously presented have been widely debated, some important issues have not been properly addressed. Concerning the scenarios presented by FAO, the same authors (e.g., [32]) discuss the possible effects of changing food habits within the emerging economies, the effect of urbanization and biofuel policies. Furthermore, the authors warn that their projections are subject to high uncertainty with regard to population dynamics, water supply and the effects of climate change, to name but a few. Nevertheless, the key role of the future of energy supply is never addressed, neither by the scenarios provided by FAO, nor by their critics. In order maintain their current performance levels, our highly productive crops (and food system) require a huge amount of energy in the form of agrochemicals, machinery, fuels, irrigation, *etc.* [15,16,22,31,39,100,150,161,182]. Alexandratos and Bruinsma [32] argue that in the next decades the bulk of the projected increases in crop production will probably come from higher yields, with the remaining part coming from an expansion in harvested areas. The authors (as the FAO publications on this topic) do not properly address the fact that higher yields require higher inputs (starting from fertilizers and water), which in turn require energy. Nevertheless, the future scenarios concerning energy supply are quite worrisome as many energy experts maintain that the production of oil has already peaked, and the peak of gas is on the way [29,161,163,183,184]. The peak of oil and gas production will affect energy prices (and in turn the cost of agricultural inputs) exponentially. Energy scarcity, in fact, will go along with the higher cost of energy extraction due to the lower Energy Return on Investment (EROI) of the energy extraction process itself [161,163,184].

Other key issues must also be further addressed. Phosphorus is a key element in agriculture, but it too may soon become scarce, creating a bottleneck for our highly intensive agriculture [185]. Again, to achieve higher productivity, especially in degraded soils, a higher amount of fertilizers must be supplied. However, these constitute a heavy economic burden for farmers, especially poor ones. The latter usually cannot afford to buy fertilizers in large quantities, and in turn cannot easily cope with the effects of soil degradation and exhaustion. Therefore, high yields depend on farmers having enough capital to invest in buying inputs and technology.

4.5. The Necessity to Embrace a Precautionary Approach and to Adopt Novel Modeling Tools

As we have previously seen, the present models suffer from a number of limitation that affect their ability to provide sound and effective scenarios. Many experts argue that the present models tend to overestimate the real availability of agricultural land. These issues concern the assessment of both soil degradation and land use.

Concerning soil degradation, we have the following issues:

- "soil degradation" is a broad definition, including many processes that affect the soil in different ways and to different extents; a unique definition of soil degradation is missing;
- there is a lack of objective criteria to define soil degradation (soil and land degradation are often used as synonyms, although they are not); in most cases, different processes take place at the same time, making the enterprise very challenging;
- it is difficult to gather basic data, and the figures provided by many local and national institutions are affected by high uncertainty and unreliability. FAO [57] argues that the quantity and quality of information on soil degradation is very variable in different regions, and that great differences exist between countries in data and data availability on soil resources and soil change information.

Concerning the scenario analysis of land use, we have the following problems:

- Uncertainty in the basic data
    - as FAO [57] (p. 8) argues, "*Crop models, especially when run at global scale, are highly complex models that differ widely in terms of process representations, functional implementations, data input choices and basic assumptions. Even with the same version of the same basic underlying mode, . . . results often differ substantially*";
    - the difficulty to know the actual land in use, its quality and the real productivity of the crops; as Alexandratos and Bruinsma [32] warn, for many countries data are unreliable or even non-existent). Unreliable data may also concern other domains such as economics, inputs and, in many countries, the population itself;
- Methodological limitations
    - data from different models are difficult to compare as they rely on different assumptions, boundaries and protocols;

    - land use is mapped at a scale that does not account for the real morphology, features and use of the land (e.g., hilly and rocky outcrops), leading to gaps in basic data;
    - the amount of land occupied by the people themselves is not properly accounted for;
    - the analysis underestimates the amount of land that is actually cultivated (e.g., illegal land occupation, forest use);
    - the lack of integration among the different domains that characterize food production, such as the future scenarios of water and energy, the fate of some key elements (e.g., phosphorus);
    - most of the land that FAO includes as potential cropland is actually represented by rain forests, grazing land and marginal land that may be providing ecosystem services;

- Oversights in the description of key issues

    - soil degradation is not taken into account, yet it greatly affects productivity and land conversion [71] provide a review on this issue);
    - the effect of climate change, the changes in water and energy supply are poorly (or not at all) included in the scenarios. It has to be stressed that the cost of inputs (and therefore the price of energy) is a key issue for maintaining high agricultural productivity;
    - the effects of trade and globalization bring a lot of uncertainty to the agricultural sector in different regions/countries. Other socioeconomic issues are not considered either (e.g., credit, financial speculation, conflicts);
    - the effects of future social and economic trends, which will pose great pressure on existing resources and on the resilience of the social fabric.

Possible approaches to provide better information and improving scenarios:

- Developing clear definitions of soil and land degradation

Some scholars argue that assessment of soil and land degradation is made difficult by the existence of different definitions of those processes. That makes it also difficult to develop methodologies able to provide comparable information. Therefore, it is important to have scholars working together to frame and solve this issue.

- Gathering more on-the-ground information/measure

It has been argued that often the information available are based on rough estimates (at times mere guesses). An effort thus should be taken to gather more on-the-ground information upon which better models can be developed. This is much needed especially in those highly populated regions where food security is at risk, and where social conflicts may be exacerbated by lack of resources.

- Integrating different sources of information (trying not to rely on a single source)

Gibbs and Salmon [83] reviewed the methods presently in use to assess land degradation, namely expert opinion, satellite-derived net primary productivity, biophysical models, and abandoned cropland. The authors argue that no single estimate accurately captures all degraded lands, but each one contributes to the overall discussion. Gibbs and Salmon [83] make the case that even if a precise map of the physical area of degraded land were to be produced, it does not suffice, on its own, to provide sound information on the actual produce potential of the land. Considering the land as detached from the other many environmental, social and political constraints may result in highly overestimating its productive potential.

- Adopting "nexus approaches": Understanding soil and land degradation within the metabolism of societies

It is becoming clear that in order to better assess farming and food system performances, a more complex approach to scenario analysis and land use management is needed [99,186]. Steps are being taken towards a "Nexus approach". International institutions, such as FAO (e.g., [57,187]), UN (e.g., [188]), IIDS (e.g., [189]), along with many other scholars (e.g., [87,190–194]) are promoting and working on this line of research, as it is believed to better respond to the complex challenges we are called to deal with. Howells *et al.*, [190] attempts to broaden the approach to integrate the effects of climate change on land, energy and water use (Climate, Land use, Energy, and Water; CLEW-model). Giampietro *et al.* [192] are working on the nexus approach to jointly study resource use and the metabolism of societies (Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism; MuSIASEM-model). Giampietro *et al.* [192] point out that in order to provide a better framing of the complex problems of our societies, it is necessary to integrate different narratives used in quantitative analysis. That is to say, we have to use technical, economic, demographic, social and ecological variables simultaneously, defined on different hierarchical levels and scales. In this way, it is possible to generate better and more complex quantitative representations of the viability and desirability of policies and technical solutions.

Nexus seems to be a promising approach for a better analysis of farming systems, as it allows us to study in a holistic way the interplay between the biophysical factors, socioeconomic forces and metabolic characteristics of societies, taking into account the constraints, potential, possible risks and bottlenecks. Such an approach would also be able to address the participative nature of sustainability, by involving stakeholders and raising awareness of the problems and trade-offs involved in the different solutions.

- Adopting a precautionary approach

Concerning long-term scenarios, it is very difficult to know how the world will be in 2050! In the 1950s nobody could have imagined that in the 1990s we would have high-speed computer and internet, and with it a new world. Thus, for good or for bad, we must take into account the inherent uncertainty of the future due to unforeseeable problems, which are unforeseeable because we just ignore that they could exist [15,29,150,195–199]. Of course, we may also make some novel discovery that could help us. Nevertheless, to play it safe, it is better to focus our attention on how to handle potential problems rather than hope for miracles to happen. Given the limitations of the models, the uncertainty about the real situation, and the high stakes at play, a precautionary approach must be adopted when carrying out soil assessment and producing scenarios. Enhancing the awareness of policy-makers and the public at large constitutes an essential contribution by soil and agriculture scholars.

5. Preserving Soil Organic Matter: Adopting Alternative Agricultural Practices

Current intensive farming practices greatly deplete soil organic matter (SOM) and soil carbon stocks. The decrease in SOM reduces the resistance of soils to erosion agents (e.g., wind, water), lowers the water holding capacity of soils and affects overall soil health. This in turn reduces crop productivity, resulting in the need for more fertilization and irrigation, making soils a net source of CO_2 emissions [5,16,20,77,86,99,124,200,201].

A main goal of "sustainable agriculture" practices is to preserve soil health, enhancing SOM content and limiting soil erosion to a minimum. The term "sustainable agriculture" emerged in the late 1980s and its use was promoted by the study "Alternative Agriculture" by the Board on Agriculture of the National Research Council and through its introduction in the USA Agriculture 1990 Farm Bill [120,122,124,125]. Sustainable agriculture should aim at preserving the natural resource base, especially soil and water, by relying on minimum artificial inputs from outside the farm system and by offsetting the disturbances caused by cultivation and harvest, while being economically and socially viable [120,121,125,202–204]. The domain of sustainable agriculture includes several definitions and practices such as agroecology, integrated agriculture, low input, precision agriculture and organic agriculture [16,124,125]. Sustainable agriculture does not refer to a prescribed set of practices and it differs from organic agriculture, because in some forms of sustainable agriculture agrochemicals (synthetic fertilizers and pesticides) may still play a role, for example, where integrated pest management strategies are employed (for a review see [16,124,125]).

The resistance of soils to erosion is closely linked to the stabilizing influence of SOM and vegetation cover. In regions such as Asia and Africa, where soil erosion is associated with reduced vegetation cover, the loss of soil carbon can trigger catastrophic shifts to severely degraded landscapes [4,9,67,70,86,140,202,205,206]. Bot [207] provides a detailed review of the role of SOM in drought-resistant soil and sustained food production.

High organic matter content inhibits erosion because SOM binds soil particles together, generating an aggregate that resists erosion. The USDA estimated that its takes 500 years to produce an inch (2.54 cm) of topsoil [9]. Most SOM is found in the topsoil (15–25 cm of the A-horizon) and is of key importance for soil fertility [70,200,202,207–210].

The soil organic carbon pool to 1 m in depth ranges vastly: from 30 tons ha-1 in arid climates to 800 tons· ha^{-1} in organic soils in cold regions, with a predominant range of 50 to 150 tons· ha^{-1} [200]. Fertile agricultural soils can contain up to 100 tons of organic matter per hectare (or 4% of the total soil weight); in the case of most agricultural soils, SOM represents 1%–5% of topsoil [209]. Conventional agricultural practices that tend to leave soil uncovered for long periods of the year are responsible for topsoil erosion and reduction of its SOM content. The soil removed by either wind or water erosion is 1.3–5.0 times richer in organic matter than the soil left behind [200,208,211]. About 95% of soil nitrogen and 25%–50% of soil phosphorus are contained in the SOM-containing topsoil layer [208,211].

Practices such as no-till agriculture or minimum tillage, and organic farming can help reduce soil loss, increase SOM and restore soil fertility and biodiversity [16,70,125,140,201,202,211–224] (Figure 10).

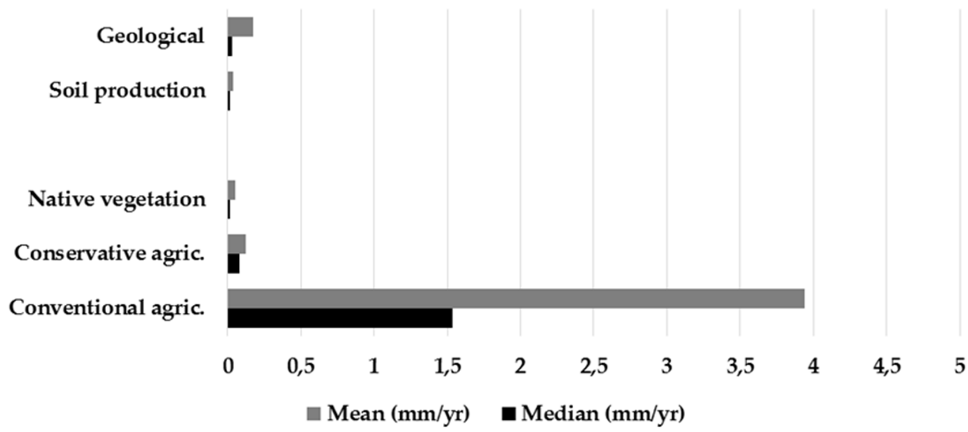


Figure 10. Soil erosion rate for managed and natural soils: result from a meta-analysis (data after [140]).

No-till farming can slow soil erosion and pollution runoff, benefiting aquatic ecosystems, improving agronomic productivity, and achieving food security [7,69,70,127–130,200,202,214]. No-till farming, however, may not suffice to properly protect the soil when other practices are not implemented alongside; for example, cover crops or appropriate rotation schedules, or when it is accompanied by the use of high amounts of agrochemicals [215,216]. Lately, it has been argued that no-till agriculture may be less beneficial than expected as a carbon sink and in the mitigation of climate change [217]. In their work, however, Powlson *et al.* [217] failed to account for the effect on no-till agriculture at the level of the whole farming system. Adopting no-till agriculture practices can reduce energy use by up to 70% (that means saving on fossil fuel emissions) and reduce the use of herbicides and pesticides (again saving on fossil fuels and on the spreading on harmful chemicals) [212].

Long-term crop yield stability and the ability to buffer yields through climatic adversity will be critical factors in agriculture's capability to support society in the future. Literature reviews [124,125] highlight a number of findings concerning the role of SOM and agriculture productivity. It has been estimated that for every 1% of SOM content, the soil can hold 10,000–11,000 litres of plant-available water per ha of soil down to about 30 cm. A number of studies have shown that under drought conditions, crops in organically managed systems produce higher yields than comparable crops managed conventionally. This advantage can result in organic crops out-yielding conventional crops by 70%–90% under severe drought conditions. The primary reason for the higher yield in organic crops is thought to be the higher water-holding capacity of the soils under organic management, up to 100% higher in the crop root zone. Other studies have shown that organically managed crop systems have lower long-term yield variability and higher cropping system stability. It has also to be highlighted that low-input farming systems, such as organic agriculture, significantly increase the level of biological activity in the soil (e.g., bacteria, fungi, springtails, mites and earthworms) [124,125].

Of course, alternative "sustainable" methods may have limits and constraints (e.g., [125,218–220]). For example, they may result in reduced yields, as is the case of organic farming (a serious constraint in poor and highly populated regions of Asia), or require an increase in the use of dangerous herbicides and pesticides (as may be the case for the no-tillage system). Again, when not properly managed, they can lead to high N leaching and NO_x. At present, however, comparative studies and meta-analyses are difficult to compare. Other than the inherent heterogeneities in the ecological and social-economic contexts and farming systems, studies are characterized by a lack of homogeneity (e.g., different boundaries, diverse assumptions and estimates, different methodologies and protocols) [125,221].

Adopting agro-ecological and low input practices may allow us to preserve soil health while still increasing overall farm productivity, for example by adopting a more complex multi-cropping strategy [47,101,120,123,222,223].

The development of perennial grain crops is also a long-debated issue. Perennial crops are reported to be 50 times more effective than annual crops in maintaining topsoil. They can reduce N losses by 30 to 50 times, and store about 300 (but as much as 1100) $kg{\cdot}C{\cdot}ha^{-1}$ per year compared to 0 to 300–400 $kg{\cdot}C{\cdot}ha^{-1}$ per year as is the case for annual crops [21,127–130,224–226]. Experts maintain that perennial crops, with their roots exceeding depths of two meters, can also greatly improve ecosystem functions and services, such as water conservation, nitrogen cycling and carbon sequestration (more than 50% when compared to conventional crops). Management costs are also reduced because perennial crops do not need to be replanted every year, so they require fewer passes of farm machinery and fewer inputs of pesticides and fertilizers, thus reducing fossil-fuel use.

Lal *et al.*, [200] point out that although the adoption of low-input, conservative agricultural practices may experience a short-term yield reduction in some soils and climates, they may represent a win-win alternative in the long run. The adoption of agroecological practices is a necessary strategy for degraded soils, in areas where farmers cannot afford to buy inputs, such as in sub-Saharan Africa [222].

As we have learned from past and recent experience, the intensive exploitation of soil (although possibly providing short-term benefits) leads to the wasting away of the capital which our real business (staying alive) is based upon, which is a certain recipe for disaster. Furthermore, soil degradation forces us to use more inputs (which will become increasingly expensive) and convert more land to agriculture, making high quality land extremely scarce.

In order to implement more sustainable agricultural practices, action should be taken in parallel at different levels: in the field as technical actions and at the national level as policy actions (Table 3).

Table 3. Actions to be undertaken at different levels, as summarized by some leading scholars.

In the Field—Technical Actions (as Summarized by [214])	At the National Level—Policy Actions (as Summarized by [6])
	Premise: the first step is being aware of the problem; the second is realizing that those problems will not solve themselves and action needs to be taken
minimizing bare soil by using cover crops and perennial crops in rotation or between perennial woody species such as in orchards	integrating production with conservation
reducing tillage	gaining better information concerning all aspects of land resources
applying organic amendments, albeit wisely (*i.e.*, in accordance with crop and system needs)	improving management methods, linking research to the work of farmers and learning from them as well for bidirectional knowledge exchange
reducing chemical inputs by increasing nutrient use efficiency and using integrated pest management concepts	facing the population issue, as gains in productivity can be stripped away by the rapid population growth
	national governments taking responsibility for their actions
	Warning: the value of the local knowledge of the environment and of local land resource management should be fully recognized and integrated in the survey work

Research is needed to develop integrated pest management systems that can reduce the use of pesticides, and to develop reduced tillage systems that decrease or eliminate the use of herbicides, both of which improve nutrient use efficiency (reducing the environmental impact of inputs). Wide experimentation is also needed in order to gain a better understanding of the potential and of the limits of alternative agricultural practices under different conditions and constraints. It is also of fundamental importance to strengthen collaboration between researchers, policy-makers and farmers in order to implement sustainable practices that are feasible and viable [6,7,37,71,80,83,101,214].

Unfortunately, up to now, investment in the study of these practices has been limited, or nearly non-existent (as in the case of organic farming); too little is invested in the assessment of the environmental and social impact of conventional farming. The American agriculture NRC [202] notes that only one-third of public research spending is devoted to exploring environmental, natural resource, social, and economic aspects of farming practices.

In practice, the adoption of sustainable land management technologies is a complex matter. To start, we must concede that there is no such thing as a "silver bullet" solution. Solutions have to be tailored to local problems and be carried out within specific local biophysical and socioeconomic contexts. The task is a hard one, as many obstacles may prevent the adoption of new more sustainable practices, especially where they are more needed (e.g., where there is a lack of a proper extension service, limited credit facilities, unreliable markets, lack of infrastructure, local conflicts).

Effective governmental policies should be implemented in order to facilitate the adoption of more sustainable management practices, for example, by implementing policies that favour the provisioning of ecosystem services. More importantly, agricultural policies should be concerned with guaranteeing food security for people on a long-term scale (access to sufficient amounts of healthy food), taking also into account the potential outcome of extreme events. It must be emphasized that in the latter case, "the market", left on its own (and in particular the global market), is rather oriented towards the maximization of short-term profits, rather than to the maintenance of long-term sustainability. Nevertheless, we should be aware that nothing is farther from reality than thinking that capitalistic industrial agriculture runs on a truly free-market basis. Almost no other sector is as politically influenced as agriculture [40,47,100,157–159] and the food system [227–230]. There is one main reason why this is so: the life of people depends on it. Some of the problems are that large vested interests lobby for political control of the agricultural sectors to secure their profits, sometimes acting to exploit farmers, which are the weaker actor within the food chain. These issues may come into conflict with the adoption of soil conservation practices [3,40,41,47,48,100,101,169,231]. Hillel [4] argued that very often a land shortage is due to poor land management rather than to any fundamental scarcity of resources. The author concludes that "*We cannot continue to subsidize or even tolerate practices that cause erosion,* *salinization, and ground water contamination and depletion, or policies that make poor nations permanently dependent on the largesse of their rich neighbors*" [4] (p. 281).

6. Conclusions

Back in the early 1990s, Daniel Hillel, one of the most renowned soil scholars, already warned us about those who "... *may still believe that science and technology will solve all the problems in due course. But that naïve complacency can only be called pathological optimism*" [4] (p. 278). On the other hand, he also warned us about those who " ... *believe there is no solution at all and that some nations are already doomed. That kind of pessimism is equally aberrant*" [4] (p. 278). Hillel [4] calls for a "conditional optimism", where we should be fully aware of the complexity of the situation, yet recognize that changes are taking place. The population growth rate is decreasing, people are much more aware of environmental issues and are asking for changes, and governments are trying to implement programs aimed at reducing our impact on the environment. Recognizing these facts, again, cannot be a license for complacency, but should serve as a spur for doing much more work to sustain these trends. The very fact that the UN declared 2015 the International Year of Soils to raise public awareness on the issue is part of this process of change

Since the early 1990s, however, it seems that the situation has not improved much: arable land per capita is continuing to decline in nearly all nations. Even where population is not an issue, economic forces spur land conversion into more (short-term) profitable businesses (e.g., cyclical jerry-building, such as the cultivation of biofuels, that time and again has caused major economic crises in developed economies). Soil degradation is increasing, even in those nations where food surplus has to be disposed of to sustain the price of the commodities. About 30% (possibly more) of agricultural production is wasted, both in developing and developed countries, although for different reasons [15,232,233].

Following Hillel, we should not choose cynical pessimism, which would be a recipe for certain failure. In the last decades, we have accumulated a lot of experience, mostly from failures, but also from successes. Technology has greatly progressed and can provide new tools to greatly improve monitoring and fieldwork. Nevertheless, technology cannot solve the problems on its own; it can only support human decisions and actions.

The future is sure to pose us many great challenges: population growth, the potential effects of climate extremes, fresh water scarcity, together with the peak of fossil fuels and other key resources (e.g., phosphorous). The spread of social unrest due to conflicts over natural resources and to mass migration (for example, induced by climate change and lack of water supply) may exacerbate those challenges. The critical times we are facing should lead us to be very careful when assessing potential resource availability. We should adopt a precautionary approach in the appraisal of potential resources, both in their amount and quality. The risks we may incur by overlooking the complex criticalities of the real world could be dramatic. Many past civilizations succumbed to soil exhaustion and soil degradation, and we may pity them. Although the dramatic effects of soil degradation have been experienced in recent times too, we still often claim they were due to a poor knowledge of soil ecology and the inexperience of the socioeconomic system. Nevertheless, since then, we have gained plenty of experience, and the advances in science and technology have been enormous. Now we have no excuses. If that old drama repeats itself, we will have only ourselves to blame.

Economists, although appointed to decide over many aspects of our society, seem unfit to properly deal with the complex problems we are called to face. Economics, a century-old discipline, has not fully evolved from its founding axioms and paradigms (many of which have been proved wrong by science and within economics itself). The discipline has evolved to become increasingly de-linked from natural resources, which are treated as perfectly substitutable commodities: for example, in economics the idea that soil can be substituted with techno-gadgetry and that society would be even wealthier, is part of a mistaken theoretical assumption inherent to this discipline. To think that market forces will solve any problem is a major mistake, as we know from experience. Waiting for future technologies to be developed to fix everything is also a major risk, to say the least. Economics is, of course, important, and technology much needed, but they do not suffice (as we have seen in the case of the USA).

Policy-makers and society should become aware that we must develop new models of organization to support lifestyle patterns of consumption that are more sustainable. Wastage and overconsumption are behaviors that we cannot afford, if we care for the future generations. Poverty alleviation is a priority if we wish to prevent future conflicts and the erosion of the social fabric and to reduce the human pressure on the environment. Nevertheless, in many cases poverty may be delinked from agricultural productivity or from the scarcity of natural resources. Poverty is related more to the possibility of people having access to food than to the availability of food per se (as we have seen in the case of the USA). At the global level, most of the poor are farmers, especially women. Often poverty has been a matter of farmers being unable to get a fair price for their products. Lack of infrastructure has also often been an obstacle to rural development, as well as the shortage of extension programs and proper credit policies. Access to land is again a problem in many regions, a problem exacerbated by the phenomenon of "land grabbing". Soil conservation needs to be addressed both in the field and at the national level (nowadays also at the supranational level); it must be treated in a comprehensive and participative way.

Eventually, an increase in awareness should be followed by the spread of an environmental ethic. In keeping with one of the ideas of Aldo Leopold, it should be time for our educational and economic systems to head towards a more intense consciousness of land (and soil) as well as toward a realization of our dependence on nature.

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