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The imperative for regenerative agriculture

CHRISTOPHER J. RHODES

Professor Chris Rhodes is Director of Fresh-lands Environmental Actions (www.fresh-lands.com; E-mail: cjrhodes@freshlands.com). He has catholic scientific interests which cover radiation chemistry, catalysis, zeolites, radioisotopes, free radicals and electron spin resonance spectroscopy, and more recently have developed into aspects of environmental decontamination and low-carbon energy production. Chris has given numerous radio and televised interviews concerning environmental issues.

ABSTRACT

A review is made of the current state of agriculture, emphasising issues of soil erosion and dependence on fossil fuels, in regard to achieving food security for a relentlessly enlarging global population. Soil has been described as "the fragile, living skin of the Earth", and yet both its aliveness and fragility have all too often been ignored in the expansion of agriculture across the face of the globe. Since it is a pivotal component in a global nexus of soil-water-air-energy, how we treat the soil can impact massively on climate change – with either beneficial or detrimental consequences, depending on whether the soil is preserved or degraded. Regenerative agriculture has at its core the intention to improve the health of soil or to restore highly degraded soil, which symbiotically enhances the quality of water, vegetation and land-productivity. By using methods of regenerative agriculture, it is possible not only to increase the amount of soil organic carbon (SOC) in existing soils, but to build new soil. This has the effect of drawing down carbon from the atmosphere, while simultaneously improving soil structure and soil health, soil fertility and crop yields, water retention and aquifer recharge – thus ameliorating both flooding and drought, and also the erosion of further soil, since runoff is reduced. Since food production on a more local scale is found to preserve the soil and its quality, urban food production should be seen as a significant potential contributor to regenerative agriculture in the future, so long as the methods employed are themselves 'regenerative'. If localisation is to become a dominant strategy for dealing with a vastly reduced use of fossil fuels, and preserving soil quality – with increased food production in towns and cities – it will be necessary to incorporate integrated ('systems') design approaches such as permaculture and the circular economy (which minimise and repurpose 'waste') within the existing urban infrastructure. In addition to growing food in urban space, such actions as draught-proofing and thermally insulating existing building stock, and living/working on a more local scale, would serve well to cut our overall energy consumption. In order to curb our use of fossil fuels, methods for reducing overall energy use must be considered at least equally important to expanding low-carbon energy production. In synopsis, it is clear that only by moving from the current linear, 'take, make, dispose *(waste-creation)' model for resource-consumption, to the systemic, circular alternative of 'reduce, reuse, recycle, regenerate', are we likely to meet demands for future generations.*

Keywords: *regenerative agriculture, sustainable agriculture, permaculture, holistic management, soil erosion, carbon sequestration, soil organic carbon, soil organic matter, SOM, SOC, green revolution, seed saving, 4 per 1000, peak oil, peak phosphorus, climate change, circular economy, regenerative cities*

1. Introduction

In WWI, the UK was confronted by a short supply of agricultural workers, who had joined the armed forces, while the wheat harvest of 1916 was smaller than normal and the potato crop failed in Scotland and parts of England. On 9 January 1917, Germany announced unrestricted submarine warfare, which meant that the food shortages would likely be further worsened by the sinking of British merchant ships carrying provisions in from overseas. Thus, concerns over the availability of food were paramount at the time, and in the 1917–1918 volume (XII) of this journal[1] appeared an article entitled "The Electroculture of Crops", by Ingvar Jorgensen and Walter Stiles, which surveyed the potential application of a particular technology in service of enhancing the growth of crops. As they describe their coverage of the subject:

> *"For the sake of simplicity we shall only deal in this article with the form of electroculture in which electricity is discharged through the air to the plants from an overhead wire system, kept charged at a high potential by an electrical machine, or simply charged by atmospheric electricity collected at a higher altitude. This is the only form of apparatus for electroculture which has been employed on anything like a commercial scale, although very numerous experiments have been also made by passing currents through the soil in which the experimental plants are growing."*

While some further exploration of this, and related technology has been made during the intervening years since this paper was published, such methods are not a feature of contemporary agriculture. In 1918, the Ministry of Agriculture and Fisheries established a committee to investigate the phenomenon of 'electro-culture', but this was axed in 1936, arguably for economic reasons, rather than that its basic premise was unfounded[2]. Nonetheless, it appears apposite to identify this paper from 100 years ago, as a point of reference from which to more broadly view where agriculture – with its many subsequent technological innovations – presently sits, and where it needs to go, particularly in regard to the issue of 'sustainability'. It has been pointed out that while agriculture needs to be made sustainable, and the term 'sustainable agriculture' might be considered an oxymoron[3,4], since agriculture is by its very nature unsustainable, with much of modern food production being reliant on inputs of finite fossil fuel energy, and that it renders the soil vulnerable to erosion, with the progressive and global loss of productive land[4]. Even when types of farming are referred to as 'sustainable agriculture', in many cases their result is merely a reduction in the rate of an inexorable degradation of the land, in terms of the quality of its soil, water, fertility and biodiversity; the employment of machinery powered by diesel fuels refined from a finite supply of crude oil, is clearly also an unsustainable component. Accordingly, this article focuses particularly on counteractive methods which serve to improve the land and its vital components, *i.e.* those which are 'regenerative', hence its title.

2. Agriculture

Agriculture may be broadly defined as the cultivation and breeding of animals and crops (including fungi) in order to provide for and improve the human condition. Thus are delivered, food, fibre and biofuels, along with plants for medicinal purposes. In the modern age, the practice of monoculture farming on a very large scale is the basis of what is often termed 'industrial agriculture', which has brought its own problems and challenges, and is regarded as being unsustainable over the longer term[3]. While one third of all those employed globally work in food production (in second place only to the number working in the service sector), the proportion is significantly lower in developed countries. It is through the introduction of irrigation, selection of particular strains of plants, and the application of fertilisers, pesticides and herbicides[3,4], that yields from cultivation have risen steeply; however, these same innovations have also caused negative effects to the environment and human health. Meat yields have similarly been increased by selective breeding, and through the use of antibiotics and growth hormones, but against a backdrop of concerns about the welfare of animals, and the negative health effects of the many chemical compounds that are an integral part of the technologies employed. Increasingly, genetically modified organisms (GMO) are being introduced into the global food production system, although some countries have resolutely banned their use. The over-pumping and depletion of aquifers, along with water contamination from agricultural runoff, is a significant problem globally[3,4], as is the degradation of soil, primarily through erosion[4]. Indeed, the management of the world's soils is a critical issue, since soil and water form a nexus, and soil with a good structure, and which is covered, can efficiently infiltrate and transmit rainfall so allowing the aquifers (groundwater reservoirs) to recharge[4]. The converse is also true, that soil with poor structure, that is left bare, has lost significant soil organic matter, or is compacted, is much less effective in absorbing water, which instead forms run-off and exacerbates the erosion of more soil, contributes to flooding and does not percolate through the soil into the aquifers[4]. However, it should be noted that small family farms manage more than half the world's agricultural land[5], and provide for around 70% of the world's food needs[6]. Agriculture appears to have originated[7] at least 15,000 years ago, with the domestication of pigs in Mesopotamia, while rice was cultivated by humans in China as far back as 13,500 years ago; sorghum was domesticated in Africa 7,000 years ago, and maize was grown 6,000 years ago in Mesoamerica. Food surpluses were a result of farming domesticated species, and this empowered the development of human civilisation[8]. Since the beginning of the 20th century, a rise in the use of mechanisation on farms, mainly in the developed nations, has meant that less of the energy for food production has been provided by human labour, and this process of agricultural 'industrialisation' has been further driven by the Haber–Bosch process for making ammonia (Figure 1) which provides nitrogen fertilisers on a massive scale, greatly enhancing crop yields. Some 450 million tonnes of nitrogen fertiliser – mainly anhydrous ammonia, ammonium nitrate, and urea – are produced annually, which consumes 3–5% percent of the world's natural gas supply, and about 1–2% of all the energy used globally[9]. By the application of these nitrogen fertilisers, along with pesticides, it has proved possible to quadruple the productivity of agricultural land. Accordingly, the Haber–Bosch process has been described as "the detonator of the population explosion", propelling upward the number of humans on Earth from 1.6 billion in 1900 to 7.4 billion in 2016[10]. It has been estimated that only 3.5 billion people, or around half the current global population, could be fed in the absence of synthetic nitrogen fertilisers[11]. It has also been stated that: "With average crop yields remaining at the 1900 level, the crop harvest in the year 2000 would have required nearly four times more land and the cultivated area would have claimed nearly half of all ice-free continents, rather than under 15% of the total land area that is required today"[12]. However, in the absence of these synthetic fertilisers, the population would simply not have risen to current levels, meaning that a far smaller crop harvest, and land area to grow it, would have been required in the year 2000. Since less than 50% of the nitrogen content is actually incorporated into crops, the runoff of excess fertiliser is exerting a significant negative impact on biological habitat of all kinds[13]. It may be deduced that the Haber–Bosch process accounts for some 47% of the overall energy consumed by European agriculture, and some 52% of the total energy used can be ascribed to nitrogen fertilisers, once their actual application to land and other logistical factors, such as distribution, are factored in. Phosphorus and potassium fertilisers together account for 8% of the total, leaving the remaining 40% for other farm inputs and on-field work. Thus, fertiliser use accounts for 60% of the energy required to run agriculture across Europe[14], a situation that clearly cannot be maintained.

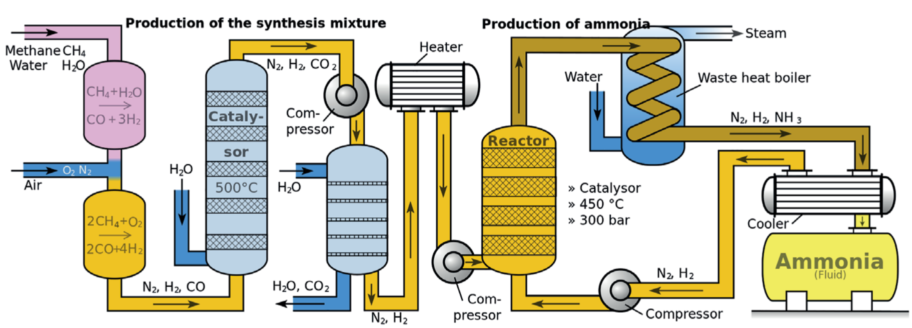

Figure 1 *Haber–Bosch process for converting methane to ammonia, via synthesis gas (H_2 + CO) + N_2 (from air). Credit: Francis E. Williams. https://commons.wikimedia.org/wiki/File:Haber-Bosch-En.svg.*

As a result of an increasing awareness regarding the detrimental environmental consequences of industrialised agriculture, the organic and sustainable agriculture movements were born. The European Union first certified organic food in 1991, and in 2005 began to reform its Common Agricultural Policy (CAP), to repeal commodity-related farm subsidies. However, in 2007, there were food shortages in Asia, Africa, the Middle East and Mexico, caused in part by higher incentives for farmers to grow non-food biofuel crops, along with higher consumer demand in China and India, increased transportation costs and rising food prices worldwide. Food riots ensued, with some fatalities, and by the end of that year, 37 countries faced food crises, 20 of which had imposed price controls over food. It has been proposed by The International Fund for Agricultural Development that overall food security (and price stability) could be achieved by increasing the amount of food produced by small farms: their example is Vietnam, which (mainly as a result of establishing smallholder agriculture) became a large food exporter (rather than the net food importer that it was) and saw a significant decrease in the nation's poverty[15]. The main causes for concern in contemporary agriculture are land degradation and the emergence of crop diseases, such as the epidemic of stem rust which is advancing across Africa and spreading into Asia, and has resulted in crop losses of above 70% in some regions[16]. According to Pimentel and Burgess, about 80% of the world's agricultural land suffers moderate to severe erosion, while 10% experiences slight erosion[17], although estimates of the severity of the phenomenon are disputed and various[4]. However, it has been concluded that, due to various factors, including soil erosion, Africa may only be able to produce one third to one half of the grain needed to feed its expected population in 2050[18]. On this basis, arguments[4] that the population of Africa will have more than trebled from the current (2016) 1.2 billion, to 4.2 billion by the end of this century (2100) are less than convincing.

3. The Green Revolution

The origins of the Green Revolution[19] are usually attributed to Norman Borlaug, an American agricultural scientist who, in the 1940s, began conducting research in Mexico, where he developed new disease-resistant, high-yield varieties of wheat (Figure 2). These are plants bred specifically to respond to fertilisers, and produce a greater amount of grain per hectare of land that is planted. Thus, although Mexico initially imported half the wheat it consumed, through a combination of these new wheat strains and mechanised farming methods, by the 1960s, the country was able to not only feed itself, but to become an exporter of wheat. Many nations have benefited from the methodology of the Green Revolution. In the early 1960s, India was facing mass starvation because existing methods of food production were insufficient to keep pace with the burgeoning population of the country. Supported by the Ford Foundation, Borlaug developed a new variety of rice, IR8, which yielded far more grain per plant, thus overcoming the problem, and now India is one of the world's major exporters of rice. It should be noted, however, that it is only through the input of large quantities of artificial fertilisers, pesticides and adequate

Figure 2 A critical feature of the Green Revolution was the development of new varieties of wheat and other grains. Credit: Carol Spears. https://sco.wikipedia.org/wiki/File:Wheat-haHula-ISRAEL2.JPG.

irrigation, that these high yielding plants can flourish. By maximising the seed or food portion of the plant, through selective breeding, more of the energy captured through photosynthesis went directly to the food portion of the plant. Furthermore, plants were bred that were not affected by day-length, and so were not restricted to be grown only in particular regions, according to the amount of light available to them. Overall, this led to a doubling in the crop productivity.

3.1 Consequences of the Green Revolution

Undoubtedly, the use of Green Revolution technologies has vastly increased the amount of food produced across the world, and for example, India and China have not experienced famine since they adopted IR8 rice and related crops. The practices of agriculture have been changed, however, by the dependence of these high-yield crops on inputs of synthetic fertilisers, which cannot grow without their application. Prior to the Green Revolution, much of agriculture was largely confined to areas where the rainfall was appreciable, but through large-scale irrigation systems, more land can be used for crop production, further raising the total amount of food available. As a downside, only a few high-yield varieties, *e.g.* of rice, are now grown, whereas prior to the Green Revolution, some 30,000 types of rice were grown in India. Such monoculture systems are less resistant to disease and to pests – in the absence of competitive biodiversity – which has necessitated an increased use of pesticides.

3.2 Negative aspects of the Green Revolution

A major criticism of the Green Revolution is that its success has led to world overpopulation, in contrast to the ('Malthusian') predictions made by Thomas Malthus, that the geometric growth in population would exceed that of food production, which increases at an arithmetic rate. A similar culpability may be brought against mass vaccination projects, *e.g.* to 'cure' malaria and other diseases, which otherwise would have acted to cull the human population, now in excess of 7 billion. It has been argued that, should the number of humans reach 10 billion by the end of this century, our consumption and excretion will overwhelm the natural limits of Planet Earth. Most likely, it is these limits of resources, and a finite buffering capacity of the planet to cope with our waste, that will initiate a die-off in the human population, perhaps to less than one half the present number by the year 2100[20]. In contrast to India, African nations have benefited little from the Green Revolution, but this is mostly due to a lack of infrastructure for implementing the necessary new technologies, government corruption, and general economic and societal insecurity throughout the continent. Moreover, the issue of feeding the world is not entirely about the quantity of food that can be grown, but also its quality. Undoubtedly, the Green Revolution increased grain production and helped avoid famine, but it has also led to nutritional problems since many of the high-yield crop strains are poor in their mineral and vitamin content. Ironically, large numbers of people who have been spared from starvation have been incapacitated through deficiencies in iron, zinc, vitamin A and other essential nutrients, as traditional dietary sources are supplanted by new food sources. Iron deficiency, in particular, has become a notable global problem, since it affects 1.5 billion children, and half of all pregnant women worldwide are anaemic. The problem is most acute in South and South East Asia, where the Green Revolution has been most successful[21,22]. Maintaining the Green Revolution has required a continuing, and likely increasing, use of pesticides and fertilisers, which have proved hazardous to the environment, and also toxic to humans and animals. The necessity to reduce these inputs, such that agriculture becomes more sustainable, is likely to further reduce levels of food production, and at a time of greatest ever population. The situation is problematic, to say the least.

4. Land degradation and soil erosion

The term ‘land’ may be understood[23] to refer to an ecosystem, and thus to include land, landscape, terrain, vegetation, water, and climate, while ‘soil’ is a specific entity and a component of land. Degradation or desertification of land refers to an irreversible decline in its ‘biological potential’: a term which, in itself, resists definition due to its association with a multitude of interacting factors. Since the soil mediates collectively (holistically) many essential processes involving vegetation growth, overland flow of water, infiltration, land use and land management, its quality is a prime indicator of land degradation – hence, when soil is degraded the land is too. The principal cause of land degradation is soil erosion (Figure 3), and in combination, water and wind erosion are accountable for around 84% of the amount of degraded land that exists globally (56% from water; 28% from wind). While soil erosion is a complicated phenomenon, and estimates of its severity vary[4], it is clear that it is one of the most serious issues to be addressed by humankind. The phenomenon has been dubbed ‘peak soil’, in analogy with ‘peak oil’, and is not confined to Africa but is a global feature. Indeed, the situation has been summarised in an article[24] published in *Scientific American* with the disquieting title: “60 years of farming left if soil degradation continues.”

Figure 3 *An actively eroding rill on an intensively-farmed field in eastern Germany. Credit: Katharina Helming. https://commons.wikimedia.org/wiki/File:Eroding_rill_in_field_in_eastern_Germany.jpg.*

Remote sensing measurements[25] (which are discussed later in more detail) indicate that more than 20% of all cultivated areas, 30% of forests and 10% of grasslands are undergoing some degree of degradation[26,27]. Land degradation and desertification are thought to affect 2.6 billion people in more than 100 nations[28]. The global scale of these issues was reinforced at the United Nations Convention to Combat Desertification, the Convention on Biodiversity, the Kyoto protocol on global climate change and the millennium development goal[29]. Various inappropriate uses of land may cause soil, water and vegetative cover to become degraded, with the loss of both soil and the biological diversity of flora, with impacts on the structure and functions of ecosystems[30]. Once land has become degraded, it is more vulnerable to the effects of climate change, particularly rising temperatures and droughts of greater severity. The entire regional environment is encompassed by the term land degradation; however, individual aspects of soils, water resources (surface, ground), forests (woodlands), grasslands (rangelands), croplands (rain-fed, irrigated) and biodiversity (animals, vegetative cover, soil) are implicit here[31]. Land degradation is a complex process, and involves a number of interactive amendments in the properties of the soil and vegetation – being physical, chemical and biological, in their nature. Hence, the definition of land degradation varies from one region to another, according to the emphasis on particular topics, but the effect is most severe in drylands, and thus the 40% of the Earth's surface that contains them[32]. It has been estimated that around 73% of rangelands in dryland areas, 47% of marginal rain-fed croplands and a significant percentage of irrigated croplands[33] have been degraded. 20% of the world's pastures and rangelands are degraded through overgrazing, and it is estimated that, through erosion and both chemical and physical damage, some 65% of agricultural land in Africa is degraded, along with 31% of the continent's pasture lands and 19% of its forests and woodlands[33]. The prevailing opinion has been that overgrazing is the main driver of land degradation in Africa, *i.e.* human impacts, but more recent thinking is that climatic factors are those most important – particularly rainfall variability and long-term drought[33]. It is in Sub-Saharan Africa that land degradation is most extensive, where it impacts on some 20–50% of the land and therefore affects the daily lives of well over 200 million people[30].

According to the study of global land degradation, made from the International Soil Reference and Information Centre by Oldeman *et al.*[34], and termed Global Assessment of Human-induced Soil Degradation GLASOD[34], of the different erosion mechanisms, it is water erosion that is the most important, and this afflicts some 1,094 million ha (56%) of the total area that is impacted upon by human-induced soil degradation. Globally, wind erosion affects 548 million ha (28%) of the terrain that is degraded. Chemical soil deterioration affects 239 million ha (12%) of the total, and physical soil deterioration occurs over 83 million ha (4%). Loss of topsoil by water or wind erosion is the dominant subtype of displacement of soil material. These subtypes cover an area of 920 million ha, affected by water erosion (365 million ha in Asia, and 205 million ha in Africa), and 454 million ha by wind erosion. The principal chemical deterioration of soils involves the loss of nutrients and this affects 135 million ha worldwide, of which 68 million is in South America. Salinisation follows next in order of its impact, and afflicts some 76 million ha globally, of which 53 million ha is in Asia. An area of 22 million ha is affected by pollution, of which 9 million ha is located in Europe. The most significant subtype of physical soil deterioration is compaction, and this occurs over an area of 68 million ha, of which 33 million ha is in Europe, and 8 million ha is in Africa.

GLASOD categorises four degrees of soil degradation. ‘Light’ refers to a somewhat reduced productivity of the terrain, but which is manageable in local farming systems, and applies to 38% of all degraded soils (749 million ha). ‘Moderate’ requires improvements which are often greater than can be achieved by local farmers in developing nations, and accounts for 46% of the Earth’s degraded soils. Thus 910 million ha of the Earth’s surface has a greatly reduced productivity: >340 million ha of these moderately degraded lands are in Asia and >190 million ha are in Africa. There are 296 million ha globally of ‘strongly degraded’ soils (124 million ha in Africa, and 108 million ha in Asia), and it is these that are not possible to reclaim at the farm level and which may therefore be regarded as lost land. Such terrains can only be recovered through major engineering work and/or international assistance. Finally, soils that are ‘extremely degraded’ are regarded as irreclaimable and beyond restoration, amounting to a global total of 9 million ha (>5 million ha in Africa).

GLASOD is not without its critics[35], and indeed its authors were well aware of, and the first to indicate, its limitations: principally that it was based on the perceptions of experts, rather than being a direct measure of land degradation. More recently[26,27], methods of remote sensing have been applied to determine the extent of global land degradation: LADA (Land Degradation Assessment in Drylands).

These aim to determine the degree and trends of land degradation in drylands, degradation hotspots and bright spots (both actual and potential), using changes in net primary productivity (NPP) as a proxy measure of land degradation. (Net primary productivity [NPP] is defined as the net flux of carbon from the atmosphere into green plants per unit time. NPP refers to a rate process, *i.e.* the amount of vegetable matter produced [net primary production] per day, week, or year.) The most heavily degraded regions are identified to be in Africa: south of the equator (13% of the global degrading area and 18% of lost global net NPP); South East Asia (6% of the degrading area and 14% of lost NPP); South China (5% of the degrading area and 5% of lost NPP); north-central Australia and the western slopes of the Great Dividing Range (5% of the degrading area and 4% of lost NPP); the Pampas (3.5% of degrading area and 3% of lost NPP); and swathes of the high-latitude forest belt in Siberia and North America, directly affecting the livelihoods of the 1.5 billion people who live there. The results indicate that 24% of the total global land surface has suffered degradation during the past quarter century, and may be compared with the 15% of the world's soil (not land) being degraded, according to the GLASOD study. Much of the degradation identified by GLASOD[34] does not overlap with the areas newly highlighted by LADA, demonstrating that land degradation is both cumulative and global. The authors stress that land-use changes which reduce NDVI (remotely sensed Normalised Difference Vegetative Index [Figure 4]), *e.g.* from forest to cropland of lower biological productivity, or an increase in grazing pressure, may or may not be accompanied by soil erosion, salinity or other symptoms of land degradation that are of concern to soil scientists. They note further that while long-term trends in NDVI derivatives are only broad indicators of land degradation,

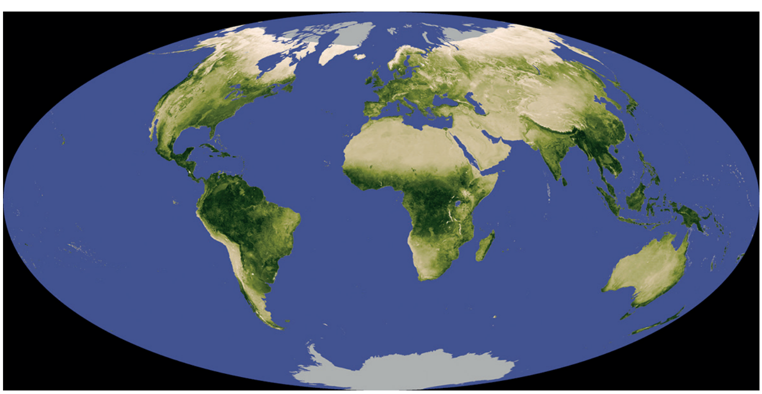

Figure 4 *Normalised difference vegetation index (NDVI) from 1 November 2007, to 1 December 2007, during autumn in the Northern Hemisphere. Food, fuel, and shelter: vegetation is one of the most important requirements for human populations around the world. Satellites monitor how 'green' different parts of the planet are and how that greenness changes over time. These observations can help scientists understand the influence of natural cycles, such as drought and pest outbreaks, on vegetation, as well as human influences, such as land-clearing and global warming. Credit: NASA. https://commons.wikimedia.org/wiki/File:Globalndvi_tmo_200711_lrg.jpg.*

taken as a proxy, the NDVI/NPP trend is able to yield a benchmark that is globally consistent and to illuminate regions in which biologically significant changes are occurring. Thus attention may be directed to where investigation and action at the ground level is required, *i.e.* to potential 'hot spots' of land degradation and/or erosion.

Montgomery[36] has made a global compilation of studies which confirms the long held contention that the erosion rates from conventionally ploughed soils are 1–2 orders of magnitude greater than the background rates of soil production, of erosion under native vegetation, and long-term geological erosion. He concludes that on a global basis, hill-slope soil production and erosion evolve to balance geologic and climate forcing, whereas agriculture based on conventional ploughing increases the rates of erosion to unsustainable levels. At a rate close to 1 mm year^{-1} of soil loss (amounting to around 14 t ha^{-1} year^{-1}), net erosion rates in conventionally ploughed fields can erode a typical hill-slope profile on a timescale of major civilisations, whereas no-till methods of farming cause rates of erosion that are nearer to those of natural creation rates of soil, and hence might set the cornerstone of a system of sustainable agriculture.

4.1 Establishing a relationship between land degradation, soil productivity and crop yields

The productivity of some lands (Figure 5) has fallen by 50% as a result of soil erosion and desertification, and the according reduction in crop yields in Africa lies in the range 2–40%, with a mean loss of 8.2% for the continent overall[23]. The loss of productivity in South Asia has been reckoned at 36 million tons of cereal equivalent with a value of $5.4 billion as a result of water erosion and $1.8 billion from wind erosion[23]. It is a vexed matter to make a definite connection between the extent and processes of soil erosion and declining crop yields, since the latter may result from various influences. In some cases, the crop yields do not fall markedly, and may even increase for a time, despite the soil being eroded, *e.g.* if a compensatory increase is made in fertiliser inputs. Crop yields may be impaired[37] by an excessive removal of nutrients from the soil which are not replenished, the impact of pests and diseases, weed infestations, and the greater frequency of drought as a consequence of climate change. Other factors – which may be associated with soil erosion – can also be culpable for a reduction in crop yields, *e.g.* a restriction in the possible rooting depth (when the soil depth becomes limited and the roots touch the bedrock or a clay layer), a reduction in the water capacity of the soil, a decline in soil organic matter (SOM) and soil organic carbon (SOC) content, an increasing salinity or sodicity of soil, other changes in the chemical composition of the soil (*e.g.* the presence of aluminium or heavy metal cations), or a reduction in soil pH (acidification) in general. All of the above, in one way or another, are connected to some type of soil degradation, the most common being soil erosion by water[37]. It can be said that practically any adverse environmental change is likely to lead to soil erosion and a decrease in biomass yield, such is the inextricable complexity of the underlying components of these phenomena. To invoke a spectrum of impact, we may at one extreme consider the conversion of dryland savannah to continuous cropping (the practice of growing the same crop in the same space year after year) of soya beans (soybeans). As a result of this change, the combined influence of loss of vegetative cover and soil disturbance will aggravate and accelerate soil erosion. Although the crop (a legume) will contribute some nitrogen to the soil, and some organic matter, a tipping point will ensue eventually when production is impaired, as a result of a thinning of the topsoil, colloid loss, and a reduction in the water-retaining capacity of the soil. However, the input of resources (*e.g.* fertilisers, irrigation) and technological means can allow production to be continued unabated. At the other end of this spectrum are the 'badlands' (Figure 6) – a result of the mistreatment of semi-arid ground, where serious soil erosion has occurred, with gullies, rills, pipes and other related aspects – which are completely lacking in vegetation. As far as apportioning blame for the loss of vegetation to soil erosion is concerned, both extremes are really 'chicken and egg' situations: erosion must result in a reduced soil quality, which impairs plant production and reproduction – allowing that this might be masked by technology and

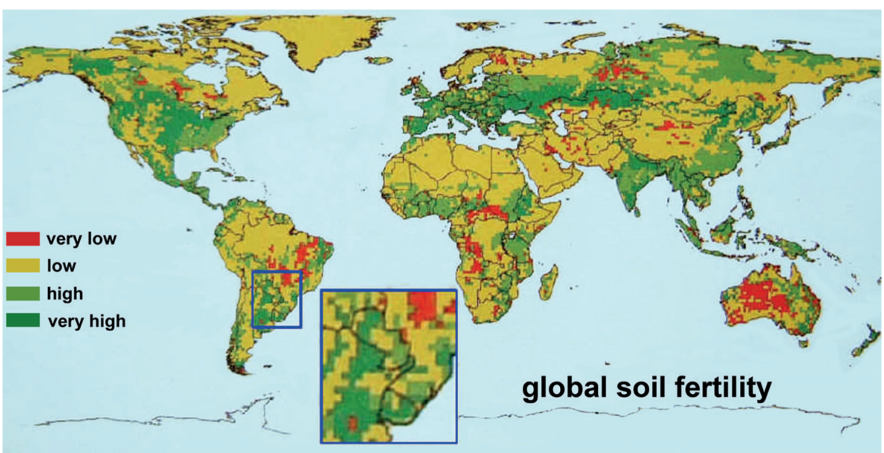

Figure 5 *Fertility of world's soils. Adapted from:http://www.pvoss.de/Agro/globalfertility.jpg*

Figure 6 *The Chinle Badlands at Grand Staircase-Escalante National Monument in southern Utah. Credit: United States government. https://commons.wikimedia.org/wiki/File:Chinle_Badlands.jpg.*

other inputs – but at the same time, a loss of vegetative cover provokes soil erosion. It is rare, however, that a landscape becomes entirely barren, because soil that is 'lost' by erosion is transported to other regions, bearing nutrients, organic matter and water. Such bestowals are prevalent particularly in South Asia, where 'sediment harvesting' is possible, *e.g.* the *nullah plugs* in India. Hence, the 'cause and effect' paradigm of soil erosion and crop productivity should be treated with caution, since an adverse effect on one location may transfer an advantage to somewhere else[37].

Some confidence is justified in connecting soil erosion and crop yields, primarily on the basis of experimental runoff plots, where measured soil losses are related to both current and future yields, though not exclusively to the underlying mechanisms of soil erosion. As a general trend, plots of crop yield *versus* cumulative soil depletion (t ha^{-1}) reveal curvilinear, inverse-exponential type relationships, *i.e.* the yield drops as the soil gets thinner. Hence, there is an initially sharp loss of productivity, followed by stages in which the impact is successively less. While alternative behaviour has been identified, the overall message is that it is comparatively easy to bring back slightly degraded land into economic use, and that the net returns are always better if the yield has not fallen to under 50%. In contrast, when land has been severely degraded, to bring it back into useful (or even economic) production is a tremendously difficult task, and having reached this stage, it is often abandoned.

5. Sustainable agriculture

Sustainable agriculture encompasses many different aspects, but its underpinning philosophy is a repudiation of what is often termed 'conventional agriculture', though in reality the latter only fully came to pass in the years of WWII and beyond[3,4]. More appropriately, the term 'industrialised agriculture' is used, since the modern system is far from conventional (as in 'traditional'), and relies on monoculture cropping, an increasing use of mechanisation, the application of synthetic fertilisers, pesticides and herbicides, and biotechnology (GMO), along with liberal government subsidies. Although this approach can be considered successful, in that it has managed to feed (but also urged) a massively rising human population, a range of environmental and social burdens have also been incurred, including: eroded, depleted and contaminated soil; compromised water resources; a sufficiently dramatic loss in biodiversity[38] that we may be in the midst of the 'sixth mass extinction' era; loss of forests and desertification; human labour abuses; and naturally the decline of the traditional family-run farm.

The term 'sustainable agriculture' entered the popular lexicon in the late 1980s, but was reportedly first used by Gordon McClaymont[39], an Australian agro-scientist; credit is afforded to Wes Jackson for the first expression of the phrase in print, in his 1980 book *New Roots for Agriculture*[40]. The philosophy of sustainable agriculture embraces many different (and alternative) methods, which may be considered 'organic', 'low-input', 'free-range', 'biodynamic', 'integrated' and 'holistic'. At their core, these approaches all embody farming practices that simulate processes of natural ecology. Thus, the use of ploughing (tillage) is kept to a minimum; the application of pesticides is obviated through encouraging organisms that keep pests under control; the use of water is minimised; the application of artificial fertilisers is avoided; and by integrating the use of land that is used to grow crops with grazing livestock, healthy soil is nurtured. Sustainable agriculture extends beyond the aspects of food production *per se*, to the welfare of those involved in the food-growing, in terms of equitable treatment of farm workers and a proper food pricing system that provides a decent living for the farmers themselves.

Those farming practices employed in sustainable agriculture[41] are underpinned by a knowledge of 'ecosystem services', *i.e.* the benefits conferred to humans by ecosystems, such as the production of food and clean water and air, the decomposition or detoxification of wastes, carbon sequestration and climate regulation, and pest and disease control. Although there had been an implicit consideration of these things for many years, it was only early in the present millennium that the Millennium Ecosystem Assessment (MA) brought the term and concept of it into broader discourse. The MA listed ecosystem services under the following headings[42]: (1) *provisioning*, for example the provision of food and water; (2) *regulating*, such as the control of climate and disease; (3) *supporting*, which includes nutrient-cycles and crop-pollination; and (4) *cultural*, so to emphasise spiritual and recreational benefits. In an effort to assist decision-makers, economic parameters are now ascribed to many ecosystem services. One definition of sustainable agriculture is:

> "*An integrated system of plant and animal production practices having a site-specific application that will last over the long term*."[43]

Sustainable agriculture aims to avoid practices that can cause long-term damage to soil, such as excessive tillage, which contributes to erosion, and irrigation without adequate drainage, which may cause salinisation; furthermore, any methods of irrigation which withdraw water from their source at a faster rate than can be replenished naturally, cannot be regarded as sustainable. It is unavoidable that when crops are grown and harvested, nutrients are taken from the soil, and if these are not replaced, the land becomes sufficiently depleted in nutrients that crop yields are reduced, eventually to the extent of being unusable, at which point it is typically abandoned[4]. The methods employed in sustainable agriculture aim to recharge the soil, but in such a way that inputs of non-renewable resources, such as natural gas (used to make synthetic 'nitrogen' fertiliser), or phosphate and potash minerals, are kept to a minimum. In view of the fact that the Haber–Bosch process[9], which fixes atmospheric nitrogen gas into ammonia is highly energy-consuming, and inputs of fossil fuels, such as natural gas are not sustainable[3], the use of more 'renewable' sources of nitrogen is preferable. The latter might include: (1) recycling crop waste (rubble) into the soil, and the addition of both animal and human manures; (2) growing leguminous crops whose roots form symbiotic combinations with nitrogen-fixing bacteria (rhizobia); (3) long-term crop rotations; (4) growing crops, following natural cycles that return depleted nutrients indefinitely (such as the flooding of the Nile); and (5) using genetic engineering to transform non-leguminous crops, so they either form similar nitrogen-fixing arrangements as do legumes, or are able to fix nitrogen without the use of microbial symbionts. However, while option (5) is approaching technical feasiblility[44], it is arguable if it is truly sustainable, and while there are clearly a number of viable means for the provision of nitrogen fertilisers from renewable sources, the possibilities[14] for supplying potassium and phosphorus (Section 5.4), while avoiding (unsustainable) mineral inputs, are far more limited.

5.1 Water use

In those regions where there is insufficient rainfall to allow crops to grow satisfactorily, irrigation is required; however, proper management is required to circumvent problems of salinisation, and the water consumption rate must not exceed the natural recharge rate of the water source. Through technological innovations, it has become possible to sustain the production of high-yielding crops, even in areas that had hitherto been unpredictable in terms of agriculture, due to variations in rainfall. Improved devices for drilling water-wells, and the employment of submersible pumps along with drip irrigation and low-pressure pivots, have all contributed to the present situation, which is marked by the over-pumping of underground water sources, most notably the Ogallala Aquifer, although the problem is pervasive across the world[3,4]. As a flip-side to this, evidence has been published that the vast volumes of water being withdrawn from aquifers may be responsible for 42% of the sea-level rise observed between 1961 and 2003, since either as river runoff, or through evaporation and rain, it eventually ends up in the world's oceans[45]. However, a more recent study[46] concluded that this might be an overestimate.

Some indicators for sustainable water resource development have been proposed[48]:

"(1) Internal renewable water resources. This is the average annual flow of rivers and groundwater generated from endogenous precipitation, after ensuring that there is no double counting. It represents the maximum amount of water resource produced within the boundaries of a country. This value, which is expressed as an average on a yearly basis, is invariant in time (except in the case of proved climate change). The indicator can be expressed in three different units: in absolute terms (km³/yr), in mm/yr (it is a measure of the humidity of the country), and as a function of population (m³/person per year).

(2) Global renewable water resources. This is the sum of internal renewable water resources and incoming flow originating outside the country. Unlike internal resources, this value can vary with time if upstream development reduces water availability at the border. Treaties ensuring a specific flow to be reserved from upstream to downstream countries may be taken into account in the computation of global water resources in both countries.

(3) Dependency ratio. This is the proportion of the global renewable water resources originating outside the country, expressed in percentage. It is an

expression of the level to which the water resources of a country depend on neighbouring countries.

(4) Water withdrawal. In view of the limitations described above, only gross water withdrawal can be computed systematically on a country basis as a measure of water use. Absolute or per-person value of yearly water withdrawal gives a measure of the importance of water in the country's economy. When expressed in percentage of water resources, it shows the degree of pressure on water resources. A rough estimate shows that if water withdrawal exceeds a quarter of global renewable water resources of a country, water can be considered a limiting factor to development and, reciprocally, the pressure on water resources can affect all sectors, from agriculture to environment and fisheries."

However, as we discuss subsequently, through the creation of good quality soil, the absorption of rainfall is enhanced, both reducing flooding and allowing groundwater sources to recharge. Soil should also not be left bare (which encourages erosion), but rather covered with grass/plants/trees. Thus, methods of regenerative agriculture may further serve to protect the global freshwater supplies. Furthermore, the practice of 'sealing' the ground with impermeable materials, such as asphalt and concrete, should be avoided as far as possible.

5.2 Soil, soil formation and the soil food web

We have already noted the issue of land degradation (primarily caused by soil erosion), and its likely negative impact on future global food production. To address this problem, actions are necessary to attenuate the rate of erosion of the soil, but moreover (as we see later) to build new soil in a regenerative strategy. This would lead to a restoration of the soil food web, and an improvement in the quality and fertility of soil, while locking-up carbon from the atmosphere in the same process of creating soil organic matter. The activities of plants, animals, insects, fungi, bacteria, and humans too, all play a part in the formation of soil[3,4]. Fauna, *e.g.* earthworms, centipedes, beetles, *etc.* and microbes, mix soils by forming burrows and pores, which allow moisture and gases to diffuse through the soil matrix. As plant-roots grow in soil, channels are also created. Plants with deep taproots can penetrate the different soil layers by many metres and draw-up nutrients from considerable depths. Organic matter is contributed to the soil by plant-roots that extend near the surface, where they are quite readily decomposed. Micro-organisms, including fungi and bacteria, facilitate chemical exchanges between roots and soil and act as a reserve of nutrients. Soil erosion may arise from the mechanical removal, by human activities, of plants that provide natural surface cover. The different soil layers may be mixed together by micro-organisms, a process which stimulates soil formation, since less-extensively weathered material is mixed with more well-developed layers closer to the surface. Some soils may contain up to one million species of microbes per gram (most of these

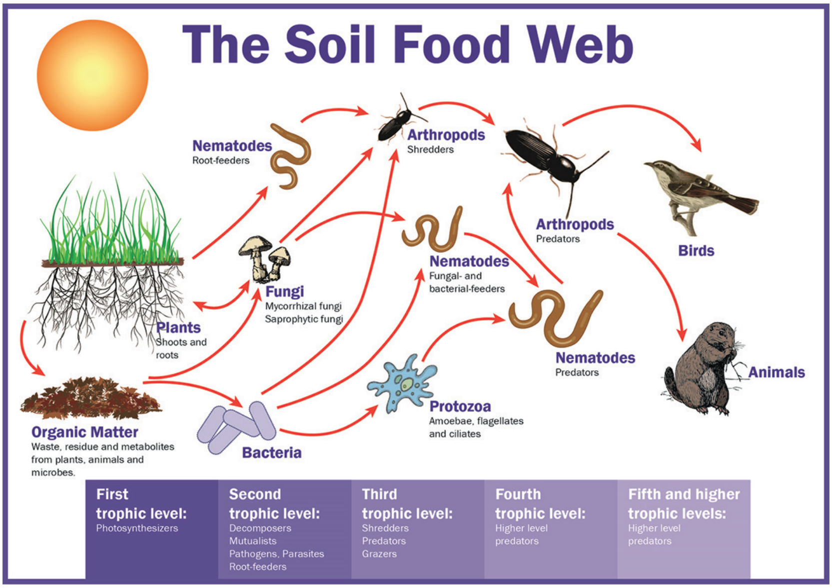

Figure *7 An example of a topological soil food web.*

species being unclassified), making soil the most abundant ecosystem on Planet Earth. One quarter of the biodiversity (total number of organisms) on Earth live in the soil. It is thought that one teaspoonful of soil may contain up to a billion organisms, which collectively comprise the soil food web (Figure 7).

Vegetation can prevent soil erosion caused by excessive rain and resulting surface runoff. Plants are also able to shade soils, keeping them cooler and reducing the loss, by evaporation, of soil moisture; yet conversely, through transpiration, plants may also cause soils to lose moisture. Plants can synthesise and release chemical agents (including enzymes) – 'exudates' – through their extended root-systems, which are able to decompose minerals and so improve the structure of the soil. Dead plants, fallen leaves and stems begin their decomposition on the surface, where organisms feed on them and mix the organic material into the upper soil layers; these additional organic compounds become part of the soil formation process. In addition to the essential characteristics of a particular soil – *e.g.* its density, depth, chemistry, pH, temperature and moisture – the precise type and quantity of vegetation that may be grown at a particular location depends on a combination of the prevailing climate, land topography, and biological factors.

5.2.1 Time

Soil formation is a time-dependent process that depends on the interplay of various different and interacting factors[3]. Soil is a continuously evolving medium, and it requires around 200–1,000 years to form a layer of fertile soil 2.5 cm (one inch) thick

[However, see Section 11 regarding methods for more rapid formation of topsoil.] Fresh material, *e.g.* as recently deposited from a flood, shows no trace of soil development because insufficient time has passed for the material to form a structure that may be later defined as soil. Rather, the original soil surface is buried, and the new deposit must be transformed afresh. Over a period ranging from hundreds to thousands of years, the soil will develop a profile that depends on the nature and degree of biota and climate. Soil-forming mechanisms continue to proceed, even on 'stable' landscapes that may endure sometimes for millions of years. In a relentless process, some materials are deposited on the surface while others are blown or washed from the surface. At the behest of such additions, removals, and alterations, soils are always subject to new conditions. It is a combination of climate, topography and biological activity that decides if these changes are rapid or protracted.

5.3 'Peak oil' and 'peak gas'

The greatest adverse impact on our system of industrialised agriculture would be the loss of a cheap and plentiful supply of crude oil[48] ('peak oil'), and the fuels, pesticides and herbicides that are derived from it. Although there is a cornucopian counterargument that peak oil can be disregarded, on the grounds that there are vast quantities of 'oil' in the earth, it ignores or confounds what the term actually means. Specifically, peak oil refers to the maximum *rate of production* of crude oil, not the size of the total hydrocarbon body that may lie in the multifarious reservoirs of global geology. To use an analogy: it is the size of the tap, not the tank, which determines the overall rate of flow of oil from below the ground to the surface. The 'size' of the tap will embody technical, geological and economic factors. Much of the 'oil' that remains will be recovered only with a far lower energy return than conventional crude oil, and much of what is claimed may not prove worth recovering at all. It is thought that conventional oil (that recovered onshore or in shallow offshore locations using normal vertical drilling methods) production peaked in 2005, and the overall global oil supply is being maintained by an increasing production from unconventional sources, *i.e.* hydraulic fracturing of (mostly) shales (Figure 8), bitumen from tar sands, extra-heavy oil, and ultra-deepwater drilling. The bulk of the world's tally of unconventional oil is present in oil shale, and is not petroleum but a solid, primordial material called kerogen, which must be 'cracked' (thermally decomposed) by heating it to 500 °C, in order to produce a liquid form that resembles crude oil[3,48]. Unsurprisingly, this requires a high input of energy, and which is comparable to the amount of energy that would be recovered by burning the resulting shale-oil [The, generally good quality, crude oil that is contained in shales, and recovered by fracking, is more correctly termed "tight oil", although it is often referred to as "shale oil" both in the media, and in popular discourse. There is a source of confusion, however, since "shale oil" is also the term given to "oil" that is produced by thermally decomposing kerogen from "oil shale". Which is meant, however, should be clear from context of the particular process described]. In addition to its restrictive influence on running farm machinery, the loss of a cheap

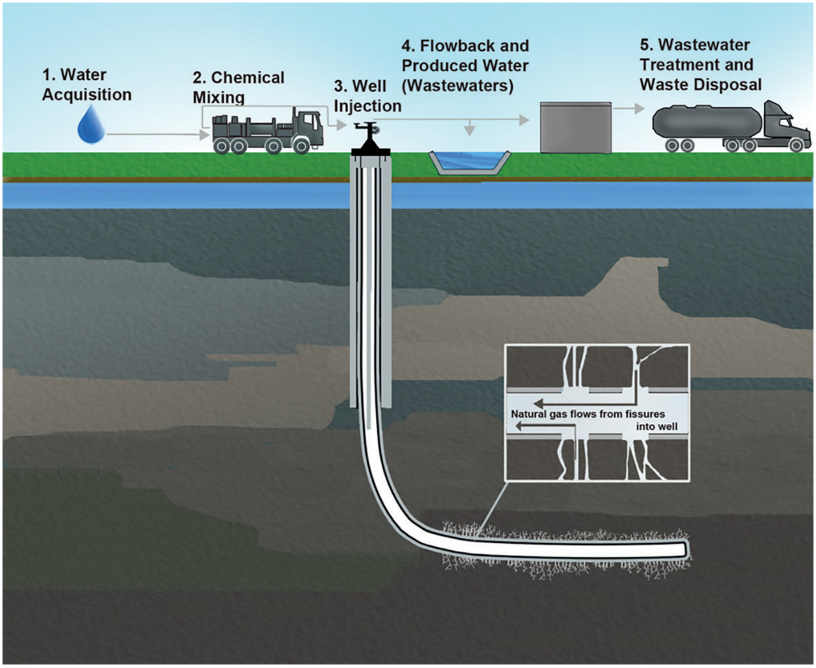

Figure 8 *Hydraulic fracturing 'fracking' and related activities. The low-permeability shale is fractured so that the gas or oil it contains can flow out and be brought up to the surface. Credit: US Environmental Protection Agency. https://commons.wikimedia.org/wiki/File:Hydraulic_Fracturing-Related_Activities.jpg.*

supply of crude oil would impact on the production of phosphorus fertilisers, since the phosphate rock from which they are made is mined[49] using machinery powered by fuels refined from crude oil. Food distribution systems are also highly dependent on crude oil to provide liquid fuels, since most food is transported around nations and globally, rather than being consumed close to its point of production. This is especially true in developed countries. (However, it is worth noting that 70% of the world's food needs are met by small farms[6], rather than being produced industrially and widely distributed.) The United Nations Environment Programme (UNEP) has stressed the need to reform the global food system in order to adapt to peak oil, and hence avoid future shortages and increased prices of food[50]. They point out that sustainable food production requires sustainable energy resources, and cite some examples where farms have managed to reduce their fossil fuel use, mainly by converting to 'organic' no-till methods which reduce the inputs of pesticides and fertilisers, the latter representing more than half the energy use of conventional (industrialised) agriculture. Potential links between peak oil, food systems and public health have also been considered, leading to the conclusion that advance investment and preparation for the event might serve well to mitigate the degree of dislocation and hunger expected from a peak oil event[50].

Indeed, it is the occurrence of peak oil, and peak natural gas (a source of hydrogen, and hence ammonia from which nitrogen fertilisers are made), with their attendant consequences, that may invalidate many predictions made about how agriculture might prevail (and all other human activities for that matter), for the next 100 years, or even the next 20 years, since we may have to grow food largely in the absence of their inputs. In which case, protecting the soil is paramount.

5.4 'Peak phosphorus'

The synthetic fertilisers which are used in modern agriculture contain the critical elements, nitrogen, potassium and phosphorus (NPK); the latter being derived from mined phosphate rock. However, it has been estimated that production of rock phosphate will fail to meet demand for it, at some point during this present century[49], and that a maximum rate in the production of phosphate will occur in the year 2033. It is anticipated that this phenomenon, termed 'peak phosphorus', will cause fertiliser costs to increase as rock phosphate reserves become inexorably more difficult and expensive to extract, with the knock-on effect of rising food prices. One test of the validity of the peak phosphorus model is the production rate that it predicts, at peak. Thus, an analysis based on Ultimately Recoverable Resources (URR) of 24 billion tonnes of rock phosphate yield a peak production of 29 Mt of phosphorus in the peak year (2033), which accords with around 210 Mt of phosphate rock (containing 31.5% P_2O_5). In 2010, 176 Mt of phosphate rock was produced and so such an increase is conceivable. Since the peak is predicted to occur in 2033, the implication of a Hubbert-type symmetrical curve is that production will have fallen back to 176 Mt by 2060, and this does not accord with an expected population rise of >30% from the present number of seven billion. Prior to 1996, the world reserves of rock phosphate (URR) were reckoned at around 24,000 Mt, with around 18,000 Mt remaining; a figure that was reckoned-up to 71,000 Mt, by the United States Geological Survey (USGS), in 2012. However, as is true of all finite commodities, what matters is the rate at which phosphate rock can be produced, and that once the peak is reached, what remains will be inexorably harder (of diminishing energy return on energy invested; EROEI) to recover. There are complex issues over what the demand will be for phosphorus in the future, as measured against a rising population (from seven billion to over nine billion in 2050), and a greater per capita demand for fertiliser to grow more grain, in part to feed animals and meet a rising demand for meat by a human species that is not merely more populous but more affluent[49]. As a counterweight to this, we may expect that greater efficiencies in the use of phosphorus, including recovery and recycling from farms and from human and animal waste, will reduce the per capita demand for the element, but that, increasingly, such reprocessing of animal manure and 'humanure' will be necessary if food production is to be sustained. As noted in Section 5.3, the unseen game changer is peak oil, since phosphate is mined and recovered using machinery powered by liquid fuels refined from crude oil. Hence, peak oil and peak phosphorus might appear as conjoined twins. Thus, there is no unequivocal case that we can afford to ignore the likelihood of a supply-demand gap for phosphorus occurring sometime this century, and it would be perilous to do so[49].

5.5 Energy for agriculture

As noted in Section 2, around half of the energy used in (European) agriculture is consumed by the Haber–Bosch process in its conversion of nitrogen gas taken from the atmosphere into ammonia to produce synthetic nitrogen fertilisers[14]. Industrialised agriculture is a highly energy intensive process and accounts for around 10% of the total energy used in Western Europe[14]. Energy is used at all stages of the food chain, from farm to fork, and it has been estimated that for each calorie of energy finally delivered in the food we eat, 10 calories have been consumed to put it on onto the plate. On-farm mechanised activities, food processing, storage, and transportation, all need energy, derived mainly from the fossil fuels[52]. In total, the food sector in the UK consumes 17% of the entire national energy budget[3], for farming, transport, packaging, refrigeration and so on. Accordingly, there is a close correlation between the price of energy and the price of food. Crude oil and natural gas are also used as agricultural inputs to provide fuels and chemicals, and it is expected that the price of such fossil resources will increase as they become increasingly depleted[48]. Therefore, unless energy and chemical inputs from oil, gas and coal (for electricity) can be 'decoupled' from food production, there is a threat to global food security. This has encouraged a shift in the direction of 'energy-smart' agricultural systems[52], of which a prominent example is the adoption of solar powered irrigation systems in Pakistan, which provide a closed system for using water for agricultural irrigation[53]. Results from the Rodale Institute (Section 7.3) have shown that their regenerative crop-systems use around half the energy of 'conventional (industrial) agriculture', mainly due to the avoidance of using synthetic nitrogen fertilisers, and the overall carbon footprint is accordingly reduced.

5.6 Practices of sustainable agriculture

When a small number of plant varieties are grown in place of a natural ecosystem (with its innate biodiversity), the species are rendered vulnerable to outbreaks of disease; one famous example being The Great Irish Famine (1845–1849) when the potato crop failed in successive years. While monoculture is very widely used on industrial farms, the practice is increasingly being recognised as unsustainable, particularly so if the same crop is grown year on year. Crop rotation and soil amendment are two methods used in sustainable agriculture, the aim of both being to provide the necessary nutrients to cultivated crops so that they can achieve a healthy growth. In addition, compost available locally from community recycling centres can serve to provide local organic farms with a nutritious soil amending agent. This approach enables the utilisation of yard and kitchen waste from a local area, by converting it into cheap organic compost, rather than discarding it into landfill. Another approach involves planting a mixture of perennial crops in the same field,

Figure 9 *Polyculture practices in Andhra Pradesh. Credit: Carla Antonini. https://commons.wikimedia.org/wiki/File:Polyculture.JPG.*

chosen to grow in different seasons, thus avoiding competition between them for the same natural resources[54]. Such a system of polyculture (Figure 9) engenders a greater resistance to diseases and protects the soil from being eroded and depleted in its nutrient content. Planting legumes (nitrogen fixers) in a combined strategy with plants that need soil-nitrate to grow, assists the annual reuse of the land to grow more crops. The legumes grow for one season and in so doing recharge the soil with ammonium and nitrate; in the following season, seeds from other crops can be planted in readiness for harvesting. Crop rotation is a typical feature in many traditional and organic farming practices: sometimes, legumes and non-legumes are alternated, or non-legumes may be planted twice in successive seasons, followed by a legume. In either case, the soil is replenished sufficiently in nitrogenous compounds that a healthy crop results, even when the crop itself is non-leguminous. In a more general context, legumes are often described as being ‘green manure’. While polycuture systems achieve a reduction in problems of diseases or pests[55], there appears to have been no comparative study made of this method with the very widely used alternative of crop rotation (where different crops are grown in succession) so to achieve the same overall crop diversity. As has already been noted, polyculture and/or rotation systems are able to harvest nitrogen when legumes are included, but there is additional evidence that they can use resources such as sunlight, water, or nutrients more efficiently too[56].

Sustainable agriculture is a multifarious subject, and its intentions and practices need to be tailored to suit each specific case. Thus, there is no ‘one size fits all’ way of achieving it, and certain farming methods are inherently at odds with the underlying tenets of ‘sustainability’. The rapid increase in the number of

***Figure 10** Rotational grazing practices in use with paddocks. Credit: Charlie Rahm, photo courtesy of USDA Natural Resources Conservation Service. https://commons.wikimedia.org/w/index.php?curid=24834913.*

farmers' markets means that local farmers can, in principle, sell their produce in the cities that provided them with recycled compost to grow it. Local recycling of this kind is likely to provide a favourable alternative to slash-and-burn techniques often used by 'shifting cultivators'. While it has been said that slash-and-burn farming was a feature of Amazonian agriculture over a period of 6000 years, or more[57], it was not until the 1970s, when changes in various programmes and policies of the Brazilian government were made, that deforestation emerged on an acute scale[58]. However, the traditional methods may well have involved 'slash-and-char' (rather than the detrimental 'slash-and-burn' practice), meaning that 'charcoal' became incorporated into the soil as an amendment to form 'terra preta'[59] which is a highly fertile soil, and furthermore is unique in being able to self-regenerate. When charcoal is deliberately incorporated into soil as an amending agent it is now usually referred to as 'biochar'[60]. Animals may also be managed sustainably, for example by reducing the size of their grazing area, with fences to provide paddocks (Figure 10), reducing the density of animals per unit area, and herding them between different areas/paddocks fairly frequently. The latter technique has been termed 'pulse grazing'[3].

Off-farm impacts should also be considered, and if the activities of a farm harm the wider environment, this cannot be considered as sustainable agriculture. For example, although synthetic fertiliser or animal manures can make a given farm more productive, their use in excess causes eutrophication, where rivers and coastal waters become laden with 'nutrients', resulting in algal blooms and hypoxic 'dead zones'[49]. At the other end of the scale is the practice of clearing forest (usually by 'slash-and-burn') to grow crops for animal feed. The soil rapidly loses its fertility due to erosion and the depletion of nutrients, meaning that it is necessary to clear yet more forest, and so on *ad nauseum*, with the ultimate consequence of deforestation on a massive scale[4].

5.6.1 Conservation agriculture

'Conservation agriculture'[61,62] is a term used to describe a systems-based approach to no-till farming, which arose in the late 1990s. Fundamentally, four principles are involved: (1) keeping crop residues on the ground as mulch; (2) incorporating cover crops in the overall production cycle; (3) using integrated nutrient management (INM) to enhance the fertility of soil, to promote the healthy growth of crops, and the biochemical conversion of carbon from biomass into soil organic matter; and (4) causing a minimum degree of, or zero (no-till) disturbance to the soil. In support of these principal strategies, are: (1) managing agroecosystems using a holistic approach; (2) allowing a period of 3–5 years for the transformation from long-term plough-tillage to conservation agriculture to be made, so that the soil health is recovered sufficiently that its agronomic and ecological benefits are maximally obtained; and (3) incorporating crop varieties and genotypes which emit molecular 'signals' that can be detected by remote-sensing, at the behest of particular stress events, so that ground-based interventions can be made. Accordingly, conservation agriculture has been defined[62] as: "A farming system comprised of crop residue mulch, cover cropping, INM, and NT techniques in a rotation cycle for effective soil and water conservation, SOC sequestration, sustainable intensification, and climate change adaptation and mitigation." A meta-analysis has been made[63] in an effort to determine the crop yields that might be achieved using conservation agriculture and to compare them with those from conventional agriculture. The response is variable, and while under appropriate conditions, no-till can match or even outperform conventional tillage, overall the yields from no-till are reduced. When no-till is combined with residue retention and crop rotation, the yield reduction is ameliorated: indeed, this combination of techniques significantly increases crop yields in dry climates. From another study[64] of 'organic' *versus* conventional agriculture, it was concluded that the organic systems overall gave smaller yields (average organic-to-conventional yield ratio of 75%). However, there is considerable variation between different crops and countries. The conclusion is drawn that under appropriate growing conditions and management practices, with particular crops, modern organic systems can practically match conventional yields; however, in many cases they do not. Such knowledge is likely to be of considerable assistance in devising resilient farming systems that will prove sustainable in climatic conditions that may prevail in the future.

6. 'Regenerative' *versus* 'sustainable'

All sustainable solutions are unsustainable over the longer term, if they are not also intrinsically regenerative[38]. Hence, we need to embrace regenerative development, by adopting measures that implicitly drive the regeneration of soils, forests, watercourses and the atmosphere, in contrast to the vexed policy of 'sustainable development' which essentially permits these vital elements to be maintained in conditions of inexorable degradation, as has been the case for a number of decades. That which is sustainable maintains what already exists, but does not restore (eco)systems that have been lost. The word ‘sustainable’ strictly means ‘self-sustaining’ but is often understood, particularly in the media and by the general public, to merely mean ‘able to last’ or ‘the capacity to endure’. This has been represented, humorously, by the example of two men talking together. One asks the other, “How’s your marriage going?” To which the other man replies, rather dejectedly, “Well, it’s sustainable.” The term has also been used to describe materials, products, or processes that are in some degree (probably) less toxic or damaging to the environment than their more usual versions.

Fundamentally, the word ‘regenerative’ means ‘the capacity to bring into existence again’; hence, if an item or system is regenerative, it has the inherent capacity to bring itself into existence once more. A perfect example of a completely sustainable/regenerative system is a forest, in which there is no waste, and the detritus from one year becomes the soil from which the new life of the following year is brought forth. For ‘regenerative’ to be an accurate description of a product, it must be not only 100% recycled and recyclable, but also improve the environmental conditions at all stages of its manufacture and use, *e.g.* the factory that made it, those businesses and other organisations which used it subsequently, and so on throughout its lifecycle.

These improved conditions might include the creation of habitat (including building soil), water purification, and the enhancement of nitrogen- and carbon-fixing processes in the soil, and so on. Hence, to achieve this for a completely artificial system is a challenge. The size of a system is an important factor in whether or not it is regenerative, with smaller designs more likely to be stable and fulfil the criterion. It is possible to create larger regenerative systems by linking together smaller regenerative ‘units’ so to provide inputs for multiple human-inclusive-ecological systems[38].

In principle, a completed object can generate more energy than was used in its own manufacture (emergy, or embodied energy), a good example being a solar panel which over its lifecycle produces more energy than its emergy. However, the energy costs of making the solar panel are large, when all inputs such as the ultra-high-purity silicon are accounted for, and the device can only be regenerated if enough energy is produced, from solar PV, to generate the materials used to make up the solar panel, and to recycle them into a new one. In terms of foods, it can be said that regenerative food is all organic, but not all organic food is regenerative. If the by-product of the food crop is not used as an input for the crops of the following season and if other inputs for the crop did not come from other resources within the farm on which it is grown, the food system is not regenerative, and may not even be sustainable, *e.g.* if it relies on liquid fuels derived from crude oil, and natural gas, mined phosphate and potash to provide, respectively N, P and K fertilisers.

The co-founder of permaculture (Section 8), David Holmgren, has identified four scenarios[65] for the future of humankind, one of which is "green-tech stability", where we move down from the current unstable situation of overuse of resources, environmental destruction *etc.*, with more use of renewable energy and eco-friendly technology, but the status quo of industrial affluent society, and its economy, largely remains intact. This scheme is popular with many environmental groups and with progressive political parties, and may be identified with the term 'sustainable'. Another scenario is 'earth stewardship', which involves coming to terms with our dependence on renewable resources such as soil, plants, animals and forests, as was the case for those living in the pre-industrial era. This implies a period of continual change, lasting probably centuries, where societies adapt to using inexorably less energy and resources, as is available to each succeeding generation. Naturally, this is quite contrary to notions of steady-state, and stability, but in its decreasing dependence on finite resources, and renewal of natural ecosystems, the strategy can be seen to be 'regenerative'.

Holmgren sees permaculture as a design path toward earth stewardship[65]. There is a resemblance between the early phases of both the green-tech stability and earth stewardship scenarios, but then they diverge massively, so that over centuries, a more likely symbol for the solar economy is a tree, rather than a photo-voltaic panel.

Critical drivers will be resources, especially of energy, but ultimately it seems likely that earth stewardship is the only sustainable scenario, and indeed the only one that is regenerative of essential resources.

7. Regenerative agriculture

Many agricultural practices that are labelled as 'sustainable' in fact represent relatively small improvements on prevailing farming methods, and merely slow down the rate of deterioration of a landscape[38]. The introduction of 'regenerative' practices requires a fundamental redesign of the system, so that the resource base is restored and revivified by means of natural ecological services[66]. Regenerative agriculture has at its core the intention to improve the health of soil or to restore highly degraded soil, which symbiotically enhances the quality of water, vegetation and land-productivity. It typically employs techniques that are used more generally in organic agriculture, with the aim to preserve/build soil organic matter, including minimum tillage, growing cover crops and green manures, composting, mulching and crop rotation. Its best practices mandate an avoidance of artificial inputs – pesticides, fertilisers, herbicides – that damage the living organisms in the soil. The inexorable effects of erosion, desertification, salinisation and loss of carbon from the soil, mean that there may be insufficient topsoil remaining to feed the world, hold-back current biodiversity loss or constrain the mean rise in global temperature to within the 2 °C limit by the end of this century. It is therefore necessary to begin in earnest the protection and regeneration of soil on some 1.5 billion hectares of cropland, 3.3 billion hectares of pasture and just over four billion hectares of forest land that exists on the Earth's land surface[67]. (The Food and Agriculture Organisation of the United Nations estimates that around 13 million hectares of forests were converted to other uses or lost through natural causes annually between 2000 and 2010. Their estimated annual rate of forest area increase was five million hectares[68].) Critically, regenerative agriculture is not only sustainable, in that it maintains ('does no harm' to) the existing soil, but further enhances its quality *via* methods that not only renourish, but actually regenerate soil. Natural ecosystem services are enhanced, rather than replaced, and the natural resource base is improved, not merely sustained. The approach is evolving and integrated, and incorporates elements of permaculture and practices of sustainable organic farming, such as conservation tillage, composting, cover crops, crop rotation, and pasture cropping[69]. It is a long held belief by practitioners of organic farming that building soil organic matter provides comprehensive advantages for the sustainability of a farm, in terms of improved health for the soil and the crops grown in it, along with clean water and clean air using inexpensive inputs which are local to the farm. So encouraged are agricultural practices which minimise soil disturbance and losses from erosion, while simultaneously incorporating amendments with a high carbon content, and retaining the biomass of roots and shoots in the soil. Some approaches[70] that may serve for the purposes of regenerative agriculture are outlined in the following subsections.

7.1 Holistic management (holistic decision making)

There are clear connections between holistic management (HM) and permaculture (Section 8), in that both approaches use 'systems thinking' to create a design in which chosen elements work together to create an integrated, functioning 'system'. HM was founded by Allan Savory, and has been likened to "a permaculture approach to rangeland management"; primarily the two differ in terms of scale, as is indicated in Table 1. Savory introduced the practice of 'holistic planned grazing' (HPG)[71] which involves moving single vast herds containing thousands of animals (cattle, sheep) around on grassland. HPG is aimed to mimic the behaviour of grazing animals in the wild, where they move in large groups (to protect themselves against predators), and graze one patch intensively, before moving on elsewhere. In this way, the grassland has time to recover completely, before it is grazed again, which benefits both the soil and the wildlife, and the animals' manure is more evenly distributed, while their hooves incorporate more organic matter into the soil. It is the focus on planned recovery periods (so that the grazing unit only has livestock on it for 10% of the time, or less), rather than on grazing periods, which differentiates HPG from the more usual practice of rotational grazing. In the latter case, grazing periods are planned forward so that animals are moved (typically in a clockwise direction) from a particular grazing division or paddock to another, and another, and so on[72]. HPG is sometimes also referred to as 'pulse grazing'[3].

The growth of longer grass provides better ground cover and a more extensive root mat, so that rainfall is better infiltrated into the soil, which leads to decreased flooding, less drought and the recharge of depleted groundwater systems (aquifers). This approach is of particular benefit for restoring grasslands in semi-arid or arid

Table 1 *Comparison of the permaculture movement versus the holistic management movement*

	Permaculture	Holistic management
Land base	Relatively small	Huge (hundreds of millions of acres)
Number of people	>200,000	<50,000
Location	Urban areas, homesteads, gardens	Rural areas, large-scale agriculture
Demographics	More popular among young people	More popular among older generations
Online presence	Large and growing fast	Small but growing
Influence	Generally not taken very seriously by outsiders	Generally has more respect among conventional farmers and in the industrial food system

climates ('brittle environments' in HM terms), where the more conventional approach of removing animals from the land, sometimes for decades, fails. Savory is of the view that HPG could absorb sufficient carbon in the soil, to bring atmospheric CO_2 levels back to pre-industrial concentrations, as he describes in a TED talk[73]. A useful, summary comparison between HM and permaculture is in Table 1[74].

7.2 Keyline subsoiling

Predating permaculture, keyline design was invented by P.A.Yeomans in the early 1950s[75]. In essence, it is a method of landscape design which focuses on the capture of water that would normally run off the land, and has a remarkable ability to build new soil, so increasing the soil depth in a relatively short time of a few years. Keyline planning follows the natural topography of the land, and uses this to determine the best location for farm dams, irrigation areas, roads, fences, farm buildings and tree lines. The critical device is the 'Yeomans Plow'[76] which has narrow shanks with shallow digging blades. Over several passes, each deeper than the previous one, a depth of 14–20 inches is finally reached, so providing channels that aid the infiltration of water, and also root growth. The surface disturbance caused by the shanks can be attenuated by attaching a roller to follow the shanks. Due to the cutting depth, soil is connected with subsoil, and the soils are loosened further down, so to create a soil conduit which carries water below ground, in the direction of the plough[77]. Due to the fact that more volume is created to be explored by roots, and more water is available than is the case in previously dry soils, keyline ploughing is considered to be a method for building topsoil. The method causes minimum disturbance to the overall soil profile, and in contrast with conventional ploughing, avoids causing harm to plants that are already growing in the area and does not injure the soil food web. The technique serves to spread water evenly across the landscape, by ploughing in a very specific pattern, according to the topography of that landscape. As Albert Bates describes it[78]:

"During cultivation, the soil is gently raised and loosened without turning a furrow. Rain and air enter the soil and release the minerals that chelate and loosely attach themselves to clay particles and humic acid. The released minerals are not water-soluble and are readily available to roots. Immediate results are dramatic and magical. Water moves from valleys to ridges.

"Every piece of land is unique and will be influenced by how water passes through it, irrespective of where the farm, cattle ranch, shopping mall, or four-lane highway gets put. By directing that water from valley to ridge, gravity and rain make the life of the farmer and rancher much easier. Keyline design combines cultivation, irrigation, and stock management techniques to greatly speed up the natural process of soil formation, and results of 400 to 600 tons of topsoil per acre each year are possible. Keylining can annually deepen topsoil four to six inches, and darken it a meter deep in less than a decade."

7.3 The Rodale Institute

The term 'regenerative organic agriculture' was coined by the late Robert Rodale (of the Rodale Institute), whose regenerative practices have been shown to build soil organic carbon and so potentially to contribute to atmospheric carbon sequestration, by natural means. The Rodale approach defines regenerative farming as "a long-term, holistic design that attempts to grow as much food using as few resources as possible in a way that revitalises the soil rather than depleting it, while offering a solution to carbon sequestration." According to Rodale, "when coupled with the management goal of carbon sequestration, regenerative farming becomes, once again, a knowledge intensive enterprise, rather than a chemical and capital-intensive one."[79] The Rodale Institute have published their results from a 30-year comparative study[80] of plots farmed using conventional agriculture with those managed using regenerative organic practices. They find that the yields from organic systems at least match those from conventional plots, but outperform the latter in times of drought. The organic systems use 45% less energy overall than do the conventional plots, mainly due to the fact that the former avoid the use of synthetic nitrogen fertiliser. Accordingly, the organic farming systems are more profitable than their conventional counterparts. Greenhouse gas emissions were 40% greater from the conventional than the organic plots. Organic farming builds soil organic matter, rather than depleting it as conventional agriculture does. This is significant in the context of sequestering atmospheric carbon in the soil, as is described in Section 11. It is worthy of note, however, that despite the overall reduction in energy use by nearly a half over the conventional plots, the use of diesel fuel is nearly double on the organic plots[80]. Thus we may conclude that this kind of organic farming remains dependent upon a prevailing supply of crude oil, and vulnerable to a potential 'peak oil' situation. Thus, it may not prove sustainable in the long run.

8. Permaculture

As a working and practical definition, permaculture[3,81,82] may be described as a low impact method which uses perennial cultivation methods to produce food crops, working *via* principles that are in harmony with nature. The term permaculture[81,82] (a portmanteau word derived from *permanent agriculture*, or *culture*) was coined by Bill Mollison (1928–2016) and David Holmgren in the mid-1970s, to describe an "integrated, evolving system of perennial or self-perpetuating plant and animal species useful to man." According to Holmgren, "A more current definition of permaculture[82] is 'Consciously designed landscapes which mimic the patterns and relationships found in nature, while yielding an abundance of food, fibre and energy for provision of local needs.' People and their buildings, and the ways they organise themselves, are central to permaculture. Thus the permaculture vision of permanent (sustainable) agriculture has evolved to one of permanent (sustainable) culture." Broadly, permaculture may be classified (insofar as such an holistic entity may be) as a branch of ecological design and ecological engineering which aims to develop sustainable human settlements and self-maintained agricultural systems modelled from natural ecosystems. One major change that converting to permaculture would incur is that, because cereals cannot be produced at the scale of industrialised agriculture, amendments in our diet would be necessary, to consume more vegetables, fruit, nuts, berries *etc.*, which can be produced effectively by its means.

Permaculture is based on three core ethics:

- **'Earth Care' (take care of the Earth)**: provision for all life systems to continue and multiply. This is the first principle, because without a healthy Earth, humans cannot flourish.
- Work with nature.
- Act to oppose destruction and damage.
- Consider the choices we make.
- Aim for minimal environmental impact.
- Design healthy systems to meet our needs.

- **'People Care' (take care of the people)**: provision for people to access those resources necessary for their existence.
- Look after ourselves and others.
- Working together.
- Assist those still without access to food and clean water.
- Develop environmentally friendly lifestyles.
- Design sustainable/regenerative systems.

- **'Fair Shares' (share the surplus)**: healthy natural systems use outputs from each element to nourish others. Humans can do the same; by taking control of our own needs, we can set resources aside to further the above principles.

- Resources are limited and only by curbing our consumption and population will there be enough for all, now and in the future.
- Build economic lifeboats.
- Develop a common unity.
- Modify our way of life now – do not wait: become part of the solution not part of the problem.
- Need to become reconnected with the natural world: shift in thinking and being.

Permaculture is about making an effective design, emphasising patterns of landscape, function, and species assembly. It asks the questions: *Where does this element go? How can it be placed with other elements for the maximum benefit of the system overall?* The fundamental principle of permaculture is, therefore, to maximise useful connections between elements to achieve their best synergy in the final, and optimal design. A forest garden, with its component system of 'layers', is one example of this (Figure 11). Permaculture does not focus on individual elements, in isolation, but rather on the relationships created among those elements in the way they are placed together; the whole becoming greater than the sum of its parts. It accordingly involves, integrated, 'systems thinking'. Permaculture design aims to minimise waste, human labour, and inputs of energy and other resources, by building systems with maximal benefits between design elements to achieve a high level of holistic integrity and resilience. Permaculture designs are 'organic' and evolve over time according to the interplay of these relationships and elements and can become extremely complex systems, able to produce a high density of food and materials

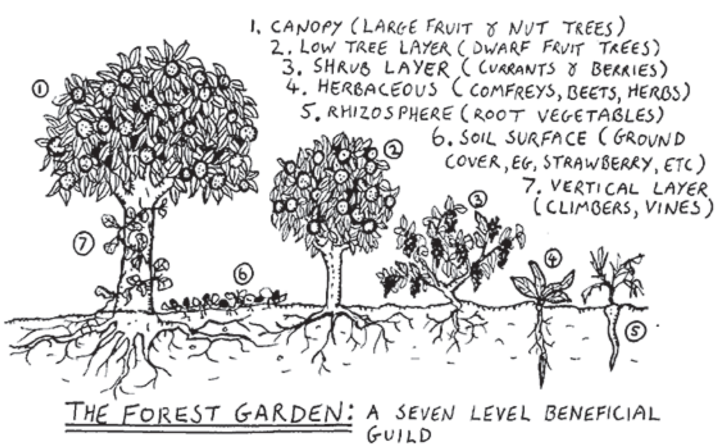

Figure 11 *The seven layers of the forest garden. Credit: Quercusrobur at the English language Wikipedia. https://commons.wikimedia.org/wiki/File:Forgard2-003.gif.*

with minimal input. A regenerative farm based on permaculture principles will develop an evolving ecological structure and biological production that increases in its complexity with time; however, it is a characteristic of such a system that once established, the overall biological yields continue to increase, while external inputs decrease[83]. For the system to be regenerative, there must be an increase in both biodiversity *and* quantity of biomass. The health of the soil and the water within the design system are critical determinants of the *overall* health of the wider ecological system, which merely hosts the farm and attendant human members as guests. Permaculture principles can also be used to restore (regenerate) landscapes which have become very highly degraded and barren, mainly through soil erosion, *e.g.* the Chikukwa project[4] in Zimbabwe, and to grow plants (food) in 'surplus' urban environments, *e.g.* the RISC Roof Garden[3], which is on top of the Reading International Solidarity Centre building (Section 9; Figure 12).

9. Use of urban space for food production

Recent research led by a group at Sheffield University has identified the poor quality of soils on UK farms and made the prediction that there will be a national agricultural crisis at some point during this century. In contrast, they note that soils in small scale local food production systems such as allotments are 25% richer in total nitrogen, contain 32% more soil organic carbon, have 36% higher C:N ratios and 10% lower bulk densities, which indicates them to be significantly less compacted[84]. The conclusion is that it is necessary to use urban space more efficiently, and that the towns and cities must become places of food production. In addition to the greater preservation of the soil quality than is the case on industrial farms, there is the aspect that the more food that is grown locally, the less needs to be imported, from across the country and indeed the wider world. It has been estimated[85] that just 30% of the global urban area would be required to produce all the vegetables consumed by urban dwellers, although this mean value veils the substantial variation between different countries, and the particular food production methods employed in each one. However, it is clear that a substantial contribution to providing local food security for communities can be made by local food growing, as is a cornerstone of the Transition Towns movement[3]. In addition, more of food that is grown locally in gardens and allotments, tends to be actually eaten, in contrast with an annual 1.3 billion tonnes of food, produced for human consumption, that is lost or wasted globally, which amounts to about one third of the total. Losses occur down the entire supply chain, from the initial on-farm production, through to final household consumption[86]. Thus, urban food production should be seen as a significant potential contributor to regenerative agriculture in the future, of course so long as the methods used are themselves 'regenerative'.

A fine example of what can be grown in unused urban space is the RISC Roof Garden[3] (Figure 12), which is on top of the Reading International Solidarity Centre (RISC). RISC is a development education centre located in the middle of Reading

Figure 12 *The roof forest garden, grown in just 30 cm of soil, on the roof of the Reading International Solidarity Centre (RISC) building, in Reading, south east England. Credit: Karen Blakeman. http://www.flickr.com/photos/rbainfo/7956444356/in/set-72157631467628340/lightbox/.*

(the largest town in the UK), and was inspired by Robert Hart's permaculture forest garden in Shropshire. It is used as an educational resource for sustainable development and is a member of the National Gardens Scheme. Occupying an area of 200 m^2, the garden is composed of dense plantings (including trees) of over 180 species of edible and medicinal plants and is fed by rainwater and composted waste from the centre. Remarkably, all of this is growing in just 30 cm of soil, and the whole project demonstrates what can be achieved by applying urban permaculture to 'waste' – both the building itself, which had fallen into disuse, and its accompanying roof space.

Since 54% of the global population lives in towns and cities (74% in the more developed and 44% in the less developed countries)[87], it is probably unrealistic to suppose that every urban dweller can escape to the countryside, and have their own patch of land to grow food on. For one thing, there is probably not enough rural space available (certainly not in crowded Western Europe), but also the majority of us are not farmers, and lack the necessary skills and cultural background to 'go back to the land'. While there are impressive energy-efficient designs for buildings, *e.g.* passivhaus[88] (Figure 13), it is not a practical proposition to simply raze our existing towns and cities to the ground and build-up again from scratch. Rather, we need to work within the framework that we have, *i.e.* the urban environment. From this kind of thinking arises the notion of 'regenerative cities'[89], where such integrated ('systems') design approaches as permaculture and the circular economy[90] (which minimise waste by cycling resources, so to retain them within the 'system' as long as possible: in the manner of how water and nutrients are cycled in a natural system,

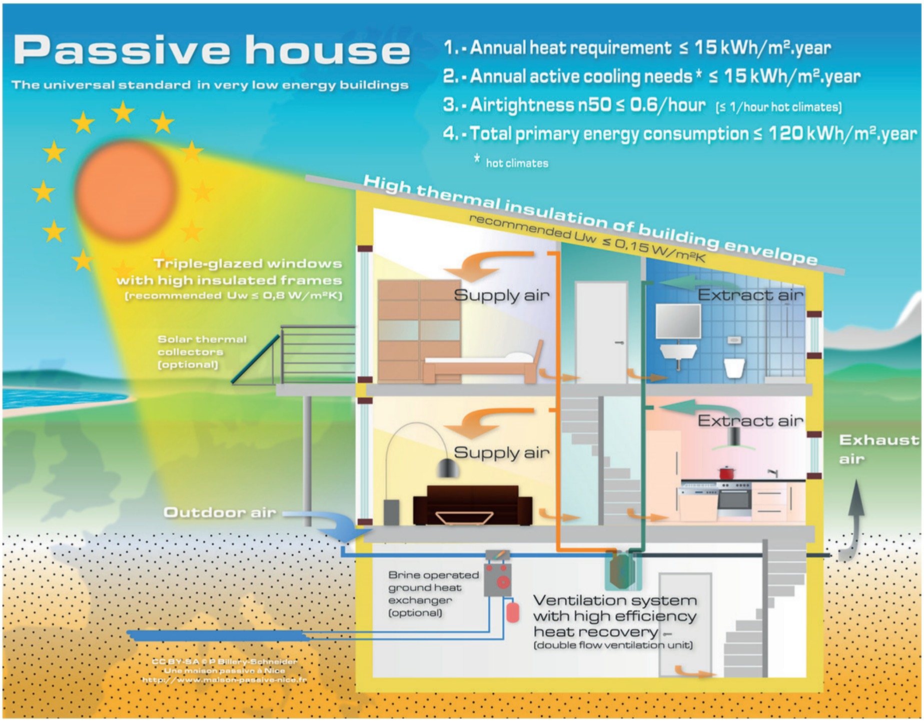

Figure 13 *Extremely low-energy consumption building: Passive house (passivhaus) scheme. Credit: Pascal Billery-Schneider. https://commons.wikimedia.org/wiki/File:Passive-house_scheme_HQ.png.*

such as a forest) are incorporated within the existing urban infrastructure. In addition to growing food in urban space, such actions as draught proofing and thermally insulating existing building stock, and living/working on a more local scale, would serve well to cut overall energy use[3]. In order to curb our use of the fossil fuels (which provide well over 80% of global primary energy[91]), methods for reducing overall energy use must be considered at least equal in importance to expanding low-carbon energy production.

10. Seed-saving and climate change

In many primitive societies, to save and preserve seeds was considered as an almost sacred duty. While the practice has lapsed in the past several decades, it may prove necessary to embrace it once more. This is the message from a recent report by the Ecumenical Advocacy Alliance, The Gaia Foundation and The African Biodiversity Network, 'Seeds for Life: scaling up agrobiodiversity'[92], in which it is argued that adapting agriculture to cope with climate change cannot be done without preserving seed diversity. Thus, in the absence of a wide gene pool of crops, it will not be possible for farmers to spread their risk, or breed new varieties to adapt to changing weather patterns. The blame for a profound loss of global diversity is placed on the fact that modern agricultural methods and the marketing of agribusiness corporations rely on relatively few crops and their varieties. The report proposes that to remedy this situation, farmers must be supported in a revival of their traditional seed saving practices and the accompanying knowledge, such that this diversity is maintained and made accessible both for farming today and into the future. Many farmers grow from just one or two varieties of purchased seed, but the entire crop may fail if the rains arrive too late or too early, are too heavy or there is no rain. Climate change is expected to cause irregularities of this kind, and yet it is those seed varieties that were harvested traditionally and saved, but were then abandoned decades ago, that may serve best in the future. The Green Revolution (Section 3) has changed the face of farming since the 1960s. Before then, it was the practice to plant dozens of different crops, from which the seeds were routinely saved, in a process of developing and adapting new varieties in order to address the many and various challenges of soil, pests, disease, nutrition and flavour. Since the Green Revolution came about, there has been an enormous loss both in the diversity itself and the associated knowledge of how to tend and nurture it, particularly on farms in North America and Europe. There is currently a rising pressure on farmers to adopt corporate seed varieties at the expense of their locally-adapted versions, in Africa, Asia and Latin America.

11. Climate change mitigation, carbon capture in soils, creation of biological soils

2015 was declared by the 68th UN General Assembly to be the International Year of Soils (IYS)[93], some objectives of which may be summarised:

- to create full awareness of civil society and decision makers about the fundamental roles of soils for human's life;
- to achieve full recognition of the prominent contributions of soils to food security, climate change adaptation and mitigation, essential ecosystem services, poverty alleviation and sustainable development;
- to promote effective policies and actions for the sustainable management and protection of soil resources;
- to sensitise decision makers about the need for robust investment in sustainable soil management activities aiming at healthy soils for different land users and population groups; and
- to advocate rapid enhancement of capacities and systems for soil information collection and monitoring at all levels (global, regional and national). Of potentially great environmental significance is the prospect that climate change might be mitigated through the removal of atmospheric carbon, taken up by plants through photosynthesis, which is then stored in the soil[94].

Afforestation/reforestation is considered a key action in storing carbon in biomass (trees) and in soils. Sound management practices offer the potential to mitigate and adapt to climate change, and it is the latter that threatens to increase the potential for soil erosion, diminished soil quality, and lower agricultural productivity, with expectedly adverse impacts on food security and global sustainability. Hence, this provides one of the more severe tests that might be imposed on humans during the remainder of the 21st century: not only must we mitigate climate change but accept the reality of it and adapt our behaviour and practices to best effect. Relevant management practices are those pertaining to carbon, nitrogen, manure, in low-input systems (another term for sustainable agriculture) and grazing land[4]. Management choices over conservation practices such as no-till, conservation agriculture, and returning crop residue (rubble) to the field to improve nutrient recycling can exert a positive influence on carbon sequestration and assist in the mitigation of and our adaptation to climate change. Additionally, management of grasslands, restoration of degraded or desertified lands, nitrogen management (to reduce N_2O greenhouse gas emissions), precision conservation management on a field and/or watershed scale, along with other management choices can also aid in this cause. Management for climate change mitigation and adaptation is essential for environmental conservation, sustainability of cropping systems, improving the quality of soil and water, and ensuring food security[4].

Estimates vary as to how much carbon can be sequestered in the world's soils, and indeed what its residence time is likely to be. For example, in their white paper[79], the Rodale Institute claim the following:

"We could sequester more than 100% of current annual CO_2 emissions (total global greenhouse gas emissions reckoned at 52 Gt CO_2e) with a switch to widely available and inexpensive organic management practices, which we term 'regenerative organic agriculture'.

"If management of all current cropland shifted to reflect the regenerative model as practised at the research sites included in the white paper, more than 40% of annual emissions (an estimated 21 Gt CO_2/year) could potentially be captured. If, at the same time, all global pasture was managed to a regenerative model, an additional 71% (37 Gt CO_2/year) could be sequestered. Essentially, passing the 100% mark means a drawing down of excess greenhouse gases, resulting in the reversal of the greenhouse effect."

To arrive at these figures, sequestration rates[79] of 4.1 Mg C ha^{-1} y^{-1} and 3.04 Mg C ha^{-1} y^{-1} were used for cropland and pasture, respectively. However, while the latter corresponds with the United Nations Environment Programme (UNEP) report[67], that there is a global total of 3.3 billion hectares of pasture land, the former figure indicates that a global total of 1.4 billion hectares of cropland has been assumed, which is marginally less than the UNEP figure of 1.5 billion hectares. The rate of sequestration by cropland assumed in the Rodale estimate[79] of potential global carbon capture is rather higher than that used by Kittredge[95] (obtained from studies of row crops which ranged from 0.23 metric tons per acre to 1.66 metric tons per acre, and averaging at 0.55 metric tons per acre or 1.36 metric tons per hectare). However, for grassland sequestration, Kittredge assumed 2.6 metric tons per acre, which at 6.42 metric tons per hectare is more than twice the value used by the Rodale group. Interestingly, the Rodale group also quote a rate of 2.36 Mg ha^{-1} y^{-1}, for corn-vegetable-wheat crops, grown using organic, tillage, composted manure, legume cover crops, which suggests a total global sequestration of 12 Gt CO_2 from cropland managed in this way. Kittredge concludes[95] that it would be possible to sequester an annual global 2.1 Gt CO_2 in croplands and 21.6 Gt CO_2 in grasslands, making a total of 23.7 Gt CO_2; although this is rather less than estimated in the Rodale study, both analyses indicate that appropriate management of the global pasture (grasslands) areas could prove to be a critical determinant in ameliorating atmospheric CO_2 levels. The Rodale estimate of how much carbon could be taken from the atmosphere and stored in the world's soils is probably the most optimistic, and that by Kittredge assumes that we can remove 50 ppm of CO_2 in five years, although this must be offset against a relentless backdrop of carbon emissions at 9 Gt per year. As reported in the primary scientific literature, however, some estimates are rather less sanguine, at 3%[96] and 15%[97] of total annual emissions. According to the IPCC (International Panel on Climate Change)[98], in 2010 total global greenhouse gas emissions had reached 49 (±4.5) Gt carbon dioxide equivalents (CO_2e) per year. This may be deconstructed into the following specific contributions: 30.4 (CO_2 from fossil fuels plus industrial processes), 6.4 (CO_2 from forestry and other land use), 7.8 (methane), 3.0 (N_2O) and 1.0 (fluorinated gases). Clearly, there is potential for reducing N_2O emissions by converting from industrial to regenerative agriculture, though the avoidance of nitrogen fertilisers, and reduction in CO_2 emissions due to land use, by implementing practices which both protect soil against the loss of existing SOM and sequester carbon in the soils.

11.1 Making agriculture the solution, not the problem: the '4 per 1000' initiative

Along with forestry and other land use, agriculture is estimated to contribute some 24% of global greenhouse gas emissions[99]. Thus, if farming practices can be adapted to reduce existing emissions as well as increasing soil carbon, agriculture can become one of the solutions to climate change, rather than the problem it currently is. Thus motivated, at the 2015 Paris Climate Change conference (COP21) was launched the '4 per 1000' initiative, which aims to increase soil carbon over a 25 year period[100], with the effect of halting the annual increase in CO_2 in the atmosphere. It is important to be clear about what '4/1000' means: it is *not* an increase in the overall soil carbon by an annual '4 grams per kilogram of soil' as has been claimed[101], but an increase in the *existing* carbon in the topsoil by 0.4%/year. This has been described from an Australian perspective[102]:

"Let us start with the analogy of a football field (soccer, not rugby!). Imagine it is a fifth larger than normal – making it one hectare in size. The top layer of soil on the field, 30 cm deep, is known as the topsoil.

"Carbon is the main ingredient of organic matter, so organic matter is often referred to as 'soil organic carbon'. In Australian soils, this organic matter makes up on average, between 1 and 3 percent of the topsoil. For

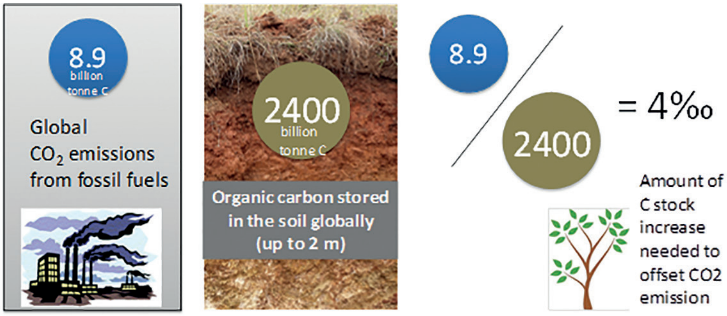

Figure 14 *The 4 per 1000 soil carbon sequestration initiative. Taken from http://sydney.edu.au/news/agriculture/1272.html?newsstoryid=15532.*

the purpose of the exercise, we will assume that the topsoil on the football field contains 1.5 percent carbon. This equates to 58 tonnes of carbon in the topsoil across the whole football field. What the French Government is calling for is to increase that 58 tonnes by 0.4 percent per annum – in our imaginary football field that would equate to an increase of 0.2 tonnes (or 200 kg) of carbon in the topsoil each year."

Thus, the annual carbon increase is 0.4% of 1.5%, or 0.006%, giving a total soil carbon content of 1.506% after year one, and 1.65% after 25 years, with around six tonnes of carbon having been captured per hectare. Done on the global scale, the impact could be enormous. The total amount of carbon stored in soils is reckoned at 2,400 billion tonnes, making it the largest terrestrial carbon pool[103]. The top two metres of soil in fact hold four times the amount of carbon that is stored in plant biomass, and soils offer the potential to store carbon over long periods by means of different protective mechanisms. The total carbon emissions by humans amounts to an annual 8.9 billion tonnes, and so the ratio 8.9/2,400 = 0.4%, which is the origin of the '4/1000' ratio (Figure 14).

However, it is the annual rate of carbon sequestration per hectare which is the critical determinant of how successful the strategy is likely to be. As has been noted[103]:

"The land area of the world has 149 million km^2, and it would be estimated that on average there are 161 tonnes of C per hectare. So 0.4% of this equates to an average sequestration rate to offset emissions at 0.6 tonnes of C per hectare per year. We know that soil varies widely in terms of C storage, for example peat soils in the tropics hold about 4000 tonnes of C per hectare, while sandy soils in arid regions may only hold 80 tonnes of C. The type of above ground vegetation and how quickly the soil biota uses the carbon also can affect this rate. Taking this into account, we would need to add about 4 times the amount of organic matter to meet this sequestration rate."

Previous studies[103] have concluded that a global mean storage rate of 0.5 tonnes of carbon per hectare per year is possible, after the adoption of best management

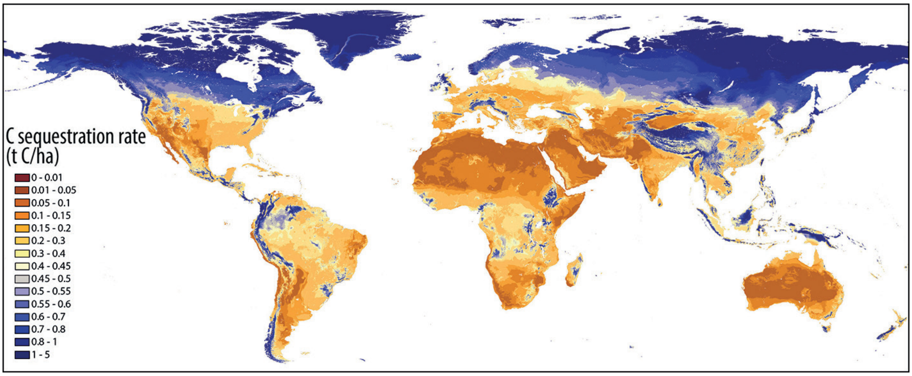

Figure 15 *Global soil C required sequestration rate (tonne C per ha per year) to achieve the 4 per 1000 initiative. Taken from http://sydney.edu.au/news/agriculture/1272.html?newsstoryid=15532.*

practices such as reduced tillage in combination with legume cover crops. Using digital soil mapping techniques, Stockmann *et al.*[104] have produced a map of global soil carbon stock at a resolution of 1 km, on the basis of which the annual sequestration rate (corresponding to 0.4% of the C stock) can be calculated (Figure 15). The C sequestration rate varies from 0.2 tonnes per year in agricultural regions of Australia and the US to 1 tonne per year in boreal areas. Thus, while achieving a global '4/1000' poses an appreciable challenge[105], even approaching this target would be of considerable benefit, not only in terms of helping to balance the global carbon books, but in improving and restoring the quality of the world's soils[3,4,38]. The world's cultivated soils are estimated to have lost between 50 and 70% of their original carbon content, a trend that can be reversed by using defined agricultural methods. The result is more productive, carbon-rich soils, and so the strategy is able to 'reconcile food security and climate change'[106]. Lal has concluded that to obtain fully the benefits of '4 per 1000' it will be necessary to combine cover cropping with a systems approach to conservation agriculture, but at best, the scheme has the technical potential to sequester just 10–15% of anthropogenic carbon emissions, in the soils of managed ecosystems[105]. There is a cost element too, and it has been estimated[107] that 5.3 Pg (CO_2e) per year could be sequestered in soils, if there were no economical constrains, but this falls to 1.5 Pg (CO_2e) per year at the lowest specified carbon price, of US$20 per Mg of ($CO_2$e) per year. Indeed, since average rates of carbon sequestration for most management practices are estimated to be <1 Mg per ha per year, it is necessary to take action over an appreciable proportion of the global agricultural land base. It has been estimated that, potentially, a rate of 1–1.8 Pg (CO_2e) per year could be captured in soils using biochar, albeit that the full economic and management constraints are as yet not fully known[107].

11.2 Evidence for carbon saturation in soils – limits to sequestration?

As we have seen, potentially, soils might be able to store very large amounts of carbon in the form of SOM, and of comparable quantity to the amount of CO_2 released into the atmosphere as a result of human activities. However, while it may be possible to capture anywhere from 3–100% of the total (35.7 Gt of CO_2 in 2015) per annum, eventually the soils will reach a carbon saturation limit, which will vary depending on the type of soil, and the prevailing environmental conditions. Once the soil has become saturated[94], it will no longer act as a sink, and may achieve a steady state where it emits as much carbon as it absorbs, or it may become a net emitter of CO_2. Six *et al.*[108] have defined the saturation point of a given soil as being "the point at which the soil carbon protecting processes of aggregation, adhesion to mineral particles, and biochemical protection cease to protect new carbon." In which case, any further carbon might be described as 'labile' and can be attacked by microbes. Such processes are strongly affected by the particular type of soil, and its clay content. However, as a result of poor management and degradation[97], most of the world's soils contain much less carbon than would exist at their point of saturation. Due to the fact that plant roots tend to penetrate soils to limited depths, those soils deep below the surface are likely to be even less saturated[109,110], as is indicated by the lower average SOC sampled at a depth of 1 m [111] compared with that in the upper 10 cm [103]. Thus, while it is not possible to continually sequester carbon in soils for an unlimited time, in the current condition of sub-saturation, most of the world's soils would be improved by increasing their SOM content.

In a paper published on the continuous effects of no-till on soil biophysical carbon sequestration, it is concluded that the overall carbon accumulation was greater by 86% over a 44 year period using no-till than with conventional tillage[112]. The rate of accumulation was greatest in the soil layers closer to the surface, and there was a levelling-off of the rate over time, but at all depths sampled (in 7.5 cm increments, down to a total of 30 cm), a plateau was evident by 20 years[112]. In another study of global co-variation of carbon turnover times with climate in terrestrial ecosystems, a mean global carbon turnover time of 23 years was determined[113]. Evidence was also obtained for an upper limit to carbon sequestration in soils under no-till systems in the Cerrado of Brazil[114]. However, it was concluded that while the time over which enhanced carbon sequestration may occur is limited, the reduction in the overall CO_2 emissions to the atmosphere which results from the smaller amount of total fossil fuel used can last indefinitely. Hence, the no-till method is effective as a long-term strategy for farming with reduced carbon emissions, and also confers an overall improvement in soil fertility and protects the land against erosion, as compared with conventional tillage[114].

11.3 Methods for rapidly building 'biological' topsoil

Dr Christine Jones has made the point that the amount of carbon that might be sequestered in soils is not limited only to the amount that can be incorporated in existing soils as SOC, but that it is possible to create new 'biological' topsoil within just a few years[115]. This conclusion runs counter to the established view that an inch of soil can take perhaps 200–1000 years to form (depending on the local climatic conditions), in reference to weathering processes and the differentiation of soil profiles. She contends that topsoil formation is a separate and far more rapid process, and that while most of the relevant research efforts have focussed on methods for curbing the rate of soil erosion, little consideration has been given to building new topsoil. Jones stresses that in order for new topsoil to form it must be 'living', *i.e.* rich in organisms, and also needs to experience optimum levels of 'disturbance', such as may be provided by holistic planned grazing (HPG; Section 7.1). In certain situations, HPG can be combined with 'pasture cropping' in which annual crops, grown to provide grain or fodder, are drilled directly into perennial groundcover. Since this is a one-pass operation, only about 10% of the soil surface is disturbed, but improved aeration, moisture infiltration and mineralisation are brought about in specific regions. Levels of biological soil activity are stimulated by the presence of the growing crop which releases carbohydrates and feeds microbes in the rhizosphere. That a vital, active topsoil is critical in underpinning the sustainability of an entire farm was recognised by P.A.Yeomans in his keyline approach to land management (Section 7.2). By means of a tillage device that has become known as the Yeomans Plow (which increases oxygen and moisture levels in the soil), along with a rest-and-recovery version of grazing and pasture slashing (serving to prune grass roots and feed soil biota), Yeomans managed to generate 10 cm of a friable (crumbly) black soil within a period of three years, and on what had been a bare, weathered red shale[115]. Jones has identified six essential requirements for the formation of biological soils: (1) minerals; (2) air; (3) water; (4) living organisms *in* the soil (plants and animals) and their by-products (soil biodiversity); (5) living things *on* the soil (plants and animals) and their by-products (soil needs to be covered); and (6) intermittent and irregular disturbance regimes (*e.g.* HPG), to encourage soil building processes.

As Jones describes[115] the process:

"Measuring the amount of new soil being formed is a little different to measuring the amount being lost. Mineral soil has a higher bulk density (is more compact) than living soil, and is far more easily eroded. Soil loss figures usually assume an average bulk density (weight per unit volume) of around 1.4 g/cm^3. If one millimetre of soil is eroded (about the thickness of a 5-cent coin) that represents about 14 t/ha soil loss.

"When new topsoil is forming, it will have better structure and will contain more air and more pore spaces than degraded soil, so the bulk density will be less. That is, a given volume of new topsoil will weigh less than an equal volume of non-living mineral soil. The bulk density of healthy topsoil may be as low as 0.5 g/cm^3. In practical terms, a one millimetre increase in the height of new soil would equate to the formation of around 5 to 10 t/ha of organically enriched topsoil."

12. Soil biodiversity

Biodiversity, in its many and varied forms, collectively comprises the complex web of interconnected systems which together hold the biosphere in a condition of homeostasis. One quarter of all the organisms on Earth live in the soils (primarily bacteria), and yet their importance and function are rarely considered specifically in devising strategies for agricultural management. However, in 2011 the Global Soil Biodiversity Initiative (GSBI) was launched[116], "based on growing international concern by scientists, policy makers and the public over the status of the world's soils and increased recognition that the life in soil is key to sustaining our food production, ecosystem maintenance and control of global atmosphere and climate warming." Of particular current interest is the connection between the biodiversity of soils and the functioning of ecosystems. It has been proposed that adopting land management practices that encourage soil biodiversity and its associated functions, including connections with above ground communities, might not only provide the means for sustainable crop production, but also improve soil fertility, soil structure and the retention of water and nutrients[117]. In another study, it was demonstrated that the loss of soil biodiversity, and a simplification of soil community composition, result in the impairment of ecosystem multifunctionality, including plant diversity, decomposition, and the retention and recycling of nutrients. Thus, the loss of soil biodiversity and changes in soil communities pose threats to the sustainability of ecosystems[118]. Another group survey the prospect that soil ecological engineering might be used[119] to produce land-use systems that serve immediate human needs while minimising environmental impacts: perhaps not surprisingly, it is concluded that the preservation of soil biodiversity is likely to be a critical factor in achieving this. Other workers propose[120] that the soil microbiome (the larger community of soil micro-organisms) might be manipulated for the purposes of improving soil health and crop productivity.

Soils store around four times as much carbon as is contained in plant biomass, and respiration by soil microbes is thought to release an annual 60 Pg of carbon in the form of CO_2 to the atmosphere. It has been shown that the temperature sensitivity of soil respiration rates is enhanced by the response from soil microbes, and this might play a significant role in the loss of carbon from the appreciable amounts that are contained in the Arctic and boreal soils[121]. The first evidence has been presented that chemically diverse, stable SOM is produced by microbes, and that the accumulation of SOM has more to do with distinct communities of microbes than clay mineralogy. Microbial derived (dead microbial cells and microbial excreta) SOM-accumulation is most effective in fungi-rich soils with a greater production of microbial biomass[122]. In another study, the formation of stable SOM, through humification, is challenged[123]. It is argued that, rather than high molecular mass and persistent 'humic substances' being formed in soils, SOM is rather a continuum of progressively decomposing organic compounds ('soil-continuum model'), spanning the range from intact plant material to highly oxidised molecular species such as carboxylic acids (which at the highest level of oxidation become CO_2).This new approach focuses on the underlying microbial processes, and whether the decomposer organisms can access SOM, or if the SOM is protected from the organisms by soil minerals. It is argued that artefacts caused by the highly alkaline (pH 13) extraction medium are partly responsible for the notion that stable 'humus' is formed in soils[123]. Finally, we note that evidence has been obtained[124] that the controversial herbicide 'glyphosate' can affect below-ground interactions involving earthworms and arbuscular mycorrhizal fungi (essential components of the soil food web), at least in a model ecosystem. Clearly, this result may have broader implications for agriculture, in terms of impacts on the soil food web.

13. The ecological impact of fossil energy scarcity

Some attention was given in Section 5 to a 'peaking' in the production rate of resources such as crude oil, natural gas, and phosphate rock, and the detrimental effect this is likely to have on global agriculture. We have also seen that healthy, living soils, with rich biodiversity, are an important and underpinning feature of regenerative agriculture, and it is clearly of relevance to consider how expected future scarcities of energy and other resources might impact on global ecosystems. Hall and his coworkers[125] conclude that, in the coming decades, it will be equally as important to regenerate, and manage sustainably, vibrant natural ecosystems, as to protect existing wild areas. Since the management of natural resources is often energy intensive, prevailing practices may become less feasible in a world with less abundant energy and other resources. Hence, future ecosystem management will involve more of 'letting nature take its course', in which case, biodiversity is expected to increase. Indeed, the preservation of biodiversity may provide the necessary resilience for maintaining ecosystem services, in the coming decades. As we have seen, design approaches such as holistic management and permaculture, can be applied to the management of ecosystems, and indeed to many other systems and activities. Czucz *et al*. conclude[126] that 'peak oil' (Section 5) may cause economic turmoil, political conflicts and social tension, with changes in human behaviour and a neglect of ecological systems, ranging from overuse to abandonment. It is likely that an inability to maintain the global oil supply will pose great challenges for the preservation of global ecosystems and their services. However, it is critical to manage judiciously global ecosystems during the necessary transition to a future economy based on a highly limited or zero use of fossil fuels, since we will need them to be functioning fully in our efforts to maintain civilisation in the post-petroleum age.

14. Conclusions

According to the United Nations Convention to Combat Desertification (UNCCD)[127], 30% of the world's cropland has been abandoned over the past 40 years due to degradation and desertification, while 52% of the land used for agriculture is moderately to severely affected by soil degradation. 44% of the world's food production systems and 50% of its livestock are considered to be vulnerable to climate change, while 12 million hectares of crop land are lost per year (23 hectares per minute), where 20 million tonnes of grain might have been grown. All of this must be considered against an estimated requirement to produce 60% more food by 2050, to feed a population that is predicted to increase from around 7 billion now, to 9.5 billion. Thus, we are destroying the productivity of the same soil from which we demand a relentless increase in production. Soil is also a critical component of both the global carbon and hydrological (water) cycles, and increasing the amount of SOM not only stores carbon, but improves the structure of soil and increases dramatically its ability to absorb and transmit water, and to recharge groundwater systems (aquifers). Thus, we must comprehend the soil as a fundamental and vital element in the processes of life on Earth, which needs to be nurtured and augmented. With no exaggeration, soil has been described[4] as "the fragile, living skin of the Earth", and yet both its aliveness and fragility have all too often been ignored in the expansion of agriculture across the face of the globe. Since it is a pivotal component in a global nexus[128] of soil-water-air-energy, how we treat the soil can impact massively on climate change – with either beneficial or detrimental consequences, depending on whether the soil is preserved or degraded. Sound soil-management practices offer the potential to mitigate and adapt to climate change, and it is the latter that threatens to increase the potential for soil erosion, diminished soil quality, and lower agricultural productivity, with expectedly adverse impacts on food security and global sustainability. Hence, this provides one of the more severe tests that might be imposed on humans during the remainder of the 21st century: not only must we mitigate climate change but accept the reality of it and adapt our behaviour and practices to best effect. Regenerative agriculture has at its core the intention to improve the health of soil or to restore highly degraded soil, which symbiotically enhances the quality of water, vegetation and land-productivity. The introduction of 'regenerative' practices requires a fundamental redesign of the system, so that the resource base is restored and revivified by means of natural ecological services. By using methods of regenerative agriculture, it is possible not only to increase the amount of SOC in existing soils, but to build new soil. This has the effect of drawing down carbon from the atmosphere, while simultaneously improving soil structure and soil health, soil fertility and crop yields, water retention and aquifer recharge – thus ameliorating both flooding and drought, and also the erosion of further soil, since runoff is reduced. However, all types of farming that use machinery powered by diesel fuels, are dependent upon a prevailing supply of crude oil; thus, they remain vulnerable to a potential 'peak oil' situation, and may not prove sustainable in the longer run.

Humankind appears to be confronted by a host of different problems, which have been described as "the world's woes"[38], among which we may list, carbon emissions/climate change, soil erosion, water shortages, resource-depletion, but also resource-waste, including 'food waste'. In reality, however, these are not individual problems, but symptoms of a single problem, *i.e.* overconsumption and injudicious use of limited resources. More than 80% of global energy production is derived from the fossil fuels[91], which contributes to carbon emissions and hence climate change, and recent analyses suggest that, rather than focussing on how to produce ever more of them, we should instead leave two-thirds of these materials in the ground, and unburned, if we wish to limit average global warming to 2 °C throughout the 21st century[129].

Crude oil and natural gas are essential to modern industrialised agriculture; however, as we have seen, its practices are driving erosion of the world's soils and a loss of biodiversity. In contrast, food production on a more local scale is found to preserve the soil and its quality. Thus, urban food production should be seen as a significant potential contributor to regenerative agriculture in the future, so long as the methods employed are themselves 'regenerative'. Permaculture is a regenerative, design system based on 'nature as teacher', which could help optimise the use of resources in town and city settings, while minimising and repurposing 'waste'. Thus, food might be produced using reduced inputs of fuels, water and fertilisers, and without pesticides and herbicides, while simultaneously building SOC. Such an approach taken by billions of individuals on the local scale, could prove of great significance in ensuring future food security and community resilience. In addition, more of food that is grown locally, tends to be actually eaten, in contrast with an annual 1.3 billion tonnes of food, produced for human consumption, that is lost or wasted globally, which amounts to about one third of the total[130].

In overview, in order to achieve a viable future will require integrated 'systems' thinking, rather than addressing isolated components/problems, *e.g.* 'climate change', 'peak oil', 'soil erosion' *etc*., because these are all interconnected, and it is the integrated issue of how we use our resources that must be addressed. Since 54% of the global population lives in towns and cities (74% in the more developed and 44% in the less developed countries), it is probably unrealistic to believe that every urban-dweller can escape to the countryside, and have their own patch of land to grow food on, since there is not enough rural space available, and the majority of us are not farmers, and lack the necessary skills and cultural background to 'go back to the land'. Furthermore, while there are impressive energy-efficient designs for buildings, *e.g.* passivhaus, it is not a practical proposition to simply raze our existing urban buildings to the ground and build-up again from scratch. Hence, if localisation is to become a dominant strategy for dealing with a vastly reduced use of fossil fuels, and to preserve soil quality – with increased food production in towns and cities – it will be necessary to incorporate integrated ('systems') design approaches such as permaculture and the circular economy (which minimise and repurpose 'waste') within the existing urban infrastructure. In addition to growing food in urban space, such actions as draught-proofing and thermally insulating existing building stock, and living/working on a more local scale, would serve well to cut our overall energy consumption. In order to curb our use of the fossil fuels, methods for reducing overall energy use must be considered at least equally important to expanding low-carbon energy production. In synopsis, it is clear that only by moving from the current linear, 'take, make, dispose (waste-creation)' model for resource-consumption, to the systemic, circular alternative of 'reduce, reuse, recycle, regenerate', are we likely to meet demands for future generations.

15. References

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