

Feeding and healing the world: through regenerative agriculture and permaculture

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ABSTRACT

The study of soil is a mature science, whereas related practical methods of regenerative agriculture and permaculture are not. However, despite a paucity of detailed peer reviewed research published on these topics, there is overwhelming evidence both that the methods work and they may offer the means to address a number of prevailing environmental challenges, e.g. peak oil, climate change, carbon capture, unsustainable agriculture and food shortages, peak phosphorus (phosphate), water shortages, environmental pollution, desert reclamation, and soil degradation. What is lacking is a proper scientific study, made in hand with actual development projects. By elucidating the scientific basis of these remarkable phenomena, we may obtain the means for solving some of the otherwise insurmountable problems confronting humanity, simply by observing, and working with, the patterns and forces of nature. This article is intended as a call to arms to make serious investment in researching and actualising these methods on a global scale. Despite claims that peak oil is no longer a threat because vast resources of gas and shale oil (tight oil) can now be recovered by fracking (hydraulic fracturing) combined with horizontal drilling, the reality is that proven actual reserves are only adequate to delay the peak by a few years. Furthermore, because of the rapid depletion rates of flow from gas wells and oil wells that are accessed by fracking, it will be necessary to drill continuously and relentlessly to maintain output, and there are material limits of equipment, technology and trained personnel to do this.

Moreover, to make any sensible difference to the liquid fuel crisis, which is the most immediate consequence of peak oil, it would be necessary to convert the world's one billion vehicles to run on natural gas rather than liquid fuels refined from crude oil, and this would take some considerable time and effort. The loss of widespread personalised transportation is thus inevitable and imminent, meaning a loss of globalised civilisation and a mandatory return to living in smaller localised communities. Permaculture and regenerative agriculture offer potentially the means to provide food and materials on the small scale, and address the wider issues of carbon emissions, and resource shortages. Since over half the World's population lives in cities, it seems likely that strengthening the resilience of these environments, using urban permaculture, may be a crucial strategy in achieving a measured descent in our use of energy and other resources, rather than an abrupt collapse of civilization.

Keywords: *permaculture, regenerative agriculture, forest garden, soil degradation, desertification, peak oil, fracking, hydraulic fracturing, shale gas and oil, plant nutrition, carbon capture, biochar, glomalin, soil fungi, transition town, water treatment, mineral deficiency, vitamin deficiency, obesity epidemic*

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1. Introduction

"The nation that destroys its soil destroys itself." Franklin D. Roosevelt (US President, 1933–1945).

The above quotation is taken from a letter¹, dated February 26, 1937, written by Roosevelt to the State Governors, urging uniform soil conservation laws, in reference to the infamous period dramatised in "The Grapes of Wrath" by John Steinbeck, and published in 1939, which draws out in painful detail the tribulations of families trying to survive in the dust-bowls of the mid-West during the Great Depression era of the 1930s, struggling toward California in a search for jobs and land, but mostly land on which crops would grow. *The Grapes of Wrath* won the annual National Book Award and the Pulitzer Prize and was cited prominently when Steinbeck won the Nobel Prize for Literature in 1962.

The study of soil^{2,3} is a mature topic, and has become a science, although much of our practical knowledge of how to use soil most effectively, stems from empirical observation – discovering directly what works and what fails. Throughout history, civilisations have thrived or declined according to the quality of their soils, since the latter is a crucial factor in the ability of humans to feed ourselves and our animals. In the 18th century, the English gentleman farmer, Jethro Tull (1674–1741)

introduced an improved seed-drill that enabled an efficient and consistent planting of seeds, such that the latter were used less wastefully. He also invented a horse-drawn hoe that allowed fields once choked with weeds to be brought back into production. It was Tull, however, who conceived the erroneous belief that weed seeds were introduced from manure, and that fields should be heavily ploughed in order to pulverise the soil and release nutrients from it. Guided by this line of thinking, in the 20th century, farmers ploughed fields well beyond the degree necessary to control weeds, and by a combination of such over-ploughing and drought, the dust-bowls were created in the prairie region of the Central United States and Canada.

The ancient Greek philosophers, who believed that they could comprehend the universe by logic alone, and without making recourse to experiments, concluded that plants obtained all their component elements from the soil in which they grew. In the 17th century, Jan Baptist van Helmont (1577–1644) grew a willow tree, weighing 5 pounds, under carefully controlled conditions, in which only water was added to it, and discovered after five years of growth, that its total weight, including its roots, was 165 pounds. The weight of the original oven-dried soil was 200 pounds, and when it was again dried and weighed, a mere two ounces had been lost. This, van Helmont assumed, was a matter of experimental error and concluded that the soil had lost nothing. Since rain water was the only additional ingredient, he inferred that water was the single essential element of growth. In fact, van Helmont's experimental technique was better than he thought: the two ounces that he had observed to be lost from the soil was genuine, since it represented the quantity of soil-minerals taken up by the tree as it grew. In 1771, the noted English chemist Joseph Priestley performed a series of experiments which imputed a role for atmospheric gases in the growth of plants. At that time, it was thought that a noxious substance, *phlogiston*, was released into the air when a flame burned. In one of his experiments, Priestley burned a candle in an enclosed container until the flame was extinguished, and found that when a mouse was placed in the "phlogistated" air of the container it died. In contrast, the air was made able to support the life of a mouse when a sprig of mint was first introduced to the container, which he concluded had changed the air by removing the phlogiston from it. The Dutch physician Jan Ingenhousz (1730–1799) then proved that plants "dephlogistate" air only in sunlight, and not in darkness, and that the green parts of plants are necessary for this process of dephlogistation; sunlight alone being ineffective for the task. The phlogiston theory was subsequently disproved by the French chemist, Antoine Laurent Lavoisier (1743–1794). Lavoisier showed that both burning candles and breathing animals consume a gas in the air which he named oxygen, leading to the inference that plants produced oxygen

when illuminated by sunlight. Tragically, Lavoisier was condemned to death and beheaded during the French revolution. Ingenhousz extended his earlier work and proposed that plants use sunlight to decompose carbon dioxide (CO_2), thus incorporating its carbon as they grow, while expelling the counterpart oxygen (O_2) as waste.

That a considerable sophistication in understanding about the growth of plants and their relationships with soil and with atmospheric gases had been attained can be seen from the following description⁴ given by William Allen Miller in his *Elements of Chemistry*, published in 1857:

“It has already been remarked that the food of plants is derived from two sources, viz., the atmosphere and the soil. From the atmosphere, carbonic and nitric acids, ammonia and water are supplied; whilst from the soil are furnished the various saline materials necessary for the healthy growth of the plant. Now, in certain cases, all these materials, with the exception generally of carbonic acid and water, may be present in quantity too scanty to produce a luxuriant crop, and the great practical problem submitted to the farmer for solution is the discovery of the nature of the missing materials in any given case; and of the means by which these materials may be most cheaply and effectively supplied.”

When a crop is carried off from the land, it necessarily takes with it a certain amount of mineral matters. If these mineral bodies be present in the soil in small quantity, and if fresh crops be continually carried off without provision for the return of the matters so removed, the land will in process of time become exhausted of one or more of these necessary ingredients and sterility will be the inevitable result.”

Thus, in the middle of the 19th century, chemical fertilisers began to be deliberately applied to soils to assist crop yields. It became clear that nitrogen was an essential element for the growth of plants and, in 1880, the presence of *Rhizobium* bacteria in the roots of legumes was found to be responsible for the increase of nitrogen in the soils in which they grew. Thus it was demonstrated that the fertility of soil depended on the living (organic) species it contained, and not only on its mineral (inorganic) components. By a combination of crop rotation, the introduction of mechanised farming, and the use of chemical and natural fertilisers, the areal yields of wheat in Western Europe doubled in the period 1800–1900.

2. Soil

Soil is made up of layers (soil horizons) which mainly consist of minerals that differ from their primary materials in texture, structure, colour, porosity, consistency, reactivity (pH, redox behaviour), and in chemical, biological and other physical characteristics. Soil is the final result of the consequences, in combination, of climate (temperature, precipitation),

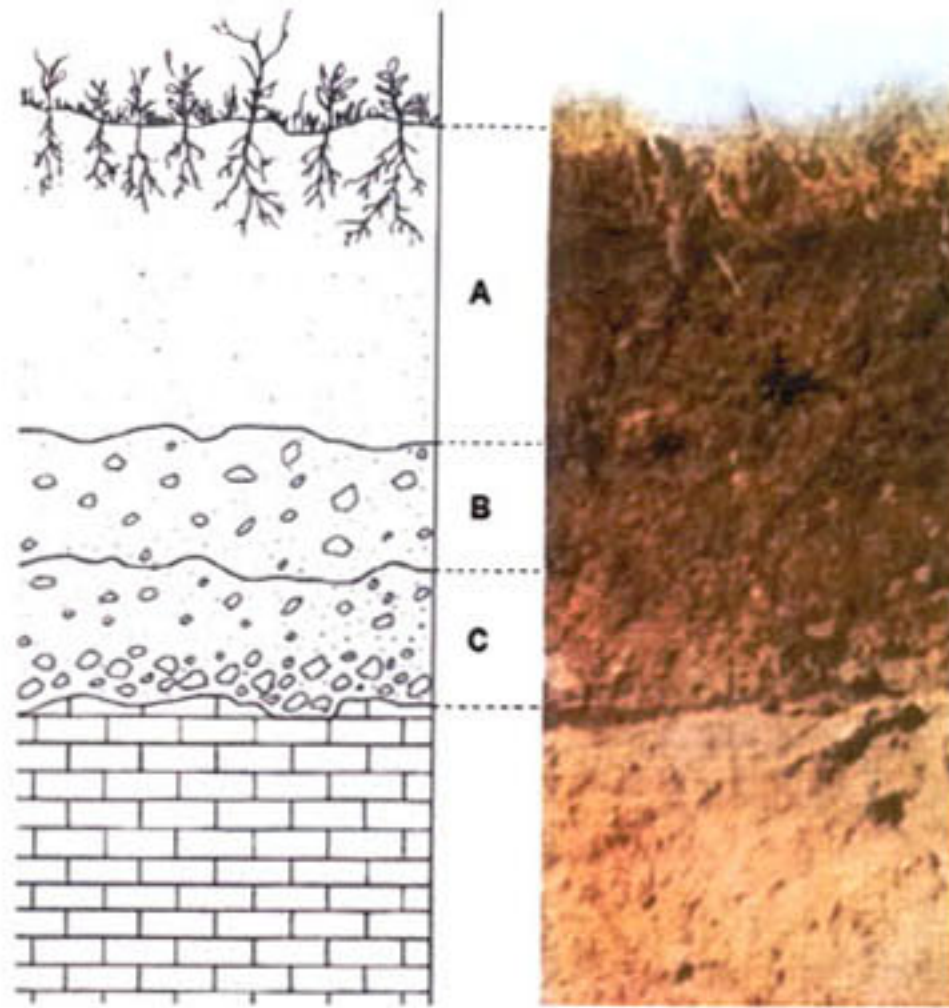


Figure 1 Vertical structure of a typical soil. Mediterranean red soil. A, soil; B, laterite, a regolith; C, saprolite, a less-weathered regolith; the bottom-most layer represents bedrock. Credit Carlosblh.

relief (slope), organisms (flora and fauna), primary materials (original minerals), and timescale. The material we know as soil (Figure 1) consists of rock particles that have been altered by chemical and mechanical processes, including weathering (disintegration) and accompanying mechanisms of erosion (movement). Soil forms a porous structure and may be envisaged as a three-state system: solid(s) (minerals – clay, silt and sand), liquid (water), and gas (air). The density of most soils lies in the range $1 - 2 \text{ g cm}^{-3}$.

A good quality soil contains (by volume) 45% minerals, 25% water, 25% air, and 5% of organic material. In a given soil, the mineral and organic components are considered to be constant, while the percentages of water and air may vary, such that the increase in one is balanced by the reduction in the other, *i.e.* air may be driven out by water, or water be replaced by air as the soil drains. The simple mineral mixture of sand, silt, and clay will evolve, as time passes, into a soil profile that contains two or more horizons, which differ in certain properties, as indicated above. The depth of the horizons can vary considerably from one to another and the boundaries between them are rarely sharply defined. Since the pore space of soil contains both gases and water, the aeration of the soil influences not only the health of the flora and fauna it contains, but also the emission of greenhouse gases.

The soil-evolution process is most strongly influenced by the presence of water, since this medium can promote the growth of plant-life, the leaching of minerals from the soil profile, and the transportation and immobilisation of various constituent components. Clay and humus are colloidal particles (< 1 micron in size) present in soil, both of which act as

a repository for nutrients and moisture, and serve to buffer the variation in nature and concentration of cations and anions that are present in the soil. Thus, the contribution provided by these materials to the health and properties of soil is far in excess of what might be deduced from their relative proportion by mass of the soil. Colloids are able to solubilise, initially immobile, ions in response to changes in soil pH, and plant root behaviour. The availability of nutrients is also influenced by the soil pH. Most nutrients originate from minerals and are stored in organic material, both living (*e.g.* bacteria) and dead, and on colloidal particles as ions. The action of microbes on organic matter and minerals may release nutrients, render them immobile, or cause them to be lost from the soil by leaching when they are converted to soluble forms, or by their conversion to gases. Most of the available nitrogen in soils originates from the “fixation” of atmospheric nitrogen gas by bacteria. Of all the components, it is water that has the greatest influence on the formation and fertility of soil, even more so than soil organic matter (SOM).

2.1. Organisms

The activities of plants, animals, insects, fungi, bacteria, and humans too, all play a part in the formation of soil. Fauna, such as earthworms, centipedes, and beetles, and microorganisms 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 microorganisms, 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 those species being unclassified*), making soil the most abundant ecosystem on planet Earth. It is said that one teaspoonful of soil may contain up to a billion organisms.

Vegetation can prevent soil erosion caused by excessive rain and resulting surface run-off. 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 ("Section 21").

2.2. Time

Soil formation is a time-dependent process that depends on the interplay of various different and interacting factors. Soil is a continuously evolving medium, and it requires around 800–1,000 years to form a layer of fertile soil 2.5 cm (one inch) thick. 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.

2.3. Water uptake by plants

90% of water is taken up by plants through “passive absorption”, which is the result of the upwardly drawing force of evaporation (transpiration) from the long column of water that extends from the plant's roots to its leaves. An osmotic pressure gradient is further generated by the high concentration of salts within the roots, and this acts to force water into the roots from the soil. The latter process becomes more important during times of low water transpiration, when the ambient temperature is lower (for example at night) or when the humidity is high. From one study⁵ of a single winter rye plant, grown for four months in one cubic foot of loam soil, it was determined that the plant developed 13,800,000 roots with a combined length of 385 miles (616 km) and a surface area of 2,550 square

feet (237 m²); additionally 14 billion hair roots were formed at a combined length of 6,600 miles (10,560 km) and a surface area of 4,320 square feet (402 m²). Since the total surface area of the root system amounts to 6,870 square feet (639 m²), and the total surface area of the loam soil was estimated to be 560,000 square feet (52,080 m²), it can be deduced that the roots were in contact with only 1.2% of the soil. Since the flow of water in soil is only around 2.5 cm per day, the roots must constantly seek out moisture, and so are constantly dying and growing as they try to locate such moisture in high concentrations. When the soil moisture is so low that the plants wilt, they may be permanently damaged with a loss in crop yields.

2.4. Consumption and efficiency of water use

Most of the water taken up by a plant is eventually lost through transpiration. Substantial evaporative loss from the soil surface also occurs. The combination of transpiration and evaporative loss of soil moisture is called evapotranspiration. The total water consumed (consumptive use) in growing a plant is the sum of evapotranspiration plus the amount of water held in the plant. This is practically identical to evapotranspiration because such a small fraction (0.1–1.0%) of the water used is actually contained in the plant. In addition to consumptive use, run-off and drainage must be added to determine the total amount of water necessary to grow crops. Application of loose mulches initially reduces evaporative losses from a field following irrigation, but ultimately the total evaporative loss is close to that for an uncovered soil; the main advantage of using mulch is that moisture is retained during the seedling stage. In some permaculture designs (see Section on Greening the desert), systems of swales are installed which, along with heavy mulching, vastly reduce the amount of water used to grow crops, perhaps by 90% or more. The efficiency of water use is measured by the transpiration ratio, which is the ratio of the total water transpired by a plant to the dry weight of the harvested plant at a particular location. Thus, alfalfa may have a transpiration ratio of 500 (depending on where they are grown) and as a result 500 kg of water will produce 1 kg of dry alfalfa. Typical transpiration ratios for crops lie in the range 300 – 700.

2.5. Soil atmosphere

In comparison with the atmosphere above it, the gas-composition of a living soil is generally decreased in its concentration of O₂ and increased in that of CO₂, because oxygen is consumed by microbes and plant roots, with the simultaneous release of CO₂. Hence, in the soil pore

space, the CO₂ concentration may be 10–100 times higher than its atmospheric concentration of 0.04%; the pores are also saturated with water vapour. If the soil porosity is sufficient, O₂ can diffuse into the soil where it is consumed, and CO₂ (whose concentration may otherwise become elevated to toxic levels) can diffuse out, along with other gases and water. The degree of porosity and consequent ability of the soil to diffuse gases is determined largely by its texture and structure. The flow of gases is impeded by platy and compacted soil, and when O₂ levels fall, anaerobic bacteria may be encouraged to reduce nitrate anions to N₂, N₂O, and NO – greenhouse gases which then escape into the atmosphere. In consequence, while O₂-rich (aerated) soil is a net sink of methane CH₄ – thus reducing the concentration of a gas with an instantaneous radiative forcing factor (global warming potential) roughly 100 times that of CO₂ – when soils are depleted of O₂ and subjected to elevated temperatures, they can become net emitters of greenhouse gases.

2.6. Soil density³

Particle density is the density of the mineral particles that make up a soil, *i.e.* excluding pore space and organics, and this averages approximately 2.65 g cm⁻³ (165 lb ft⁻³). The soil bulk density (Table 1) includes also the volume of air-space and organic materials. A high bulk density indicates either that the soil is compacted or that it has a high sand content. The bulk density of cultivated loam is about 1.1–1.4 g cm⁻³ (for comparison, water is 1.0 g cm⁻³). A lower bulk density alone does not indicate that a soil is suitable to grow plants in, since its texture and structure are also important factors.

Table 1 Representative bulk densities of soils³. The percentage pore space was calculated using 2.7 g cm⁻³ for particle density except for the peat soil, which is estimated

Soil treatment and identification	Bulk density (g cm ⁻³)	Pore space (%)
Tilled surface soil of a cotton field	1.3	51
Trafficked inter-rows where wheels passed surface	1.67	37
Traffic pan at 25 cm deep	1.7	36
Undisturbed soil below traffic pan, clay loam	1.5	43
Rocky silt loam soil under aspen forest	1.62	40
Loamy sand surface soil	1.5	43
Decomposed peat	1.55	65

2.7. Soil porosity

“Pore space” may be defined as the proportion of the bulk volume that is open space, occupied by either air or water. Ideally this should occupy 50% of the soil volume, because air space is needed to supply oxygen to

microorganisms so that they can decompose organic matter, humus, and plant roots. An adequate pore space is also prerequisite to the storage and diffusion of water and its dissolved nutrients in soil.

The four categories of pores are:

- (1) Very fine pores: < 2 microns (μm);
- (2) Fine pores: $2\text{--}20$ μm ;
- (3) Medium pores: $20\text{--}200$ μm ;
- (4) Coarse pores: > 200 μm .

In comparison, root hairs are $8\text{--}12$ μm (1 $\mu\text{m} = 10^{-6}$ m) in diameter (a human hair has a diameter of around 70 μm). When the pore dimension is less than 30 μm , the attractive forces that retain water in the pore exceed those acting to drain it, whereupon the soil becomes water-logged and unable to breathe. Hence, for a growing plant, soil pore size is of greater importance than total pore space. A medium-textured loam provides the ideal balance of pore sizes. Loam is soil composed of sand, silt, and clay in a relatively balanced proportion of about $40:40:20$, respectively. Large pore spaces that allow rapid air and water movement are more effective than smaller pore spaces. Tillage initially increases the number of larger pores, but these are eventually degraded by the loss of aggregation between soil particles.

2.8. Soil texture

The mineral components of soil, sand, silt, and clay determine a soil's texture (Figure 2). In the illustrated textural classification triangle, the only soil that does not exhibit one of those predominately is called "loam." While even pure sand, silt, or clay may be considered a soil, a loam soil, with a small amount of SOM, is considered ideal for growing crops in. Soil texture affects the behaviour of a soil, in particular, its retention capacity for nutrients and water. Sand and silt are the products of physical and chemical weathering; clay, on the other hand, is a product of chemical weathering but is frequently precipitated from dissolved minerals as a secondary mineral. The fertility of a soil depends on the specific surface area of its particles and their cation-exchange capacity (CEC). Thus, in order of decreasing particle size (*vide infra*), sand is the least effective, followed by silt, with clay being the most efficacious. According to its higher specific surface area, silt is more chemically active than sand, but for clay, the very high specific surface area and generally large number of surface negative charges, contributes a high retention capacity for nutrients and water. The presence of sand resists compaction and increases the porosity of soil. Due to stronger interactions between its particles, clay soils resist wind and water erosion better than silty and sandy soils. There are somewhat different classifications for the limits of particle size

according to which sand, silt and clay may be classified, but roughly, a silt is in the range 4–63 μm , with sand being larger (up to 250 μm for “fine sand”), while clay is $< 4 \mu\text{m}$. Clay is identified as a colloid at $< 1 \mu\text{m}$. When the organic component of a soil is substantial, the soil is called an organic soil rather than a mineral soil, *e.g.*

1. 0% clay; SOM $> 20\%$.
2. 0–50% clay; SOM 20–30%.
3. $> 50\%$ clay; SOM $> 30\%$.

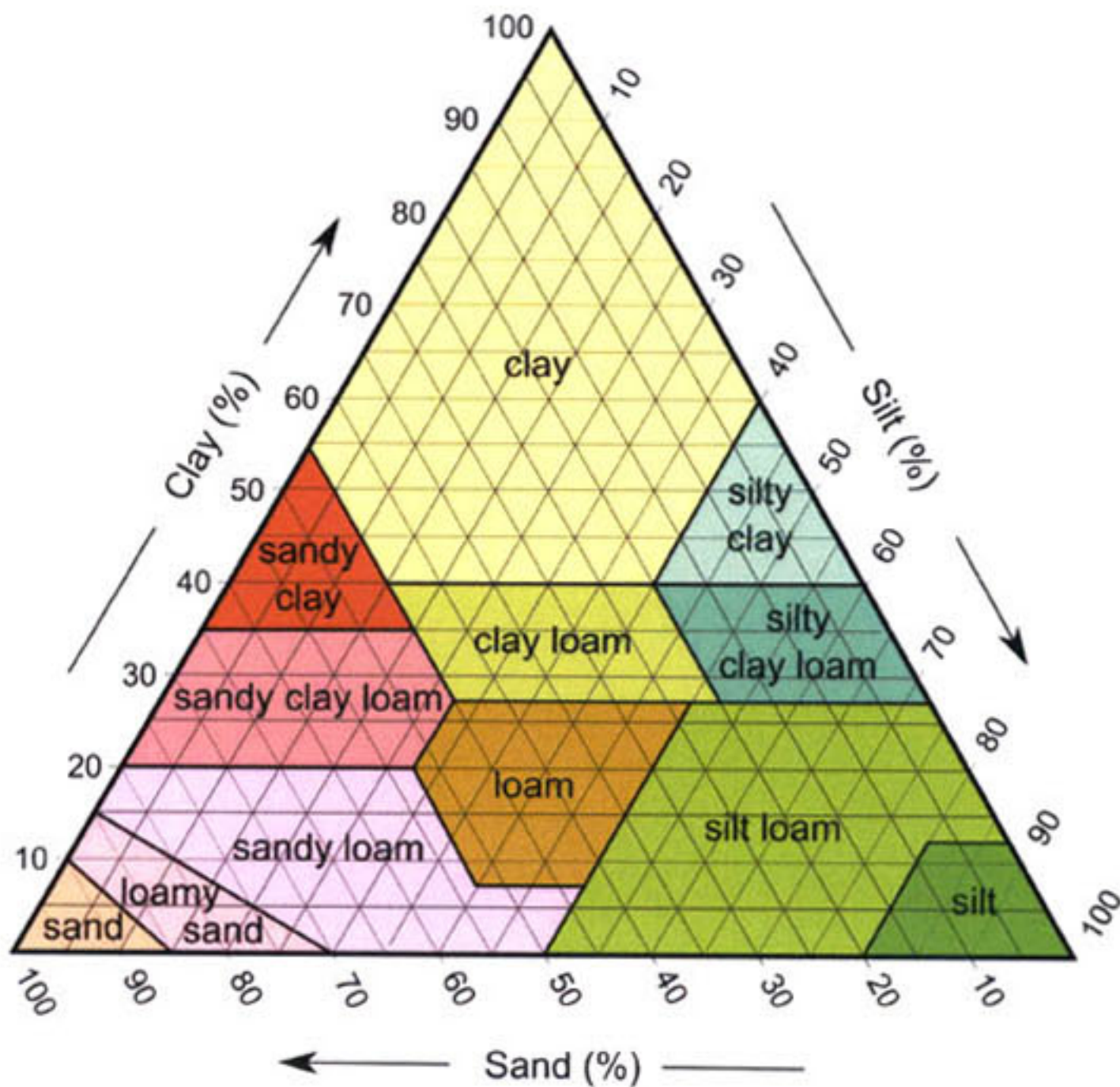


Figure 2 A soil texture diagram - soil types according to their clay, silt and sand composition, as used by the USDA, redrawn from the USDA webpage: <http://soils.usda.gov/education/resources/lessons/texture/>. Credit Mikenorton.

2.9. Soil structure

Clumping of the soil textural components of sand, silt, and clay forms aggregates and the further association of those aggregates into larger units forms soil structures called peds. The peds evolve into units that may have various shapes, sizes and degrees of development. A soil clod, however, is not a ped but rather a mass of soil that results from mechanical disturbance. The soil structure affects aeration, water movement, conduction of heat, resistance to erosion and plant root growth. Water has the strongest effect on soil structure due to its solution and precipitation of minerals and its effect on plant growth. Soil structure often gives clues to its texture,

organic matter content, biological activity, past soil evolution, human use, and the chemical and mineralogical conditions under which the soil was formed. While texture is defined by the mineral constituents of a soil and is an intrinsic property, soil structure can be improved or destroyed by the choice and timing of farming practices.

A classification of soil structures:

1. Types: Shape and arrangement of peds
 - a. Platy: Peds are flattened one on top of the other 1–10 mm thick. Found in the A-horizon of forest soils and lake sedimentation.
 - b. Prismatic and columnar: prism-like peds are long in the vertical dimension, 10–100 mm wide. Prismatic peds have flat tops, columnar peds have rounded tops. Tend to form in the B-horizon in high sodium soil where clay has accumulated.
 - c. Angular and subangular: Blocky peds are imperfect cubes, 5–50 mm, angular have sharp edges, subangular have rounded edges. Tend to form in the B-horizon where clay has accumulated and indicate poor water penetration.
 - d. Granular and crumb: Spheroid peds of polyhedra, 1–10 mm, often found in the A-horizon in the presence of organic material. Crumb peds are more porous and are considered ideal.
2. Classes: Size of peds whose ranges depend upon the above type
 - a. Very fine or very thin: <1 mm platy and spherical; <5 mm blocky; <10 mm prism-like.
 - b. Fine or thin: 1–2 mm platy, and spherical; 5–10 mm blocky; 10–20 mm prism-like.
 - c. Medium: 2–5 mm platy, granular; 10–20 mm blocky; 20–50 mm prism-like.
 - d. Coarse or thick: 5–10 mm platy, granular; 20–50 mm blocky; 50–100 mm prism-like.
 - e. Very coarse or very thick: >10 mm platy, granular; >50 mm blocky; >100 mm prism-like.
3. Grades: A measure of the degree of development or cementation within the peds that results in their strength and stability.
 - a. Weak: Weak cementation allows peds to fall apart into the three constituents of sand, silt and clay.
 - b. Moderate: Peds are not distinct in undisturbed soil but when removed they break into aggregates, some broken aggregates and little unaggregated material. This is considered ideal.
 - c. Strong: Peds are distinct before removed from the profile and do not break apart easily.
 - d. Structureless: Soil is entirely cemented together in one great mass, such as slabs of clay, or no cementation at all, such as with sand.

On the practical scale, the structure of a soil is determined by swelling and shrinkage effects whose forces tend initially to act in a horizontal direction, and result in vertically oriented prismatic peds. Since there is a differential drying rate with respect to the surface, for clayey soil, horizontal cracks are formed which reduce columns to blocky peds. The peds are further broken into spherical forms by the actions of roots, rodents, worms, and freezing/thawing cycles. At the smaller scale, plant roots extend into voids where they cause the open spaces to increase and further reduce the size of physical aggregation, while roots, fungal hyphae and earthworms create microscopic tunnels and break up the peds. Viewed at an even smaller dimension, soil aggregation continues as bacteria and fungi exude polysaccharides (exudates) that bind soil into small peds. The formation of this desirable soil structure is encouraged by the addition of raw organic matter to provide food for bacteria and fungi. At the molecular dimension, the aggregation or dispersal of soil particles is influenced by the soil chemistry. Due to the presence of polyvalent cations, the faces of the clay layers carry a net negative charge, while the edges of the clay plates bear a slight positive charge; thus the edges of some clay particles become attracted to the faces of others and flocculation can occur. However, monovalent cations such as sodium may displace the polyvalent cations: thus, the positive charge on the edges is decreased, while the negative surface charges become effectively stronger. This leaves a net negative charge on the clay particles, which tend to repel one another and so the flocculation of clay particles into larger assemblages is discouraged. As a result, the clay disperses and settles into voids between peds, causing them to close. In this way, the aggregation is impaired and the soil is made impenetrable to air and water. Such soils are called “sodic” and tend to form columnar structures near the surface.

2.10. Soil consistency

The consistency of a soil refers to its ability to stick together and resist fragmentation and provides some indication of potential problems with the material in cultivating plants and in engineering the foundations for buildings. Consistency is measured at three moisture conditions: air dry, moist and wet. Such measures of consistency are to some extent subjective because they use the “feel” of the soil in those states, rather as does “tilth”, which can be determined by the feel of soil as it moves through a farmer’s fingers. A soil with good tilth means that it has the correct structure and nutrients to grow healthy crops. Farmers sometimes make sure that their crop rotation is such to permit good seed bedding, along with the development of a strong root system that allows the nutrients to be distributed throughout the various depths of the soil. The resistance

of a soil to fragmentation and crumbling is determined by rubbing a sample of dry soil, while its resistance to shearing forces is estimated by applying thumb and finger pressure to a moist sample of soil; plasticity is measured by manually moulding a sample of wet soil. While knowing the consistency of soil is useful in estimating its ability to support buildings and roads, more precise measures of soil strength are generally made prior to actual construction.

2.11. Soil temperature

The temperature of a soil regulates seed germination, root growth, and the availability of nutrients, and may vary from permafrost at a few inches below the surface, up to 38 °C (100 °F) in soil at warmer climes. Snow cover will reflect light, and the rate at which the soil warms can be reduced by heavy mulching, which also attenuates the influence of fluctuations in the surface temperature. At a depth of 50 cm (20 inches) and below, the temperature of soil is virtually constant and can be approximated by adding 1.8 °C (3.2 °F) to the annual mean air temperature at a particular location. Agricultural activities are normally adapted to the prevailing soil temperature in order to: (1) maximise germination and growth by timing of planting; (2) optimise use of anhydrous ammonia by applying to soil below 10 °C (50 °F); (3) prevent heating and thawing due to frosts from damaging shallow-rooted crops; (4) prevent damage to soil tilth by the freezing of saturated soils; and (5) improve uptake of phosphorus by plants. Where necessary, soil temperatures can be raised by drying or by the use of clear plastic mulches, while, as noted, organic mulches tend to reduce the rate of soil warming.

2.12. Soil colour

The colour of soil depends principally on the minerals it contains. Many of the colours are owed to the presence of various iron minerals (Figure 3), and the development and distribution of colours in a soil profile are a consequence of chemical and biological weathering of the primary minerals present, particularly through redox reactions. When iron is present, secondary minerals may be produced with red or yellow colours, while organic matter decomposes into black and brown coloured compounds, while black deposits may also be formed from Mn, S and N. The many and various components, by acting as pigments, can produce a variety of coloured patterns within a soil. Uniform or gradual colour changes tend to be the result of aerobic (oxidising) conditions, while anaerobic (reducing) environments cause a rapid flow of colour, with complex, mottled patterns and points where the colour is highly concentrated.



Figure 3 Iron rich red soil near Paint Pots mineral springs in Kootenay National Park, British Columbia, Canada. Credit Marek Ślusarczyk.

2.13. Ion-exchange by soils

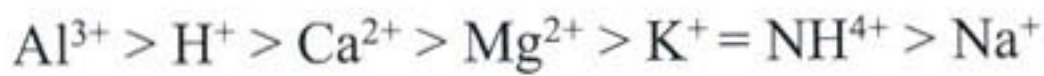
2.13.1. Cation exchange.

The exchange of cations between soil particles and soil water, buffers (moderates) the pH and changes the structure of a soil. The process may also “purify” water by adsorbing cations of all types, some of which may be desirable or undesirable, while passing other cations into the aqueous phase as water percolates through the soil.

Cations are bound at the surface of soil particles because of the presence of negative charges there – there are four sources of the latter.

1. Isomorphous substitution occurs in clay when lower valence cations substitute for higher valence cations in the crystal structure (*e.g.* when Al occupies a position that would be otherwise taken by a Si atom – clays are aluminosilicates – a negative charge is created, $(O)_4Al^-$). In terms of creating an effective surface charge on a soil particle, such substitution in the outermost layers is more effective than in the innermost layers because the charge strength decreases with the inverse square of the distance.
2. At the edges of a particle there are oxygen atoms with unsaturated valencies, because there are discontinuities in the structure, leaving some of the tetrahedral and octahedral structures incompletely bonded. These oxygen atoms carry a negative charge (O^-)
3. Hydroxyl groups on the clay surfaces may be ionised, yielding H^+ into solution, leaving oxygen atoms with a negative charge.
4. Likewise, hydroxyl groups on particles of humus may be ionised, passing H^+ into solution, leaving oxygen atoms with a negative charge.

The binding of cations to the particles tends to save them from being washed away, thus preserving the fertility of soils in areas where rainfall is moderate. Different cations have a greater or lesser affinity for the soil particles, and if they were present in equal concentrations, would be retained in the following order:



However, a far dominant concentration of a single type of cation may swamp the system, as occurs, for example, when large quantities of fertiliser are added to soil. An increase in the acidity of the soil (more protons H^{+}), may cause the other cations to be exchanged into solution, while the associated surface negative charges are balanced by H^{+} . These are referred to as pH-dependent charges, which unlike permanent charges developed by isomorphous substitution, are variable and increase with increasing pH. The charges on the oxygen atoms (O^{-}) become effectively neutralised by addition of the proton to form an $\text{O}-\text{H}$ group. Plant roots can release H^{+} to the soil thereby mobilising the cations so that they can be absorbed by them. Once in solution, however, the cations can be washed away, thus impoverishing the soil fertility.

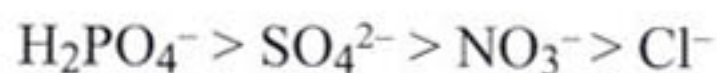
2.13.2. Cation exchange capacity

The ability of a soil to exchange cations with the soil water solution is referred to as the cation exchange capacity (CEC). This may also be considered as the ability of the soil to remove cations from the soil water solution and to hold those for later absorption by plants as the plant roots release H^{+} to the solution. More specifically, CEC is the concentration of exchangeable protons (H^{+}) that will combine with 100 grams (dry weight) of soil and whose measure is one milliequivalent per 100 grams of soil (1 mequiv./100 g). H^{+} cations have a single charge and one-thousandth of a gram of hydrogen ions per 100 g dry soil gives a measure of 1 mequiv. of hydrogen ion. The sterility of many tropical soils may be explained by an absence of both clay and humus colloids (which are responsible for the CEC) in hot, humid, wet climates, due to leaching and decomposition, respectively. Some typical values of CEC for different soils and clays are listed in Table 2.

2.13.3. Anion exchange capacity

The anion exchange capacity (AEC) of a soil may be usefully considered to reflect its ability to remove anions from the soil water solution and sequester them for later exchange as the plant roots release carbonate anions to the solution. Amorphous and sesquioxide clays have the highest

AEC, followed by iron oxides. Iron and aluminium hydroxide clays are able to exchange their hydroxide anions (OH^-) for other anions, including phosphates, which tend to be held at anion exchange sites. The order of affinity in terms of anion exchange is:



Colloids with a low CEC tend to have some AEC, although the values are always much lower than for CEC, and are of the order of tenths to a few milliequivalents per 100 g dry soil. As the soil pH rises, the concentration of hydroxyl anions (OH^-) increases, and these may displace anions from their storage points on the surface of the colloids and into solution; hence, the AEC is found to decrease with increasing pH (*i.e.* as the solution becomes more alkaline).

Table 2 Cation exchange capacity for soils; soil textures; soil colloids³

Soil	State	CEC (mequiv / 100 g)
Charlotte fine sand	Florida	1.0
Ruston fine sandy loam	Texas	1.9
Gloucester loam	New Jersey	11.9
Grundy silt loam	Illinois	26.3
Gleason clay loam	California	31.6
Susquehanna clay loam	Alabama	34.3
Davie mucky fine sand	Florida	100.8
Sands	—	1–5
Fine sandy loams	—	5–10
Loams and silt loams	—	5–15
Clay loams	—	15–30
Clays	—	>30
Sesquioxides	—	0–3
Kaolinite	—	3–15
Illite	—	25–40
Montmorillonite	—	60–100
Vermiculite (similar to illite)	—	80–150
Humus	—	100–300

2.14. Soil pH

The soil reactivity is expressed in terms of pH, which is a measure of hydrogen ion (H^+) concentration in an aqueous solution and ranges in values in the range 0–14 (acidic to basic). A neutral pH is 7, and so soils with a $\text{pH} < 7$ are acidic, while those at $\text{pH} > 7$ are alkaline. In practice,

measured soil pH values range from 3.5 to 9.5, and soils measured outside of these limits are toxic to life forms. To place this in context, at 25°C an aqueous solution with a pH of 3.5 contains $10^{-3.5}$ moles of H^+ per litre of solution (and also $10^{-10.5}$ moles per litre of OH^-). At a pH of 7, the solution contains 10^{-7} moles H^+ per litre and also 10^{-7} moles of OH^- per litre, hence its neutrality. A pH of 9.5 contains $10^{-9.5}$ moles of H^+ per litre of solution (and also $10^{-2.5}$ mole per litre OH^-). At a pH of 3.5, a solution contains one million times more H^+ per litre than a solution with a pH of 9.5 ($9.5 - 3.5 = 6$ or 10^6) and is accordingly more acidic by that same amount. Highly acidic soils tend to contain toxic levels of aluminum and manganese. Plants that need calcium require a moderately alkaline soil but most minerals are more soluble in acid soils. A high acidity has a negative effect on soil organisms, while most agricultural crops do best on mineral soils with a pH of 6.5 and organic soils with a pH of 5.5, by exchange of Na^+ for Ca^{2+} .

In areas where the rainfall is heavy, soils tend to become acidic because basic cations (*e.g.* Mg^{2+} , Ca^{2+}) are out competed and exchanged from the soil colloids by the mass action of H^+ from the water. The reason that such cations are described as “basic” is their association with carbonate anions (CO_3^{2-}), which yield hydroxyl anions *via* the equilibrium: $H_2O + CO_3^{2-} \rightleftharpoons HCO_3^- + OH^-$. Persistent, heavy rainfall can then wash out nutrients leaving the soil sterile. Once the colloids are saturated with H^+ , the addition of more H^+ (or aluminium cations) drives the pH lower still, as the soil is left with no buffering capacity. In areas of extremely heavy rainfall, and where temperatures are high, the clay and humus may be washed out or degraded, which further reduces the buffering capacity of the soil. In contrast, in areas where rainfall is low, Ca^{2+} ions remain unleached and the pH may rise to 8.5; with the addition of “exchangeable sodium” (which acts by effectively attracting carbonate anions into the solution, *e.g.* $CaCO_3 \rightleftharpoons Ca^{2+} + CO_3^{2-}$), soils may reach a pH of 10. At $pH > 9$, plant growth is reduced because the mobility of micro-nutrients is reduced; however, water soluble-chelates of them can be added as compensating agents. Levels of sodium can be reduced by the addition of gypsum (calcium sulfate) by exchange of Na^+ for Ca^{2+} .

2.15. Soil humus

Humus is a colloidal material and represents the penultimate state of decomposition of organic matter; while it may linger for a thousand years, taken over the longer scale of the age of the other soil components, it is temporary. It is composed of the very stable lignins (30%) and complex sugars (polyuronides, 30%), and on a dry weight basis, the CEC of humus

is many times greater than that of clay; cation exchange sites are also present on the roots of plants.

2.16. Soil resistivity

The electrical resistivity of soil can determine the rate of galvanic corrosion of metallic structures in contact with it. Conductivity may be increased by a greater moisture content or increased electrolyte concentration, thus lowering the resistivity, and so increasing the rate of corrosion. Typical soil resistivity values vary in the range 2–1000 Ω m, but more extreme values are fairly common.

3. Degradation of soil^{6,7}

In 2011, the world population of humans passed the 7 billion mark, and it is estimated that by 2050, there will be 9 billion of us. Soil not only provides us with food, fibres and fuel, but it supports wildlife and a range of rural and urban activities. From the end of the 1940s to the beginning of the 1990s, over 90% of the degradation of productive land occurred from overgrazing, deforestation and other degenerative agricultural practices. Such losses to the health of soil affect all of us, particularly the 3.7 billion who are malnourished and the 3 billion living in poverty. Among all other considerations of the challenge to feed such a multitude, the quality and fertility of soil is a critical aspect and good soil should be regarded as a fundamental resource that requires urgent conservation. Soil may be degraded by different processes: hydraulic erosion, wind erosion, changes in its material composition and physical degradation.

3.1. The current situation

According to the ISRIC World Soil Information data⁸, 46.4% of the world's soil is less productive than it was. Around 33% of this loss of some biological function in soil is occurring in Asia, and about 20% in Africa. Globally, 15.1% of soil is unsuitable for farming, but to regenerate it would necessitate very substantial financial investments. About 9.3 million ha (0.5%) of soil is completely biologically inactive (dead). More than 50% of the soils that have been degraded by deforestation are located in Asia and 15% in South America. Deforestation is the main cause of soil degradation both in South America (41%) and in Asia (40%) and in Europe too (38%). 36% of the world's soils that have been degraded by overgrazing are in Africa. Indeed, overgrazing is the major reason for soil degradation in Africa (50%), in the South Pacific and in Australia (80%). 37% of soils degraded by inappropriate agricultural practices are

in Asia, and these are the most common cause of soil degradation in North and Central America (58%), and the second most common cause of soil degradation in Africa (25%). 50% of the 133 million ha degraded by the overexploitation of vegetation cover for domestic purposes is in Africa. That noted, almost all the soil degraded by industrial pollution is in Europe. As a solution, the importance of soil ecosystem management, especially in the search for solutions to fight desertification and certain forms of soil degradation should be emphasised. This involves taking a holistic view of the soil system as an element which is part of a greater whole, rather than considering it in isolation, as has been done traditionally.

3.2. Human causes of soil degradation

Soil is mainly degraded by human activities, principally those of agriculture. Land-clearing, irrigation, the spraying of chemical fertilisers and pesticides, overgrazing and the mechanical effect of heavy farming equipment passing over the soil, all take their toll. Soil formation, and the composition of humus, are profoundly influenced by the clearing and deforestation of land to grow crops on, because the varied primitive vegetation is replaced by secondary vegetation, of which monoculture is the most severe example. The upper layers of soil, along with that of humus, are damaged by tillage and a compacted layer (plough sole) may form if the ploughs regularly pass through soil at the same depth. When farm machinery heavier than about 5 tonnes is used, soil compaction may be another result. By threatening the productive capacity of vegetation, overgrazing strips soils and increases their sensitivity to hydraulic erosion (56% of soil degradation) and wind erosion (28% of soil erosion). Over application of pesticides and artificial fertilisers may kill soil fauna and diminish the degree of aeration of soil, resulting in soil run-off which causes floods and mudslides. Overgrazing and excessive tillage may lead to severe dust storms as occurred in the USSR in 1960 and in Africa where 2–3 billion tonnes of soil is blown free of the continent and skyward annually, thus steadily eroding the fertility of its soil. The ability of soils to sequester CO₂ may be hampered by farming methods which change its structure and composition, and the conversion of meadows, forests and peat bogs into fields causes a reduction in the amount of soil carbon. The degradation of soil drives the loss of biodiversity, and also impacts on global warming through changes in the local albedo and the emission of greenhouse gases such as methane and nitrous oxide, as the oxygen tension of the soil becomes diminished.

4. Permaculture^{9,10} – in summary

Since permaculture is implicit to much of the following discussion, it seems appropriate to give a brief overview of the topic now, before describing it more fully in Section 12. The term “permaculture” (a portmanteau word derived from *permanent agriculture* or *culture*) was coined by Bill Mollison 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, which reflects the expansion of focus implicit in *Permaculture One*, 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. Masanobu Fukuoka¹¹ (1913–2008) was a Japanese farmer and philosopher who established an ecological farming approach called “natural farming”, which has been attributed by some as containing the essential roots of permaculture. The method is sometimes also called “the Fukuoka Method”, “the natural way of farming” or “do-nothing farming”: the latter refers not to lack of labour, but to an avoidance of manufactured inputs and equipment. The system exploits the complexity of living organisms that sculpts each particular ecosystem. Fukuoka saw farming as not purely a means of producing food but as an aesthetic or spiritual approach to life, the ultimate goal of which was, “the cultivation and perfection of human beings”. Natural farming is a closed system, one that demands no inputs and mimics nature, and also differs from conventional organic farming, which Fukuoka considered to be another modern technique that disturbs nature. Fukuoka claimed that his approach prevents water pollution, loss of biodiversity and soil erosion and yet there is no compromise in the amount of food that it can provide. Modern permaculturists make similar claims, and even that the method can produce greater yields per hectare than conventional farming can. Albeit, we should perhaps take stock of the fact that modern farming has only been “conventional” for about 60 years! One major change incurred by converting to permaculture is that cereals cannot be produced at the scale of industrialised agriculture, and amendments in our diet, to consume more vegetables, fruit, nuts, berries, *etc.* would be necessary, which can be produced effectively by its means.

The core tenets of permaculture are:

- ***Take care of the earth (“earth care”)***: 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.
- ***Take care of the people (“people care”)***: 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 systems.
- ***Share the surplus (“fair shares”)***: 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 – don’t 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 components to achieve their best synergy in the final and optimal design. 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. Therefore, 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 with minimal input.

5. Regenerative agriculture^{12,13}: the transition

Much of the energy involved in regenerative agriculture and permaculture is provided quite naturally by native soil fauna, and is derived from photosynthesis, where the fuel for soil microbes is delivered from plants as the factories that supply carbon-rich nutrients. The main difference between the two approaches is that permaculture follows an initial design, while regenerative agriculture tends to be more pragmatic and is an adaptation of existing methods of field farming. The health of the soil is improved in both processes since its organic component becomes regenerated. In a wonderful symbiosis, the living soil microbes, especially fungi, can draw other nutrients and water from the soil to nourish the plants. The individual elements of life feed one another in a mutually dependent and beneficial manner. While the strategies of the two methods can be defined and envisaged quite clearly, the intermediate means for transition from industrial to regenerative agriculture and permaculture is rather more nebulous, since it has not been done before, or at least not in the degree that necessity now demands. So how might we perform this revolution in the least painful way? Undoubtedly, a decolonising and restructuring of present industrialised agriculture is necessary, along with an appreciation and magnification of native and traditional food systems. Overall, a change in thinking and concept is required from conflict and limit to cooperation and abundance. The scale of the transition may be compared with other milestone transitions throughout human history, such as the hunter-gatherers becoming farmers, and the progression ultimately to modern industrial societies. It is the latter that are under threat and unsustainable, and a compromise devolution to a more localised collective of small communities (pods) is required, supplied by local farms and infrastructure, with rail links between them for essential movement of goods and people. The maintenance of the internet and electronic communications would seem desirable since ideas and knowledge can be transmitted from pod to pod and between countries and continents.

In the 1970s, studies were undertaken that evaluated the massive inefficiency in energy requirements for food production. It was concluded that 10 calories of energy are expended to bring 1 calorie of food onto the dinner plate. It has been stressed that essential agricultural production is needed to provide food and fibre – *i.e.* the essential products of biomass. Biofuel may also be regarded as a product, if the consideration also includes fermentation of sugars derived from starch into ethanol,

or hydrothermal production of liquid and gaseous fuels from biomass by heating it under pressure in the presence of water. The impending stress of "climate change" is well acknowledged, *e.g.* sea-level rise and the spreading desertification of formerly green lands, but its impact on agriculture is rarely mentioned by climate-modellers. However, as an example, it is speculated that the Colorado River basin could dry up. Its mighty dams would then look something like the pyramids of Egypt, maybe leaving future generations to speculate as to what their purpose was, and upon the nature of the civilisation that created them. As climate zones shift, it is the variability of the weather that will have greater impact than ramping "mean temperatures" on the enormous investment made by humans in agriculture. The capital outlays required for new dams, irrigation supplies and the retraining of farmers will need to be contrasted with that for flood-defences in vulnerable locations (*e.g.* New Orleans and the east coast of England). Most likely, both cannot be supported, and it may prove expedient to simply let some regions "go to the sea".



Figure 4 Rainforests are an example of biodiversity on the planet, and typically possess a great deal of species diversity. This is the Gambia River in Senegal's Niokolo-Koba National Park. Credit Atamari.

Biodiversity is a natural means for leveling-out the gains and losses of living system (Figure 4). It is cooperative in the sense that pests are not encouraged as they are by growing single strains of crop, and that suitably matched plants help each other to grow – the holistic whole being more robust than the simple measure of its components. The term "global village" tends to signify an interconnected unity of trade or electronic communication, while aspects of cultural diversity and biodiversity are ignored. However, it is a necessity to preserve and expand the traditional food and fibre production systems that are tried and tested and whose regenerative capabilities have been demonstrated over millennia. We may adapt to, or readopt, cultures that have been lost, as industrial civilisation has supplanted them, and it is the latter that we must seek to break away from to arrive at a sustainable future, if we are to survive as a human species that is. If "global village" means "global supermarket", the term lends acceptance to the concomitant rule of multinational corporations. If we restructure societies to become self-sustaining, rather than dependent

on inputs and indeed outputs, as they are now, we also must abandon "limited liability" and the legal designation of "corporations" as "persons" with the same rights as individual citizens. Traditional food systems are storehouses both of biodiversity and cultural diversity. It is a pity that the seed-banks around the world contain no information about the culture, economy, details of cultivation methods, flavour or other human aspects of the crops and the food they produce. Including my own musings on the topic, most commentators on the post peak oil world refer to the need to localise food systems, such that small populations are provided for locally by means of community farms. However, establishing regenerative systems to grow food and fibre must include cities too, the design of which must be analysed in terms of the natural mechanisms that interweave them.

It is seldom realised that the rural development or redevelopment urged by the industrialised nations for the developing world are precisely those they need to adopt themselves. Schumacher's "Buddhist economics" which he describes in the bestselling¹⁴ "Small is beautiful – a study of economics as if people mattered", applies equally to the industrialised world as it must de-industrialise, and take lessons from simpler societies which consume far less per head of population. The example of Cuba may be drawn-upon as a source of optimism by other nations, since it has survived and indeed thrived through implementing a system of community gardens, and using methods of permaculture, to cope with the abrupt loss of cheap and plentiful oil, fertilisers and pesticides gifted from the Soviet Union, when that latter regime collapsed in 1989. Though there are presently considerable economic problems in Cuba, the population was able to adapt and feed itself during what was initially referred to as "the special period during peacetime", and now simply as "the special period". That noted, the average number of calories consumed per day dropped from 2,908 to 1,863 in five years, and the average Cuban lost 20 pounds in weight during that time¹³. The Gaia hypothesis, originated by James Lovelock in the 1960s¹⁵, has acted as an iconic beacon to the environmental movement, drawing-in a range of people dissatisfied with the industrial and materialistic way of life, and who seek alternative, more natural and or spiritually rewarding lifestyles, and with less detriment to the planet and life upon it. "Gaia" is holistic in nature and is based on ecology. Rather than an industrialised "global village" it implies a "globe of villages". Food and fibre production is one of the most important features of the transition to a post-fossil fuel era, to which the establishment of regenerative food systems is essential.

6. Water shortages

Along with cheap crude oil, water is a resource that will begin to run-short within a few decades, as is espoused in the book¹⁶ entitled "Mirage", written by Barnett, which focuses on water-use in the USA and in Florida particularly. It is well known that to the east of the longitudinal line along the 100th meridian, rainfall is plentiful, while to the west of it the climate is relatively arid. Indeed it was once believed that farmers in the "east" would never have to worry about watering their crops, but in recent years demand for water has surged with calamitous environmental consequences. Barnett refers to a house falling into a "sinkhole", which is a collapse in the limestone rock that underlies Florida as a consequence of its natural dissolution by underground water. These can be opened-up as a result of human activities including well-drilling and moreover the excessive pumping of groundwater. She discusses the complex politics involved in "development", and the overpopulation of that southern tip of the Florida peninsular particularly by retirees ("seniors"), thus requiring an infrastructure – including very green and hence heavily watered lawns and golf-courses, *etc.* – to a degree that surpasses even what can be provided by the greatly abundant rainfall there. Meeting the shortfall necessitates the extraction of groundwater on a huge scale with environmental, economic, political and social consequences, including at least one death as Barnett describes in the chapter "Water wars". Indeed the history of water supply in the United States is wryly inscribed in the quotation (attributed to Mark Twain), "whiskey's for drinkin' and water's for fightin'."

A central theme in the book is that water is a commodity. Often the real costs of water provision are borne by states or municipalities rather than by corporations, who cash-in on a cheap resource for which no regard is consequently imbued, nor for environmental actions such as damming rivers as mighty as the Colorado for various "aquatic" projects. Bottled "spring" water is an immensely overpriced designer toy, costing around 10,000 times as much as tap water and often with much the same analytical composition. Indeed, not all spring-water does in fact come from a spring, and is to a large degree, pumped groundwater. The Ogallala aquifer flows for 174,000 square miles under the great plains from South Dakota to the Texas panhandle, and it is the main source of water for the US collective national breadbasket, supplying as it does one third of all the groundwater used for irrigation in the entire country. However, Ogallala is not replenished as most aquifers are. Instead it contains "fossil water", set in the ground from the melt of the last ice-age 10,000 years ago, and once it is used-up there is no more. Access to cheap electric pumps in the 1950s permitted farmers to draw this legacy upward at

increasing rates with the result that the Ogallala has fallen by 100 feet in parts of New Mexico, Kansas, Oklahoma and Texas. It is inevitable and a matter of time that all wells sunk into this huge aquifer will run dry, with impacts on agriculture overall, including the vast corn crop grown to produce corn ethanol, as a replacement fuel for those currently refined from crude oil. The Aquifer Storage and Recovery (ASR) technology is given special mention. The idea is that during wet periods, when water is plentiful, water is pumped into gigantic underground aquifers set deep into Florida's limestone, and which can be pumped-up again during dry months. Some 36 million gallons a day are drawn from Peace River, which starts in Central Florida's Green Swamp and ends 105 miles further south in the Charlotte Harbour Estuary. There are almost 1,700 ASR wells in the US altogether, most of them in the states of California, Nevada, Texas and Florida, and all of them particularly short of water. However, caution is urged, as the first well sunk at Peace River became seriously contaminated with arsenic, present naturally in the aquifer. Desalination is another technology often invoked as a solution to water shortages especially in near-coastal regions, even though it is very costly to set up a desalination plant in the first place, and running one requires considerable amounts of energy. Nor is the technology guaranteed: *e.g.* a plant at Tampa Bay built at a cost of \$110 million suffered all kinds of difficulties and finally the high-tech membranes required to separate water from salt by reverse-osmosis clogged up. Groundwater pumping was actually reduced by one third in the region, without the need for desalinated water, purely through more conventional means of reservoir and surface water treatment combined with aggressive water-conservation measures.

While the competition over the use of arable land to grow either food or fuel crops is a well established and critical factor in making biofuels at scale, there is less awareness about the water required to irrigate the land on which the crops are to be grown. It is unequivocal that China is the new industrial nation, in an unparalleled phase of its economic and social development. This might be expected to continue for as long as the West can afford to buy its cheap goods, but in the current recession, that duration is debatable. Underpinning Chinese industrial growth, as for all industrial growth, is energy, and in recognition of peak oil, emphasis is on biofuel (and all other kinds of energy resources in China, including coal-to-liquids, CTL conversion) as products need to be transported for sale. It is aimed that by 2020, 12 million metric tons of biofuels will be produced in China. To put this into context, this is equivalent to around one fifth of the petroleum-derived fuel used in the UK annually. The fuel is to be bioethanol, fermented from corn (maize) which is a relatively water-efficient starch crop. According to one analysis¹⁷ in order to irrigate sufficient corn to produce 12 million tonnes of bioethanol, a quantity of

water equivalent to the annual discharge of the Yellow River (Figure 5) would be required. 64% of China's arable (crop-growing) land is in the northern part of the country, and is already under pressure since the existing use of water exceeds its reserves and water tables are falling¹⁸. We have neither sufficient land nor water to maintain the illusion that we can continue as we are, certainly not in terms of liquid transportation fuel and thus transport itself, merely by substituting declining oil and natural gas supplies by biofuels. Massive water demand should be anticipated in consequence of expanding biofuel production in other countries too. For example, in India and in the western USA, water tables are falling. As already noted, agriculture in the US mid-West is maintained by draining "fossil water" from the Ogallala aquifer, which underlies eight US states. Once it is used up, this supply of water cannot be replenished. It is likely that climate change and the shifting of the temperate regions to the north may impact further on the American West. In Australia, another major producer of starch crops, water supplies are also under stress. It has been reckoned¹⁹ that some 5,000–6000 km³ of water would be needed to irrigate sufficient crop to supplant the world's petroleum-based fuel by ethanol generated from corn. We may compare this number with the entire supply of fresh water available on Earth of 13,500 km³ *i.e.* the crop would require about half of it. Other potential fuel crops, *e.g.* wheat, soybeans and rapeseed have an even greater demand for water than does corn. This is a clear warning and additional expression of the limitations of crop-based biofuels.

The quantity of water that we use in our daily lives is deceptive. For example, an average Briton is said to use 150 litres of water a day, and yet the true total rises nearer 3,400 litres per day²⁰, once the amount of "embedded water" (hidden water) is included, which is the water used to grow and produce various products. 65% of the water we use is in our



Figure 5 The Yellow River at the Hukou Falls. Credit Leruswing.

food, and the quantities of embedded water that are used to provide some very commonplace items are staggering. For example, it takes 3,000 litres of water to produce a beefburger, and in Britain some 10 billion burgers are consumed per year, therefore necessitating the consumption of 30 trillion litres, or 30 km³ of water. A tomato has about 13 litres of water embedded in it; an apple has about 70 litres; a pint of beer about 170 litres; a glass of milk about 200 litres. It takes 27,000 litres of water to produce one bar of chocolate, 100 litres of water are used to make one cup of coffee. It takes 4 litres of water to make one one-litre plastic bottle of water... that is even before the water is put into it. To make a cotton T-shirt needs 2,000 litres of water, 15,000 litres for either a pair of jeans, or 1 kg of steak. To make a car takes 400,000 litres²⁰. The amount of water used to produce food and goods imported by developed countries is worsening water shortages in the developing world, and this raises moral questions, *e.g.* whether it is appropriate for developed (legacy) nations to import beans and flowers from water-stressed countries such as Kenya. If the world's population increases to 8 billion by 2030, 50% more food and energy will be needed, and the demand on fresh water will rise by 30%. This not only reflects the rise in population *per se*, but that more affluent people eat more food – particularly meat – and the consumer society is expected to expand within its number.

7. Plant nutrition²¹⁻²⁴

As is true of all living organisms, including humans, plants require essential raw materials to provide both the energy and building blocks for growth. CO₂ is absorbed from the air along with water from various sources, mainly the soil, and together the elements carbon (C), hydrogen (H) and oxygen (O) are provided. As is discussed subsequently, in addition to these basic elements, some 16 essential nutrients are also required for a crop to thrive: three major nutrients, four secondary nutrients and 12 micronutrients²¹. During the past half century, there has been a depletion of the level of micronutrients present in plants and thus available to those creatures who eat them, including humans. There is a sanguine quote²² from Prince Charles, who runs an organic farm on his Highgrove Estate in Gloucestershire:

"The New Scientist recently reported alarming research results from a study of the long term effects of the so-called 'Green Revolution' in South Asia. New plant varieties fed with high levels of artificial fertiliser have dramatically increased food production, to no-one's surprise. But it now becomes clear that those intensively grown crops are nutritionally deficient. They lack vital trace elements and minerals, particularly iron and zinc. This deficiency has been passed on through the food to such an

extent that an IQ loss of 10 points has been observed in a whole generation of children who have a diet based largely on crops grown in this way."

Potentially, this is very a serious matter, and I note that Dr Elaine Ingham, of the Rodale Institute, claims that the nutrient values of foods are lower by a factor of 10 than those grown in the 1920s²³. She attributes²⁴ the obesity epidemic in the USA, and more widely the western world, to a craving of human bodies for essential nutrients, needing to consume more (micro-) nutritionally-deficient food in order to get them, but ingesting more calories in the process. Other factors are probably important too, including societal changes, the wide availability of cheap food rich in sugar and fat, and a modern tendency to "graze", thus continually consuming calories.

As plants grow, they remove these essential elements to a varying degree from the soil, and rainwater leaches out more, so from time to time they need to be replenished. In conventional farming/gardening, this is usually done by adding artificial fertilisers. In permaculture systems, plants die and rot-down and the nutrients are returned to the soil as part of the natural recycling process. The availability of nutrients and their uptake by plants is assisted by mycorrhizal fungi (Figure 6) which are found in the rootballs of most plants. The three major nutrients are nitrogen (N), phosphorus (P) and potassium (K). Nitrogen is required for healthy stems and leaves, and is an essential component of the amino acids which form the proteins, and of the chlorophyll molecules that harvest light to drive photosynthesis. It is normally taken up into plants in the form of nitrate (NO_3^-) and to a lesser degree as ammonium ions (NH_4^+). Nitrates are easily leached from soil by rainfall during the winter, but in spring, when the soil warms, nitrogen is extracted from the air and converted to nitrate by nitrogen-fixing bacteria. When the soil is waterlogged, denitrification by anaerobic bacteria occurs. For this reason, plants grow better in well drained soil where air can percolate through it. Earthworms play a vital role too, by burrowing through and processing soil. This increases the availability of soil nutrients and creates drainage channels and spaces for root-systems to grow into.

Phosphorus is taken up as orthophosphate ions (H_2PO_4^-), and is a critical component of the nucleic acids, DNA and RNA. The ATP-ADP energy-transfer process within plant cells requires phosphorus. The element is moved around within the



Figure 6 Root-tip mycelia of the "Amanita" type. Source: <http://biomedcentral.com/1471-2105/6/178>. Credit Thergothon.

plant, being recycled from older parts to points of new growth. The CO_2 , released during respiration, reacts with water to produce carbonic acid and this assists the uptake of PO_4^{3-} by plant roots. A critical factor in the mobilisation of phosphorus in soil is the conversion of PO_4^{3-} to more soluble protonated forms, HPO_4^{2-} and H_2PO_4^- , which depends on the availability of protons. Thus, the presence of carbonic and other acids, can solubilise phosphate from insoluble forms, *e.g.* in combination with Ca^{2+} , Mg^{2+} , Al^{3+} , $\text{Fe}^{2+/3+}$ and with other metal cations. The secondary root-system provided by mycorrhizal fungi greatly extends the reach of the primary roots and more effectively removes the phosphate anions from the insoluble soil salts. Particular types of both bacteria and fungi are known that can solubilise phosphate, and there is evidence for a symbiotic relationship between endomycorrhizal fungi and phosphate-solubilising bacteria – the phosphate must be absorbed rapidly, before it is reconverted to an insoluble form. If endomycorrhizal fungi are in the vicinity, some of this phosphorus is absorbed and delivered to the host plants. Moreover, the bacteria may travel along with the fungal hyphae in search of phosphates, and possibly the endomycorrhizal fungi are able to stimulate the plant to create more exudates (messenger molecules) to attract more solubilising bacteria. Potassium is not an essential building block of plants, but plays a central role in protein synthesis and in maintaining the balance of water. It also makes plants winter hardy and improves their resistance to disease. Taken up as K^+ ions, the ratio of N to K has an important effect on plant growth, the ideal being $\text{N}:\text{K} = 1$ for most crops and $2:3$ for root crops and legumes. Magnesium (Mg^{2+}) ions compete with K^+ for uptake, but, so long as the $\text{K}:\text{Mg}$ ratio is about $3:1$ or $4:1$, there is no problem. The four secondary nutrients are magnesium, calcium, sulfur and silicon. Magnesium, as Mg^{2+} ions, is the key metal element in chlorophyll, where it forms the centre of the molecule and its light-absorbing apparatus. It is also involved in the production of the cellular energy-transfer molecule ATP. Calcium, in the form of Ca^{2+} ions, is required for the healthy growth of new stems as it is used to give cell walls their strength. Sulfur is taken up as sulfate ions (SO_4^{2-}), and is an essential constituent of all proteins, including enzymes. Legumes have higher requirements for S than most other plants do. Silicon strengthens cell-walls in plants.

As the name implies, smaller amounts of the 12 micronutrients are required, but they, nonetheless, cannot be ignored for healthy plant growth, and are usually present sufficiently in most soils. These are sodium, as Na^+ ions; nickel, as Ni^{2+} ions; cobalt, as Co^{2+} ions; aluminium, as Al^{3+} ions; boron, as H_2BO_3^- ions; chlorine, as Cl^- ions; copper, as Cu^{2+} ions; iron, as Fe^{2+} ions; manganese, as Mn^{2+} ions; molybdenum, as molybdate (MoO_4^{2-}) ions; selenium, as selenate (SeO_4^{2-}) ions; and zinc, as Zn^{2+} ions. Artificial fertilisers are manufactured using fossil fuels and have been responsible

for massive increases in the yield of crops achieved in the last century : "the Green Revolution" (Section 20). There are estimates that the world crop yield could fall by about 75% if we stopped using them. Accordingly, it is argued in some quarters that feeding the world's population, without modern farming methods and its inputs of energy and fertilisers, would require much more land than is available. Others, however, including many aficionados of permaculture, dispute this, and argue that if the soil is brought back to its natural state there will be plenty of food for all, albeit not the cereal-based diet we are now used to. Interestingly, it seems that most of us in the UK are deficient in selenium²⁵ because, for the past 30 years, we have eaten bread made from European wheat rather than from wheat imported from Canada and the USA. The problem is the different soil, which on this side of the Atlantic is low in selenium, but is rich in the element in North America and Canada. Apparently, selenium levels can be restored to soil by adding selenium-enriched fertiliser, but this is part of the energy intensive process that we are seeking to avoid, in preparation for declining oil and gas supplies. On a personal basis, eating a daily handful of Brazil nuts maintains healthy selenium levels, but since these are grown and imported, by means of gas and oil, this is not a long-term solution. If we convert to permaculture and regenerative agriculture in general, we will need to change our diet to one with little cereal and provide more of it from nuts, fruits and vegetables, and from animals whose grazing helps to till and nourish the land naturally on open plains. Another good source of selenium is garlic, providing it is not cooked for too long which denatures the compounds that contain it.

8. Glomalin – enduring carbon glue

The name Glomalin²⁶ derives from Glomalis, an order of common root-dwelling fungi such as Mycorrhizae that colonise the root systems of plants, (Section 10) and was discovered only as recently as 1996. Glomalin itself is a glue-like protein which builds a carbon-rich sheath around the fungal hyphae (thread-like tendrils) that grow out from the fungus to form a secondary root system. Glomalin contains 30–40% of its weight of carbon, and it is thought this might account for up to one quarter of all the carbon that is contained in fertile soils. Glomalin is also a highly resistant material, and can survive decomposition in soils for anywhere in the range 7–42 years, thus making it potentially significant to carbon storage by soils. Glomalin also helps to glue together soil aggregates of other organic (humus) and mineral components, and it is believed to help in the formation of humus – a complex process called humification. Glomalin gives the soil "tilth", the discrete texture that allows experienced farmers and gardeners to "know" good soil just by

feeling its smooth granules. It is thought that glomalin may also make the hyphae sufficiently rigid they can span the air-spaces between particles of soil. It is believed that hyphae have a lifespan of days to weeks, but the much greater longevity of glomalin suggests that the current technique of weighing hyphae samples to estimate fungal carbon storage may undervalue grossly the amount of carbon stored in the soil. Sara Wright, the discoverer of glomalin, and her colleagues discovered that glomalin makes a far greater contribution of nitrogen and carbon to the soil than is made by hyphae or other soil microbes²⁶.

Dr Christine Jones, who is an independent scientist based in Australia, proposes that changes in farming methods to those of "regenerative agriculture" are necessary for the full carbon-capture potential of soil to be realised, particularly for Australian soils. She is promoting "liquid carbon pathways", in which plants pump stable carbon-rich compounds into the soil²⁷, as part of a symbiosis with root fungi, which, in return, syphon nutrients and water from the soil back to the plant *via* their extensive hyphae systems. The relationship between the glomalin and the humus is also symbiotic, since the glomalin contributes to the humification process and the humus increases the overall fertility of the soil. Humus is an important material in the retention of water in soil. Dr Jones thinks that the assistance of the humification process by glomalin is a reason that the accumulation of carbon in some Australian soils is far higher than had previously been thought possible. However, she stresses that farmers may need to rethink their farming practices, to derive full benefits from the process. She is of the opinion that the answer lies in establishing low-input "year-long green farming" methods which maintain green, growing plants throughout much of the year'

Dr David Johnson who is a specialist on mycorrhizal fungi, at Aberdeen University has said²⁷:

"Many conventionally grown crops have little or no dependency on mycorrhizal fungi because they receive lots of inorganic fertilisers that don't warrant the carbon 'cost' of forming the relationship with the fungi, for want of a better expression. So, moving to low-input farming systems is likely to encourage plants to form mycorrhizas and therefore increase carbon allocation to this group of organisms."

It is also known that long fallow periods, heavy tilling of soil, and a number of agricultural chemicals (including nitrogen fertilisers) can damage the fungi and other forms of soil life. Now, there is a corollary line of thinking from the USA, which proposes that it is soil-depth that is critical to whether or not no-till methods actually result in carbon storage. In essence, no-till involves leaving crop residue on the surface of the soil, rather than ploughing it underneath. This saves on labour, wear

and tear on machinery, soil erosion, fossil fuels and artificial (oil and gas derived) fertilisers and pesticides, makes the soil more productive (brings it "back to life"), improves habitats for wildlife and overall biodiversity and conserves water in the soil. If the carbon input (storage) exceeds the carbon output (lost), then the method can be considered successful, or the converse if more is lost than gained. Results from no-till studies are found to vary from region to region, and for example, 40% of Ohio's cropland is good for carbon storage. Where no-till (practised on a mere 6% of the world's cropland overall, and most of that in the USA and Canada, Australia and South America - Brazil, Argentina and Chile) does not prove effective, other carbon-capture methods can be applied instead; e.g. residue mulching, cover crops, complex crop rotations, mixed farming systems, agroforestry and biochar . A survey has been carried out of no-till land in Ohio, Michigan, Indiana, Pennsylvania, Kentucky, West Virginia and Maryland by Rattan Lal and his colleagues at the Ohio State's Ohio Agricultural Research and Development Centre, where he is director of the Carbon Capture Management and Sequestration Centre. According to Lal²⁸:

"Basically, those soils that are well-drained, are silt/silt-loam in texture, warm quickly and have some sloping characteristics prone to erosion are excellent candidates for no-till. Clay soils or other heavy soils that drain poorly are prone to compaction and are in areas where the ground stays cooler may not always encourage carbon storage through no-till."

Lal concludes that, at a depth of just 8 inches, in general, no-till fields will store carbon better than ploughed fields. However, at depths of 12 inches and more, the situation may be reversed. It is necessary to "know your soil", as farmers traditionally do. "Soil" is part of a complex interactive system, and there is no simple and single strategy for all cases. The means must be tailored to achieve the optimum outcome on whatever land is being worked. The real solution is likely to be found in the sum of many smaller "solutions".

9. Actual regenerative agriculture¹⁸⁻²⁰

Agriculture needs to be made sustainable, and yet the term "sustainable agriculture", in its current industrialised context, might be considered an oxymoron. Modern farming practices are based almost entirely on fossil fuels and natural gas. Liquid fuels, refined from crude oil, are used to run tractors and other kinds of farm machinery, while methane, from natural gas, is cracked in a thermal catalytic process, called "steam reforming", to make hydrogen, which is combined with nitrogen to form ammonia, using the Haber-Bosch process. Haber received the 1918 Nobel Prize