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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 letter[1], 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 the18th 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 description[4] 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),

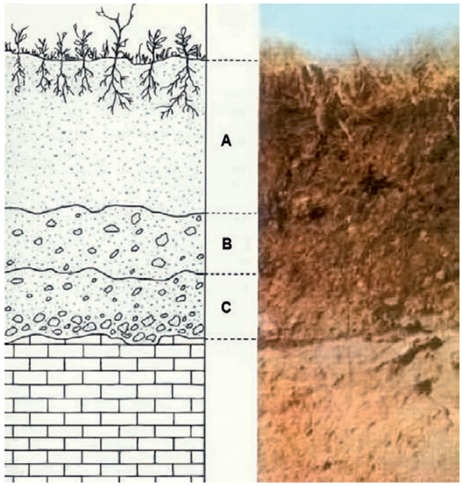

Figure 1 *Vertical structure of a typical soil. Mediterranean red soil. A, soil; B, rlaterite, a regolith; C, saprolite, a less-weathered regolith; the bottom-most layer represents bedrock. Credit Carlosblh.*

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 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 study[5] 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 m^2); 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 m^2). Since the total surface area of the root system amounts to 6,870 square feet (639 m^2), and the total surface area of the loam soil was estimated to be 560,000 square feet (52,080 m^2), 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 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 O_2 and increased in that of CO_2, because oxygen is consumed by microbes and plant roots, with the simultaneous release of CO_2. Hence, in the soil pore space, the CO_2 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, O_2 can diffuse into the soil where it is consumed, and CO_2 (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 O_2 levels fall, anaerobic bacteria may be encouraged to reduce nitrate anions to N_2, N_2O, and NO – greenhouse gases which then escape into the atmosphere. In consequence, while O_2-rich (aerated) soil is a net sink of methane CH_4 – thus reducing the concentration of a gas with an instantaneous radiative forcing factor (global warming potential) roughly 100 times that of CO_2 – when soils are depleted of O_2 and subjected to elevated temperatures, they can become net emitters of greenhouse gases.

2.6. Soil density[3]

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 soils[3]. 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: 2–20 μm;

(3) Medium pores: 20–200 μm; (4) Coarse pores: > 200 μm.

In comparison, root hairs are 8–12 μm (1 μm = 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 µm. Clay is identified as a colloid at < 1 µm. 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%.

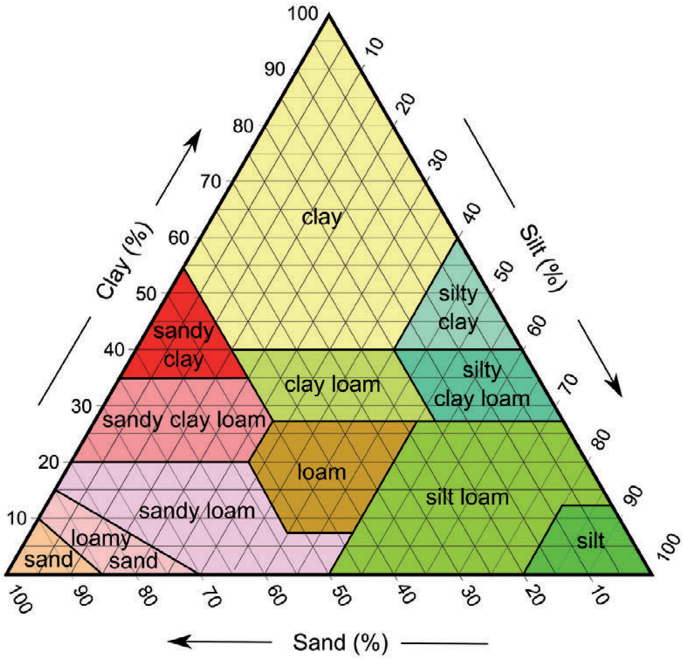

Figure 2 *A soil texture diagram - soil types according to their clay, silt and sand composition, as used by the USDA, redrawn from the USDA webpage: http://soils.usda.gov/education/resources/lessons/texture/. Credit Mikenorton.*

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 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 change 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:

$$Al^{3+} > H^{+} > Ca^{2+} > Mg^{2+} > K^{+} = NH^{4+} > Na^{+}$$

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 changes 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 O–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:

$$H_2PO_4^- > SO_4^{2-} > NO_3^- > Cl^-$$

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 colloids*[3]

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 pH < 7 are acidic, while those at 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 contains10^{-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 Ώ 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 data[8], 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 CO_2 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 Fukuota[11] (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 bestselling[14] "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 time[13]. The Gaia hypothesis, originated by James Lovelock in the 1960s[15], 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 book[16] 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 analysis[17] 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 falling[18]. 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 reckoned[19] that some 5,000–6000 km^3 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 km^3 *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 day[20], 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 km^3 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 litres[20]. 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 nutrition[21-24]

As is true of all living organisms, including humans, plants require essential raw materials to provide both the energy and building blocks for growth. CO_2 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 micronutrients[21]. 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 quote[22] 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 1920s[23]. She attributes[24] 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 mycorrizal 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.

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

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 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+}, $Fe^{2+/3+}$ and with other metal cations. The secondary root-system provided by mycorrizal 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 N: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 K: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 selenium[25] 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 Glomalin[26] 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 microbes[26].

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 soil[27], 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 said[27]:

"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 Lal[28]:

"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 agriculture[18-20]

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 in Chemistry for this work, which he developed with Carl Bosch. He has also been described as the "father of chemical warfare" for his work in developing and deploying chlorine and other poison gases during World War I. Haber's wife, Clara Immerwahr, who also held a PhD in chemistry, opposed his work on poison gases and committed suicide with his service weapon, possibly in response to his having personally overseen the first successful use of chlorine at the Second Battle of Ypres, on 22 April 1915[29]. As a schoolboy, I was taught it as simply the “Haber Process”, but Bosch has since been better recognised in this, probably the most important chemical reaction ever performed. It was Bosch who transformed Haber's bench-top demonstration into an industrial process, capable of manufacturing megatons of fertiliser and explosives. It is the fully developed system that is called the Haber–Bosch process. After World War I, Bosch extended high-pressure techniques to the production of synthetic fuel and methanol and, in 1931, he was awarded the Nobel Prize in Chemistry, together with Friedrich Bergius, for the introduction of high pressure chemistry, *e.g.* the Bergius Process for converting coal dust to synthetic diesel by reacting it, in a high boiling point hydrocarbon solvent, with hydrogen gas under pressure. Ammonia, as formed by the Haber–Bosch process, may then be oxidised using the Ostwald process to form nitric acid, and by the combination of these two materials, the fertiliser, ammonium nitrate is created. This substance may furnish a powerful explosive, to be compared with other highly nitrogenous materials such as nitroglycerine. On the morning of 1 July 1916, a charge of 60,000 lb (27 tonnes) of ammonal (a mixture of ammonium nitrate and aluminium powder) explosive was set, to start the Battle of the Somme. Upon its detonation, the resulting explosion was heard in London, some 30 miles away across the English Channel. The mine created a crater 300 ft (90 m) across and 90 ft (30 m) deep[30].

Modern farming almost entirely relies on such synthetic fertilisers in "open systems", whereas regenerative agriculture refers to "semi-closed systems": *i.e.* those in which inputs of energy, in the form of fertilisers and fuels, are minimised because these key agricultural elements are recycled as far as possible. Conventional agriculture is mostly "open", and hence large inputs are necessary since much of the materials are wasted, and it is a matter of maintaining a sufficiently productive density of fertilisers, pesticides and mechanical energy, to maintain production on poor soils with much of the living matter and natural animal life (earthworms, beetles, microbes *etc.*) gone. Indeed, modern soils have been described as dead, and only remain productive because of artificial and voluminous inputs to farming derived mainly from crude oil and natural gas. As the latter sources of energy and chemical materials begin to wane, and finally fail, so will most of the world's agriculture. Although they are usually more energy efficient overall, regenerative systems generally need higher on-farm labour than open systems do, as shown by a study[31] of 1144 farms, in the UK and Ireland. From a conventional economic standpoint, this is seen as a disadvantage and a disincentive to use regenerative systems, rather than mechanised, industrialised methods. However, in terms of re-localised communities and economies, so long as the labour costs are practicable, there may be positive benefits, in terms of the maintenance or creation of social capital and community livelihoods: *i.e.* the economy is retained within the community, possibly using some kind of local currency or barter system.

Off-farm inputs for regenerative systems are rarely zero[31], but are much lower than is the case for the open systems of conventional agriculture. SOM invariably increases as systems become more closed, and both soil quality and health appear to be related to the amount of organic matter they contain. However, the relationship between soil quality and its crop fertility varies according to the particular soil system. In specific studies, mineral fertilisers (nitrates and phosphates) and tillage were applied to compensate for the loss of soil health, and yet, as this declined further, and the soil became increasingly degraded, these mineral additions became relentlessly less effective. It might be useful if set limits were imposed on the amount of off-farm inputs, since this would provide a proactive address to various current environmental concerns: in particular, the energy costs and degree of environmental damage that is caused by agriculture. The greater amount of SOM in semi-closed systems, compared with their open equivalents, results in larger sinks for both carbon and water. Thus, both aspects of taking carbon from the atmosphere to ameliorate global warming and needing to apply less water to the land, as global water shortages ensue, are addressed symbiotically.

At the Rodale Institute, in Pennsylvania[32], the term "regenerative" has a more particular meaning, which is to regenerate the soil. Over a period of more than 30 years there, methods have been developed that not only minimise external inputs, but literally rebuild the organic components of soil and hence sequester carbon within it. According to their figures, if all of the world's crop-land were farmed using Rodale practices, around 40% of all human CO_2 emissions could be captured from the atmosphere and locked into the soil, simultaneously improving its health and productivity; a point we return to shortly, in more detail. As we shall see in later sections, if a soil is healthy and "organic", where its natural biodiversity has been restored, the energy inputs are minimal since the natural ecosystem is able to maintain and farm itself: bugs and worms aerate the soil, and nutrients are passed down through the layers of growth from tree canopy to forest mulch, to the soil food web while a diversity of natural plants naturally protects against pests, and the soil becomes better at retaining water, symbiotically at the depth of the root systems. An agricultural system is not usually "closed" entirely, because it is normally intended to grow produce that is taken off the farm. However, in a fully self-sustaining (permaculture) arrangement, full closure is possible, where those living on the farm are fed, sheltered, kept warm and supported by their own labour and by natural inputs.

Current farming practices are not sustainable[32], for various, and not entirely unconnected, different reasons. Some soils in the American mid-West contained up to 20% of carbon, in the 1950s, but this has been reduced to perhaps 2% or less now. This loss of carbon plays a significant role in breaking down the essential structure of soil, which leads to soil erosion, decreases its ability to retain water so making particular regions more vulnerable to drought, and decreases the natural nutrient value of the soil. The situation is worse than this, because the current practices of industrialised agriculture tend to break-down the soil carbon such that it is released as carbon dioxide. Indeed, recent data from the US government suggests that around 20% of American CO_2 emissions are from food production, if actual farming procedures and the manufacture and use of chemical fertilisers and pesticides are all accounted for. The figure is similar, at 19%, for the UK food industry[33]. Results from the most venerable continuous cropping test plots, in Illinois, run counter to much prevailing thinking that supplementation of soil by nitrogen fertilisers helps the soil accrue and retain organic matter. The evidence is that it does not, but merely allows plants to grow on an increasingly mineralised template, whose organic carbon quality is not improved during the process. According to the International Panel on Climate Change (IPCC), farming and the use of agricultural land may be brought culpable for 12% of anthropogenic carbon emissions (http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter8.pdf). It has been argued that the application of nitrogen fertiliser encourages the breakdown of soil fungi, so releasing its carbon as carbon dioxide to the atmosphere. Thus, we might not only lock new carbon into the soil using regenerative organic farming methods, but ameliorate a sizeable proportion of our existing emissions simultaneously. The terms "soil health" and "soil quality" are used almost synonymously, at least in the media, but in fact their semantics devolve from more specific roots. Since the quality, *i.e.* in terms of a chemical analysis of the elements present, and its biological and physical properties, does not vary spectacularly between different samples of soil, the term "soil health" might be favoured, since it represents a more holistic view of soil management, while "soil quality" is more static.

At the Rodale Institute, it has been shown[32] that regeneratively managed organic soils have increased their carbon by around 1% per year to a total of nearly 30%, over the 27 year duration of their study. In comparison, land farmed using industrial high-input methods has at best accrued no additional carbon, and in some cases the soil carbon content has declined over the same period. Soils that are richer in carbon tend to support plants that are more resistant to drought-stress, pests and disease. The sequestration of carbon in soil is principally due to the presence of mycorrhizal fungi. These fungi are able to conserve organic matter by forming aggregates of it with clay and other soil minerals. In such soil aggregates, the carbon is less vulnerable to degradation than in the form of free humus. The mycorrhizal fungi produce a highly effective natural glue-like protein, called glomalin, (Section 8) which stimulates a greater aggregation of soil particles. It is further found that more soil carbon is accreted using a manure-based system than in a legume-based organic system.

Thus, in the first Rodale trial plots[32], carbon was captured into soil at a rate of 875 pounds of carbon/acre/year, using crop-rotation with manure, and about 500 lbs/acre/year of legume cover crops. However, in the 1990s, it was shown that by using composted manure combined with crop rotations, organic systems can yield a carbon sequestration of up to 2,000 lbs/acre/year (2,245 kg/hectare/year). Contrastingly, fields worked with conventional tillage, and which relied on chemical fertilisers, actually lost 300 lbs/acre/year of carbon (337 kg/hectare/year). 2,000 lbs of carbon is the amount contained in (44/12) x 2,000 = 7,333 lbs of CO_2, and so each acre can remove this quantity of greenhouse gas from the atmosphere, per year, by trapping it in soil in fields. This amounts to 8,233 kg/ha/year. While it would not be easy to do entirely and in practice, we may recall the claim, mentioned earlier, that if all the 3.5 billion acres of tillable land could be so managed, 40% of all human carbon emissions could be sequestered in its soil. Roughly that amounts to 2,000 lbs/acre x 3.5 billion acres/2,200 lbs/tonne = 3.18 billion tonnes of carbon, which is 40% of the total of 8 billion tonnes of carbon emitted per year from burning fossil fuels, in agreement with the above estimate. [In metric units, 3.5 billion acres equals around 1.4 billion hectares or 14 million square kilometres, and is around 10% of the Earth's land area]. The USA produces roughly one quarter of the world's carbon emissions, and has 434 million acres of tillable land. If a 2,000 lb/acre/year carbon-capture was achieved, almost 1.5 billion tonnes of CO_2 would be sequestered within its soil to mitigate nearly one quarter of the entire US carbon emissions from fossil fuels. Assuming an average mileage of 15,000 miles per year and 23 miles/per/gallon, this is the emissions-cutting equivalent of taking one car off the road for every two acres of land, or removing more than half the number of cars there are on the highways of the USA[32].

Regenerative practices are also shown to result in drastic reductions in energy use, according to Rodale Institute trials. For example, a

33% reduction in the amount of fossil fuel necessary to grow organic corn/soybean is found when cover crops or compost is used instead of chemical fertiliser. Even more strikingly, by means of a no-till, organic crop rotation approach, up to 75% of the fossil fuel normally required to grow standard tilled organic crops can be saved, resulting in lower costs and fewer greenhouse gas emissions[32]. The biggest energy input in a conventional industrial corn and soybean farm is nitrogen fertiliser for corn, and then herbicides for both corn and soybean plants. The ability of regenerative farming to become a major carbon capture medium, and that it is significantly less demanding of fossil fuels, has long-term implications for global agriculture and its involvement in air-quality policies and programmes. Minimising inputs of fertilisers and pesticides means less pollution and cleaner waterways, and a reduction in environmental decontamination costs. By farming organically, the soil is regenerated to its natural condition. The input of chemical fertilisers and pesticides is either avoided or substantially reduced. These actions, taken on a single farm, extend well beyond the farm itself, and benefit the local environment and community. As the wildlands regenerate, wildlife and birds return, which help to control insects and other pests. The local rivers and streams incur less pollution from agricultural land run-off, since less fertiliser and pesticide is being applied in the first place. Local communities may also benefit from implementing recycling organic waste, which otherwise needs to be disposed of, *e.g.* on landfill sites, or becomes an environmental problem.

9.1. “Brittleness” of soil and carbon recycling

In arid and seasonally dry areas, such as in Australia and the west-American plains, continuous grazing causes extreme desertification of the land. However, a return to herding-style animal husbandry, with long recovery periods between grazings, allows the land to heal. In very dry regions, seeds must be planted deeply, so that when they germinate, the plant roots can reach groundwater. Only the hooves of animals can do this over millions of hectares. Without these actions by grazing animals, which plant seeds and recycle nutrients, dryland (arid) ecosystems become deserts for the following reasons: standing dead growth chokes the growth of new plants, instead of mulching the soil; rather than becoming well-set into the soil, the seeds instead sprout on the soil surface, and then die; as old plants die, the amount of bare ground increases, which impairs its ability to absorb and store water; this leads to rivers, springs, and wells becoming dry, and hence droughts become the norm.
Soil may be classified according to the degree of its "Brittleness" for which different kinds of animal management are appropriate[34]:

A scale has been indicated from 1 to 10: (1) Decreasingly 'non-brittle tending' (rain forest); (10) Increasingly 'brittle tending' (true desert). Brittleness[34] concerns how evenly the humidity is spread throughout the year, rather than the total rainfall. The more dry months there are, compared to humid months, the more "brittle tending" the location is. Temperate regions are more "non-brittle tending", with a fairly even balance of humidity throughout the year. In an actual rainforest, the humidity is nearly constant. In more brittle tending locations, the humidity tends to be seasonal, such that there are wetter winters and dryer summers. The more various and seasonal the humidity is, so the total rainfall (precipitation) drops, tending toward a true desert where every day is dry. Non-brittle-tending areas cover only up to one third (*ca* 50 million km^2) of the overall earth's land surface, and less than this proportion on most continents. In non-brittle regions, there is enough moisture overall to keep healthy populations of microbes, worms, beetles and bugs, which help to aerate the soil and move nutrients around. Carbon cycling is a natural feature of such environments, since grasses and woody plants are efficiently broken down by these organisms, or they are eaten by small animals that move around in small groups and contribute their manure to the system, allowing its carbon to be cycled. In conclusion, it is the humid nature of a particular environment that sustains its carbon cycling mechanism.

It is true, however, that the majority of the Earth's surface is seasonal, where there are periods of extensive growth during the growing season (as shown by the Keeling Curve[35], and its annual oscillation, where during the growing season, in the northern hemisphere, the atmospheric CO_2 concentration falls as the gas is taken up by plant growth through photosynthesis), followed by a period where not much grows and plants either die or become dormant. In order for the large volume of dry, standing vegetation and its carbon to be cycled before the next growing season, since it is now too dry for insects to take part in any decomposition processes, herds of large herbivores make their contribution. In their guts are populations of bacteria and other microbes, which convert the plants they graze into urine and dung, to be returned to the soil. As they move around in herds, their hooves trample standing plants and so provide a protecting and continually decomposing cover to the soil.

Non-brittle-tending environments are fairly resilient to the impact of human farming practices, and their carbon cycling ability is unlikely to be damaged in the long term. Any such damage that is incurred is quite quickly healed, once the particular practice is stopped. The underlying problem of agriculture is that the types of farming that are effective in non-brittle regions, have been adopted in brittle-tending areas which are less forgiving to them, and this has led to devastation of some areas. There has been the tendency for individual herds of wild and domestic animals to be reduced in size, but more spread-out in their grazing behaviour, so that the same region of land is grazed more constantly than in the natural environment. For this reason, ecosystems have broken down along with their intrinsic carbon cycling, in the majority of brittle-tending areas of the Earth. But, through an awareness of these facts, humans can change their land management practices to restore the natural brittle environment as a self-sustaining, symbiotic mechanism, by mimicking the principal key features.

9.2. Land management: regenerative grazing[34]

The same regions, notwithstanding that they have the same rainfall, the same soils and the same plant species, can be either lush or barren, depending only on how they are managed. In particular, the degree of carbon in the soil is critical, as can be noted empirically just by looking, *i.e.* the darker soils tend to contain the most carbon. Hundreds of millions of hectares of grazing land worldwide, in arid and seasonally dry areas, have been reduced to near desert, but this is no foregone conclusion. By a simple sum we may note that:

One hectare is equal to 10,000 m^2;

soil is typically 33.5 cm (about one foot) deep;

it has a bulk density of 1.4 tonnes per cubic metre;

thus the soil mass per hectare is 0.335 x 1.4 x 10,000 = 4,670 tonnes;

an increase in soil organic matter by just 1% means another 47 tonnes;

if we assume that about 50% of this is carbon, we have captured around another 23 tonnes of carbon per hectare.

This is equal to capturing 85 tonnes of atmospheric CO_2.

If grazing animals are kept in one area, they repeatedly chew fodder plants and keep them small. Because there is a virtual symmetry between the amount of carbon in the exposed (above ground) plant and that in its root system, if the visible plant is small, so are its roots. Small leaves can only nourish small roots and so overgrazed plants will wither and die, while shrubs, weeds and thorns can still reach water and thrive. It is thought that only soil is massive enough and sufficiently manageable to capture significant amounts of CO_2 over the next 30 years. All other technological carbon-capture schemes will probably take 30 years and more to be implemented and it is debatable how effective they will be. Removing CO_2 from power stations, at source, does not reduce the existing atmospheric carbon burden; neither does burying it in underground aquifers, deep cap rock formations and in exhausted oil wells, *etc.*, and it might take

100 years to know whether or not the strategy has proved effective. The outcome of simply establishing tree plantations is not certain either, since trees can actually be net emitters of CO_2 in their early stages, and may take many years to achieve their full carbon capture potential. Switching over to wind turbines and solar power does not influence existing levels of carbon either, and it is debatable at what scale, or how quickly, such renewable energy sources can be established. One alternative means, proposed for disposing of carbon, is to liquefy it and dump it on the ocean floor at depth, but this is likely to make the waters more acidic and impede shell formation in creatures that live there, thus impacting on the whole ecosystem.

According to the United Nations Food & Agriculture Organisation[36] "Soil organic carbon is the largest reservoir in interaction with the atmosphere." This sounds promising, especially when we note that there are 650 gigatons (Gt) of carbon present in vegetation; 750 Gt in the atmosphere and 1,500 Gt in soil. The US Department of Energy concludes:"Enhancing the natural processes that remove CO_2 from the atmosphere is thought to be the most cost-effective means of reducing atmospheric levels of CO_2." The total area of grazing land on Earth accounts for two thirds of the total land surface, which amounts to 2/3 x 150 million km^2 or 100 million km^2 (10 billion hectares). We can thus make a simple sum and conclude that an extra 1% of carbon at 23 tonnes/hectare x 10 billion hectares = 230 billion tonnes of carbon stored. Now we are clearly not going to cover 2/3 of the Earth's surface with grazing animals, even if we move them around to allow grazing-crops to grow, and we are looking toward appreciable efforts in permaculture on the 15 million km^2 of arable land there is available. However, the point is clear that a large amount of carbon could potentially be extracted from the atmosphere by the simple act of moving grazing animals around. As a form of land management, this has other environmental benefits too. For example, in Zimbabwe, where a river used to run freely, the effect of overgrazing has resulted in a barren land which flash floods when heavy rains fall. There is a severe loss in biodiversity; livestock are starving and most of the wildlife has gone. In contrast, a neighbouring river flows almost continually, drought is rare and wildlife has reappeared in large numbers. Again, the only difference is livestock management. The result is that the ability of the land to absorb and retain water is increased; new soil is being created; new plants are bedding-in; there are greater yields of fodder plants; greater biodiversity and a healthier landscape overall. When the livestock are not managed, there is drought, desertification and economic hardship, because of the following chain of events: food plants are killed by overgrazing; new plants cannot become established successfully; less forage grows; the majority of sunlight and rain are wasted on bare soil; soil loses its ability to absorb and hold water; streams and wells go dry; livestock production falls; and wildlife disappears[34]. The actual amount of rain falling is not the critical parameter, but what happens to the water once it has reached the ground. Again, using a simple illustrative sum, just 1 mm more rain captured in the soil each year means an extra litre per square metre. This amounts to 10,000 litres more per hectare, and an additional 1 million litres per square kilometre. The drought is reduced because the soil is able to discharge some of the water into rivers, springs and wells, and there is more forage for animals because the plants can access some of the water too, which helps their growth. Some experimental studies done in the USA have indicated that, by changing livestock management, the soil can be made 600% more effective in absorbing water. If the useable rainfall is increased in this way, even formerly arid and barren lands can be restored to fertility. In a 450 hectare pile of tailings from an old copper mine in the Sonoran desert to the east of Phoenix in Arizona, life is being restored by grazing cattle on it. As they graze, the cattle push hay and manure into the mine tailings, and have created a layer of soil up to 30 cm (one foot) thick, where there was none formed more than 60 years in the past, simply by leaving the area exposed to Mother Nature. The soil captures water and retains it in the root zone, so rendering it accessible to plants, which flourish, all the while capturing CO_2 from the atmosphere through photosynthesis. Presumably the levels of copper are insufficient to cause problems of toxicity either to plants or cattle. The strategy has proved successful even where "hydroseeding" efforts have been literally washed-away by heavy rain[34].

In northern Australia, unmanaged (free-roaming) cattle and donkeys destroyed a former wetland to the extent that, by 1992, there was not enough food growing per hectare to feed one cow for a single day. The usual consequences occurred: wildlife disappeared for lack of anything for them to eat; most of the rain evaporated and plants could not establish themselves, as a consequence of dry soil and overgrazing. However, by 2001, this same area was producing 800–1,100 cow-days worth of fodder, as harvested in three grazings by managed livestock. In summary, without grazing animals to plant seeds and recycle nutrients, dryland ecosystems desertify because: standing dead growth chokes plants, instead of mulching the soil; seeds sprout on the soil surface, then die; as old plants die, bare ground increases; bare soil loses its ability to absorb and store water; rivers, springs, and wells go dry; droughts become the norm. In arid areas, seeds must be planted deeply or seedlings will die before their roots reach reliable water. Only the hooves of grazing animals can do this economically over millions of hectares. Returning to herding-style management with long recovery periods between grazings heals the land.

As an example[34], I note that unmanaged grazing stressed forage plants in a pasture land regions in New Mexico, USA to the extent that, by 1986, 11% of it was snakeweed. The standard practice of killing weeds using chemical weed-killers, in fact, would cement the underlying problem of low biodiversity and 46% bare ground. However, by 1990, a strategy of regenerative grazing had reduced the bare ground to 30%, and the snakeweed to 1%. Nine, previously dormant, perennial grass species also reappeared. A well that had been dry since the 1950s was found to have 3 metres (10 feet) of water in it. The size of the herd and beef production doubled per hectare, while the cost to produce a kilo of beef decreased by 50%. Regenerative grazing can also be the most effective means to restore biodiversity to a region. For example, David Ogilvie's management of the U Bar Ranch in New Mexico has created a habitat that supports more endangered southwestern willow flycatchers than any preserve. The U Bar also hosts the most prolific population of flycatchers known to exist, and most interestingly they seem to thrive particularly well in areas that they share with cattle. In 2001, 132 pairs of southwestern willow flycatchers were counted on the U Bar Ranch in comparison with a mere seven in two nearby wildlife preserves, with a similar combined area, but which are not grazed by livestock. The U Bar also has more common blackhawks and spikedice (as respective examples of threatened bird and fish species) than anywhere else, and large numbers of various other rare species. There is also the greatest density of nesting songbirds known in North America and an unusually high ratio, 99:1, of native to exotic fish. Many habitats are now too badly damaged to support the wildlife that once maintained them, and simply protecting them or deliberately reintroducing wild species is usually unsuccessful. However, even in these circumstances, managed livestock practices can successfully restore, then maintain, these areas until their wildlife populations recover[34].

9.3. Pulse grazing

The term pulse-grazing was coined by Colin Seis[37], who farms 4000 head of sheep and cereal crops, including oats, wheat and lupins on 'Winona', an 840 hectare (2075 acre) farm in the central tablelands of New South Wales. In 1933, they were one of the first farmers in the area to use superphosphate fertiliser, which initially doubled wheat yields. However, it became clear to the family by the 1970s that their farming methods could not be sustained, when falling wool prices and rising superphosphate costs meant that fertilising pastures was not a long-term option. The initial benefits of adding fertilisers were no longer being recouped, and plants were responding less vigorously to fertilisers, meaning that increasingly larger amounts had to be added to achieve the same yields.

Progressive dry land salinity, soil acidity and annual weeds were also encroaching on their land, and in 1979 the farm was destroyed by a major bushfire. Because they did not have enough money to simply "rebuild", Colin looked for more traditional approaches in family history records, where he discovered that the original landscape of the tablelands had been grassland and scattered trees. He reckoned that the native grasslands must have had an innate ability to control ground water and not accumulate salinity. Colin decided to combine grazing and cropping, rather than considering them as separate activities, and to stop using superphosphate fertiliser. He also changed from set grazing practices to a cell grazing method, *i.e.* "pulse grazing", where a herd of up to 3000 sheep is moved around his 51 paddocks (average size 16 hectares), to spend 2–4 days in each one before moving them on. After 3 months, to allow the native grasses to recover, the ground is grazed again. Colin also took the line that it made no sense to plough a pasture to plant a crop on the land[37]:

"It takes 6 months to prepare a paddock to grow a crop for 2 or 3 months, and then it might be affected for 10 years afterwards, all for 2 or 3 months feed," said Colin. *"It's lunacy to do that. There had to be a better way. My father always disliked ploughing up pastures to plant crops, but in his time the technology just wasn't there to do it differently."*

Colin and his neighbour, Daryl Cluff, believed it would be possible to sow winter cereal crops directly into summer-growing native perennial pastures that were dormant through winter. The pasture could be grazed right up to the point of sowing, and stock could be put back on the pasture after harvest to graze stubble and green perennial grasses. They found it works. Sheep are put into the pasture at a density of 70–80 animals per hectare for up to 6 days to reduce the bulk of grasses. This is repeated 30 days later. The sheep control weeds, open the grass canopy, mulch the grass and help feed soil microbes. One week after the sheep are removed, a low rate of knockdown herbicide is applied to control annual weeds, and the area is almost immediately sown with zero-till seeding equipment. A one-pass operation places oat seed and fertiliser in 30 cm rows with very little disturbance to the surface ground cover. Conservation cropping protects the soil flora and fauna and promotes biodiversity, *i.e.* it restores the health of the soil. Colin's intention is 100% ground cover, 100% of the time, including under crops. The Department of Agriculture found that the pasture cropping method of farming can be more profitable than traditional methods, and that the profit-margin would depend on the current level of grazing overheads (such as pasture seed, pasture maintenance and casual labour). Winona's soils are becoming healthier as a result of the grazing and cropping methods with lower inputs of fertiliser, and some crops have been grown using no chemicals at all. Colin thinks that nutrients are now cycling through the soil and releasing phosphorus naturally, since 20% of the pastures are still healthy sub-clover[37].

"Pasture cropping and pulse grazing have dramatically increased pasture biodiversity," said Colin. "The pulse grazing definitely improves biodiversity in perennial grasses, but I was surprised to find that the pasture cropping took it to a whole new level. We had huge increases in plant diversity and numbers after just one year of sowing a crop that way. It was a spin-off that we didn't expect at all, that the crop would actually stimulate the pasture. Looking at grasslands and soils is the key to turning salinity problems around. If we can get groundcover on the saline parts of the property, then they can actually be very productive, especially in dry times. I believe our native pastures act like huge sponges, holding water in suspension. If we can get back to that, I think a lot of our salinity problems would disappear.

"Don't spend a cent. Put your animals into large mobs and start moving them around the infrastructure you already have. Focus on native perennial pastures – they've evolved here and obviously they are the best plants for Australia. Throw away your disc plough – if you're going to grow crops, use zero-till. Only kill the weeds that are competing with the crop, leave everything else alive. The hardest thing to change in all of this is to change your thinking. Once you've done that, the rest is easy," he said[37].

10. Mycorrhiza – "magic fungi"

Mycorrhizae[38] are highly specialised organisms classified among the order Glomales, and are found closely associated with the root systems of around 95% of all plants. The term mycorrhiza derives from the Greek for *fungus roots*. The fungus may colonise the roots of a host plant either intracellularly or extracellularly and is an essential part of living soil. The relationship is a symbiotic one, in which both organisms derive benefit. Because the fungus cannot perform photosynthesis, *i.e.* fix its own carbon, it receives some of the carbohydrates (sugars such as glucose and sucrose) which the plant passes down to its roots. In return, the plant receives essential mineral nutrients, and also water, from the fungus, *via* its very extensive mycelium which reaches out much more extensively than the plant roots, and effectively forms a secondary root system (hyphae). Alone, plant roots may be ineffective at imbibing immobile phosphate anions, for example if they are present in alkaline soils (pH > 7). On the other hand, the mycorrhizal fungus can access these phosphorus sources *via* its mycelium, and pass them on to those plants they have colonised. In response to the presence of phosphate, the fungus releases oxalic acid which converts phosphate to "orthophosphate", which is the principal form[39] in which plants take up phosphorus: $PO_4^{3-} + 2H^+ \quad H_2PO_4^-$. Mycorrhizal mycelia have far narrower diameters than even the smallest root, and can hence penetrate more of the soil, so allowing absorption over a greater surface area. The permaculture authority, Geoff Lawton, (a former student of Bill Mollison), has called soil fungi the "teeth of the forest", while the forest floor is the mouth.

Mycorrhizal plants are often more resistant to diseases caused by microbial soil-borne pathogens, and more readily survive under drought conditions, because they can access water more easily[40]. Tilling soil damages the mycelium and so they are best preserved using no-till methods, such as permaculture. The two principal forms of mycorrhizae are Ectomycorrhizae and Endomycorrhizae. The Ectomycorrhizal fungi have a thick network of cells which form a sheath around the root hairs of the associated plant, and do not penetrate into the cells of the plant, hence the prefix 'ecto', meaning outside (in contrast 'endo' means inside). The Endomycorrhizal fungi are a more primitive form, and have hyphae which penetrate the root cell walls and on into the cell membrane. They do not, however, enter the protoplasm. Inside the root cells, the fungal structure may be tree-like, with fine hair-like hyphae that can access plant nutrients and water through an extensive secondary root system. One well-known Ectomycorrhizal fungus is the truffle, readily sniffed-out by a pig on a lead. There are several species of truffle, the best known being the Black Truffle *T. melanosporum* which grows exclusively with oak trees. It is found that, when they are grown in a sterile medium, plants often do not thrive without a beneficial fungal comrade. To allow new plants to become established more quickly, or to get a better growth of existing plants, fungal spores can be added to the soil.

Mycorrhizal symbiosis was discovered around 100 years ago[38], and since then there has been much speculation as to its role in nitrogen fixation by plants. While there are numerous reports of the fixation of atmospheric nitrogen by mycorrhizal fungi in the earlier literature, it is now thought that only prokaryotic organisms can fix atmospheric nitrogen, and that both ecto- and endomycorrhizal fungi lack this capacity. It is important to note that many vascular plants possess both mycorrhizae and nitrogen-fixing symbiotic organs, *e.g.* legumes with rhizobial nodules and non-legumes with actinorrhizal nodules, with mycorrhizae that are either ectotrophic or endotrophic, or both. Nitrogen fixation in forests, and other natural ecosystems, has recently been attributed mainly to associative-symbiotic bacteria, *i.e.* bacteria living in the rhizosphere or close proximity of plant roots. Since the roots, in fact, are usually also infected by mycorrhizal fungi, a new concept of mycorrhizosphere has been introduced. The exact nature of the relationships between mycorrhizal fungi and nitrogen-fixing bacteria within the mycorrhizosphere are, as yet, not well understood.

Nitrogen-fixing bacteria have actually been found inside the fungal mantle of ectomycorrhizae, and so the circumstantial evidence is overwhelming that an interplay occurs between the two organisms, presumably to their mutual benefit. Permaculture systems (Section 12) are thought of as nature acting on a series of overlapping layers, where nutrients that are captured at one level are passed down to another, or may form part of the symbiotic mechanism of an individual layer. The forest garden principle, which is a series of clearings cut into forest, is the supreme example of this action of biodiversity, where each layer and each organism feeds another, forming a balanced ecosystem, throughout.

As a rider to this, by applying phosphate fertiliser to organic soil, initially the crop yield is increased, by the superabundance of phosphorus. Then the growth of the fungus is no longer encouraged by the secretion of exudates from the plant roots, since the plant no longer needs its natural, symbiotic source of phosphorus and the fungus begins to die back.Thus, the soil becomes impoverished in its native biota, and to grow a decent yield requires that more and more phosphate fertiliser be applied. The situation has been regarded as being akin to an addiction, Rebecca Hosking has recently shown[41] that by spraying fields with "compost teas", the soil is inoculated with microbes, and this kick-starts the re-establishment of the soil food web. The rider is that it takes some time to regenerate the soil, and until it does, lower yields must be suffered.

11. Six ways mushrooms can save the World?

A mycelium (plural mycelia) is the vegetative part of a fungus and consists of a mass of branching, thread-like tendrils (Figure 7) called hyphae[42]. Fungal colonies composed of mycelia are found in soil, and on or in many other substrates. Usually, a single spore germinates into a monokaryotic mycelium which cannot reproduce sexually; however, when two compatible monokaryotic mycelia join and form a dikaryotic mycelium, that mycelium may form fruiting bodies such as mushrooms. A mycelium may be minute, forming a colony that is too small to see, or it may be extensive, as expressed in the following quote:

"Is this the largest organism in the world? This 2,400-acre (9.7 km^2) site in eastern Oregon had a contiguous growth of mycelium before logging roads cut through it. Estimated at 1,665 football fields in size and 2,200 years old, this one fungus has killed the forest above it several times over, and in so doing has built deeper soil layers that allow the growth of ever larger stands of trees. Mushroom-forming forest fungi are unique in that their mycelial mats can achieve such massive proportions."

Paul Stamets, Mycelium Running[43]

It is through the mycelium that a fungus can absorb nutrients from its environment, which it does *via* a two-stage process. Firstly, the hyphae secrete enzymes onto a food source, which break down polymers into monomer units, which are then absorbed into the mycelium by processes of active transport and facilitated diffusion. In both terrestrial and aquatic ecosystems, mycelium plays a vital role in the decay of plant matter, and it contributes to the organic component of soil. The mycelium of mycorrhizal fungi acts in symbiosis with a plant whose roots it has colonised, (Section 10) and acts as a conduit for water and nutrients such as phosphorus to the plant, receiving, in return, sugars from the plant which it produces through photosynthesis[44]. Some resistance is conferred against plant pathogens by mycelium, and which also provide a food-source for many soil invertebrates such as beetles and worms. Since one of the primary roles of fungi in an ecosystem is to decompose organic compounds, it is proposed that fungi have the potential to clean-up pollutants such as petroleum (oil) and pesticides from the environment as part of a bioremediation strategy.

In a lecture[45], Stamets proposed that there are "Six ways mushrooms can save the World", from which I have summarised the following: He proposes that the Earth has now entered the sixth major extinction cycle (6X) on the planet and it is debatable whether humans will survive or not. Mycelium infuses all landscapes, is extremely tenacious and can bind together 30,000 times its own mass of soil, giving rise to the humus soils across the continents of the earth. Amazingly, there is a multi-directional transfer of nutrients between plants, mitigated by mycelium - thus the mycelium is the "mother" that gives nourishment from alder and birch trees to hemlocks, cedars and Douglas firs. Humans are related closely to the mycelia, and we both inhale oxygen and exhale CO_2. Indeed, we are closer to fungi than we are to any other kingdom of life. A group of 20 biologists, researching into eukarotic microbes, published a paper in which was proposed "opisthokonta": a super-kingdom that connects animalia and fungi. Indeed, humans and fungi share the same pathogens. Since fungi resist the action of bacteria through natural antibiotics, our best antibiotic drugs come from fungi. It is only once they have spored (sporulation) that fungi rot, and the sequence of microbes that grow on rotting mushrooms is vital for the overall health of the forest. The microbes give rise to the trees and create the debris fields that feed the mycelium, which spreads underground. In a single cubic inch of soil there can be more than eight miles of cells. Fungi were the first organisms to come onto land some 1.3 billion years ago, followed by plants several hundred million years afterwards. The two realms are connected mechanistically: namely that the mycelium produces oxalic acid (two CO_2 molecules joined together) and many other kinds of acid and enzymes. The acids produced react with

Figure 7 *Fungal mycelia. (Mushroom roots). Credit http://nl.wikipedia.org/wiki/User:Lex_vB.*

rock, releasing nutrients such as phosphate, and form calcium oxalate and other salts, which causes the rock to crumble and is the first step in the generation of soil. Hence fungi and mycelium sequester CO_2 in the form of calcium oxalate.

Specifically, the six solutions are[45]:

(1) To decompose diesel and other petroleum waste *e.g.* as in an oil spill. Notably, the mushrooms grow well and decompose even toxic polyaromatic hydrocarbons (PAH). The ecosystem is restored too, since the fungi act as vanguard species that provide an entrance for other biological communities.

(2) As biological filters called "bunker spawn" – to remove *E. coli* or other biological undesirables, from downstream water from farms or factories. Mycelium can also be used to filter the silt run-off from logging roads.

(3) Mycelium and its metabolites are active against smallpox viruses, and both flu A viruses – H1N1, H3N2 – and flu B viruses. In a blend combination, a selectivity index of greater than 1,000 was found against H5N1.

(4) Extracts of mycelium are powerful insecticides, and are active against carpenter ants, termites and fire ants, which has huge implications to prevent insects from eating wood-framed houses, which are common in the USA.

(5) Paul Stamets has invented the Life Box, which is a means for producing various seeds, fungi, crops, beans or corn, or even an old growth forest. A box, in which is initially supplied shoes, say, but unlike the standard lifeless "cardboard box", which may simply be recycled as cardboard, the corrugated structure of the life box having been previously seeded, thus generates new plant life if simply put outside and watered.

(6) In the latter example, the mycelium converts cellulose into fungal sugars, and so offers the potential for ethanol production from the sugars. The "fuel" is called Econol. Growing mycelium in soils helps to regenerate the soil and acts as a carbon storage system.

There is much to be recommended here and I feel that mycelia could be a useful member of the family of biological methods with which to restore soil health and capture unwanted atmospheric carbon, along with other methods of regenerative agriculture, and also to produce useful chemicals without the need for crude oil as a raw feedstock.

12. Permaculture

This topic was introduced in Section 4. Permaculture[9,10] is based on establishing a “good design”, and may be applied to any new project or aspect of one’s life, not only to growing food. However, as alluded to throughout the discussion in the previous sections, it may be described as a low impact method which uses perennial cultivation methods to produce food crops, in harmony with nature. This might sound a little "new age", but it is worth noting that much of the energy used for mechanised agriculture is employed to drive processes that restrain the land from returning to its natural wilderness. If productive agriculture can be performed at a minimum of the energy input required by conventional farming methods, this constitutes a far more naturally harmonious process. Certainly in developed nations, food is not grown locally but is delivered from other parts of the country, and much of it is imported globally. The monoculture system, that is a feature of modern farms, drains nutrients from the land, which is fed with artificial fertilisers, and many of the natural flora and fauna no longer exist. Such single crops are vulnerable to pests and diseases: for example, the Irish potato famine was a result of Blight disease, which rapidly devastated the single species of potato which was being grown at the time, and was the staple food for the poor. Previous generations grew cereal crops, but since the potato was more robust to changes in the weather, and produced about four times as much food per hectare, it became the crop of choice. Production of biofuels is diverting more land to the growth of monoculture crops, and along with the eradication of vast swathes of rainforest, is far less “green” as a fossil-fuel alternative than is frequently claimed. The necessary competition between growing crops to feed humans and animals or cars has also driven-up the price of staple foods like wheat and corn.

The permaculture approach resonates philosophically with the Gaia hypothesis[15], first introduced by Lovelock. He has himself appeared less green of late, for example in his conviction that building more nuclear power stations is a must, to curb fossil carbon emissions and so to ameliorate global warming. Through "Gaia", the whole Earth is viewed as a single large organism with many interdependent systems, that cooperate through feedback mechanisms, to maintain a viable equilibrium. Human disturbance of this balance of nature is believed to have resulted in a loss of biodiversity, and raised climate change as a spectre of the apocalypse. Although it would undoubtedly mean a complete revamping of the modern lifestyle, especially in the West, it is thought that a population density of 6–10 people per acre might be supported through permaculture, (see section 15) and in excess of the number that our current cereal-based food economy can sustain. The word permaculture contains elements of *permanent agriculture*, as well as *permanent culture*, in an expression of its underlying philosophy. The Australians, Bill Mollison and David Holmgren coined the concept in the 1970s *via* a series of publications, in which they addressed the matter of sustainable (low-input) farming (and living) by means of careful design to create "living spaces" that are entirely harmonious with their surroundings, including perennial agricultural systems which capture water, and the growth of a diversity of species as an overall food source. This is an entirely reasonable strategy, since much of our labour and energy inputs are expended to hold back nature, and to support a bubble whose lifespan is limited by the availability of cheap resources, such as oil, natural gas, coal and uranium. Within the natural living space, all materials for living quarters and fuel are provided fully from sustainable, locally sourced materials, *i.e.* what can be grown within the community. One tenet of permaculture is that “the problem is the solution”. As an example, we may consider a surplus of slugs (the problem) that are consuming cabbages that humans want to eat. However, the problem can be viewed alternatively as a lack of ducks, so that by increasing the number of ducks (the solution), the slugs are eaten, and not only are the cabbages saved, but more eggs are produced for human consumption. It is both amusing and useful to apply this kind of mental repositioning to other challenges and “problems” that can be thus recast as advantages.

Two different interpretations of permaculture have been identified[9,10]:

(1) Original permaculture, which aims to create a forest garden in which plants and animals (including humans) live in harmony.

(2) Design permaculture, which is a kind of compromise, and uses natural processes to create a sustainable living space ecosystem following ecological principles in a more structured way.

The latter is a significant and necessary adaptation of the "pure" notion, since it is unlikely that some creator will recreate, from scratch, a Garden of Eden (perhaps the first self-maintaining forest garden, or the idea of it), but it can be used in the less adaptive and more prescriptive integrity of a city (Sections 16 and 17). Original permaculture attempts to closely replicate nature by developing food layers which closely resemble their wilderness equivalents. While the end result of Design permaculture may lack the "natural" appearance of a forest garden, the design rests on similar ecological principles. The strategy chosen is derived from observation and imitation of the natural world. Obviously, this appeals to the "back to nature" movement and its philosophy to reject the industrialised world, which it perceives as the source of all evil. In reality, it is the means for industrialisation that is rejecting us, since our immense use of energy is but a brief fling when set against the timescale of human existence. To create a permaculture (forest) garden, a layer system is followed where farming is organic and the source of irrigation is rain water. The level of cultivation, including tilling, is minimised, according to a minimalist use of energy, including human and animal labour. Perennials (year round plants) provide leaves, roots (which regenerate the health of the soil) and fruit. The upper storey of tree-cover can provide a staple food, *e.g.* fruit or nuts, while its foliage can be fed to animals or eaten by humans; within the symbiosis of flora and fauna, bees naturally pollinate flowers and provide honey in the process. If there is sufficient living space, pigs and chickens can be kept too, since this is not a necessarily vegan lifestyle. Indeed, in nature, animals and plants have a mutually beneficial relationship. By maintaining a high density of desirable plants, unwanted plants, weeds, *etc*. are out-competed and kept down in volume. By means of a diversity of plant types, pests are reduced further by competition rather than being encouraged as they are in monoculture farming.

As two distinct examples of the success of this approach on the scale of nations, we may consider Ethiopia[46] and Cuba[47]. The Ethiopian soil is poor and there is little rain, thus three mutual kinds (levels) of plant growth are employed, all of which provide food. The upper canopy creates a microclimate that tends to retain moisture, and the plant roots grow at different depths, so they do not compete directly for water in the same soil space. Cuba[47] is a nation which was forced to adapt when the Soviet regime collapsed in 1989, and they could no longer rely on gifts of artificial fertilisers, pesticides and fuel for intensive farming, as a reward for providing the Russians with a missile and observation base conveniently close to the USA. The fuel shortages curtailed the transport of crops grown in the rural areas, to the cities. Hence a more localised approach has been adopted, using permaculture techniques, known as urban farming, in which many small land spaces and even rooftops have been turned into growing areas. Cuba is the more salient example in terms of a necessary adaptation of an industrialised society to a low-input arrangement, which is precisely the challenge now facing the West as it must confront the depletion of reserves of cheap oil and energy *per se*. It is probably little coincidence that modern permaculture found a voice in the 1970s, when the first (politically driven) oil crises (oil shocks) materialised. It became clear that, in order for people to be fed, they must find an alternative to industrialised agriculture which without large and constant inputs of cheap liquid fuels and natural gas would collapse. Without these inputs it could not have risen to its monster proportions and its products of monoculture. Permaculture emphasises the exact opposite, since it is both low-input and necessitates crop-diversity. David Holmgren is a major innovator in permaculture design, which is optimised to achieve the productivity of natural ecosystems, and to use renewable (nature's own) energy sources (wind, gravity, solar power, fires, wave, and so on), to satisfy human needs for food and shelter. A summary of some principles of structure and design follows.

12.1. Layers (the forest garden).

Layers[10] are one of the principal design strategies for sustainable functional ecosystems that may be used to provide for humans. A mature ecosystem is thoroughly holistic and contains a vast network of interactions between its separate component elements, which include trees, understorey, ground cover, soil, fungi, insects, and animals. The basis of the later concept is that plants grow to different heights, meaning that a diverse community of flora (food forest) may flourish over a relatively small area, because each layer is piled one on top of another, thus maximising the third dimension of space. There are seven identified layers in this system (Figure 8):

1. The canopy: the tallest trees in the system. Large trees dominate but do not saturate the area, *i.e*. there exist patches where trees are absent.
2. Low tree layer: dwarf fruit trees, citrus trees and other short trees
3. Shrubs: a diverse layer that includes most berry bushes
4. Herbaceous: these may be annuals, biennials or perennials; most annuals will fit into this layer.
5. Rhizosphere: root crops, including potatoes and other edible tubers.
6. Soil surface: cover crops to retain soil and lessen erosion, along with green manures to add nutrients and organic matter to the soil, especially nitrogen.
7. Vertical layer: climbers or vines, such as runner beans and lima beans (vine varieties).
8. An eighth layer, Mycosphere (fungi), is often included.

In a mature ecosystem, manifold and complex interactions are established over a long time. For example, in an ancient woodland, there are mutual relationships between trees, understorey, ground cover, soil, fungi, insects and other animals and birds. Plants grow at different heights, and set their roots accordingly at different depths into the soil, thus sampling different regions of nutrients and water and avoiding unhelpful competition.

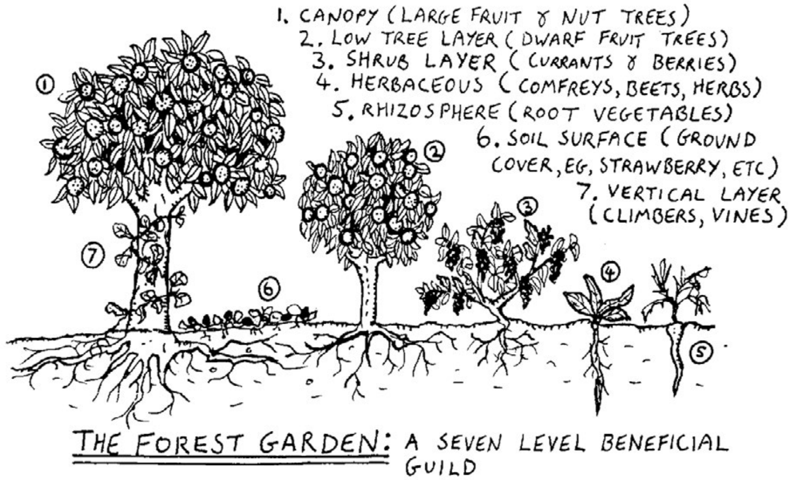

Figure 8 *The seven layers of the forest garden. Credit Graham Burnett.*

Comfrey is an important plant, called a "dynamic accumulator", due to its deep and extended root system, which allows it to draw-up nutrients (particularly, potassium and phosphorus) from further down in the soil, and contribute them to the forest garden. This is biodiversity in action, namely that a diverse and interactive community flourishes in a relatively limited space. Furthermore, plants come into leaf and fruit at different times of year, "come into season" as it was called before everything was available throughout the year by energy-intensive growing methods and global imports, thus different "depths" of time are sampled too, again avoiding detrimental competition between the different species. In the absence of following growing seasons, we have lost yet more of our connection with the flow of nature. We are less aware of the changing seasons of growth throughout the course of the year, and the rich and unique bounty that each one brings. The "three sisters" method, known to the Native Americans, is an example of "companion planting", where corn, beans and squash are grown together[9,10]. The corn provides a support for the beans to run up; the beans are nitrogen fixers which fertilise the soil and feed the corn plants; the broad prickly leaves of the squash deter large herbivores and shade the soil. Shading soil is an important aspect of permaculture since it reduces water evaporation (so less water is required to grow plants) and discourages weeds.

12.2. Holmgren's 12 design principles

These are restatements of the principles of permaculture from David Holmgren's *Permaculture*: principles and pathways beyond sustainability[10]; also see permacultureprinciples.com:

(1) Observe and interact By taking the time to engage with nature we can design solutions that suit our particular situation.

(2) Catch and store energy By developing systems that collect resources when they are abundant, we can use them in times of need.

(3) Obtain a yield Ensure that you are getting truly useful rewards as part of the work that you are doing.

(4) Apply self-regulation and accept feedback We need to discourage inappropriate activity to ensure that systems can continue to function well.

(5) Use and value renewable resources and services Make the best use of nature's abundance to reduce our consumptive behaviour and dependence on non-renewable resources.

(6) Produce no waste By valuing and making use of all the resources that are available to us, nothing goes to waste.

(7) Design from patterns to details By stepping back, we can observe patterns in nature and society. These can form the backbone of our designs, with the details filled in as we go.

(8) Integrate rather than segregate By putting the right things in the right place, relationships develop between those things and they work together to support each other.

(9) Use small and slow solutions Small and slow systems are easier to maintain than big ones, making better use of local resources and producing more sustainable outcomes.

(10) Use and value diversity Diversity reduces vulnerability to a variety of threats and takes advantage of the unique nature of the environment in which it resides.

(11) Use edges and value the marginal The interface between things is where the most interesting events take place. These are often the most valuable, diverse and productive elements in the system.

(12) Creatively use and respond to change We can have a positive impact on inevitable change by carefully observing, and then intervening at the right time.

12.3. Patterns

Permaculture design focuses heavily upon natural patterns. All things, even the wind, the waves and the Earth moving around the Sun, form patterns. In pattern application, permaculture designers are encouraged to develop an awareness of the patterns that exist in nature, how these function and how they can be best followed to meet the particular design needs of a specific site. "The application of pattern on a design site involves the designer recognising the shape and potential to fit these patterns or combinations of patterns comfortably onto the landscape".

12.4. Guilds

A guild is any group of species that exploit the same resources, often in related ways. Guilds are groups of plants, animals, insects, *etc.* that function cooperatively and effectively: *e.g.* some plants may be grown to produce food, some to attract beneficial insects and other fauna, and others to repel insects *etc*. that are harmful. When grouped together these plants form a guild – biodiversity in action.

12.5. Edge effect

The edge effect is the result of juxtaposing contrasting environments or other elements on an ecosystem. The view from permaculturists is that at the boundary between entirely differing systems, an intense area of productivity is created that leads to beneficial connections between them. For example, where land and sea meet at the coast, there is a particularly rich area that provides food, fish, water, wind, sand, *etc.* In permaculture design, the idea of an edge effect is emulated using spirals in the herb garden or by creating ponds that have undulating perimeters, as opposed to simple circles or ovals, thereby increasing the amount of edge for a given area. Edges between woodland and open areas (including hedgerows) appear to be highly productive.

12.6. Zones

Zones provide a means by which design elements implicit to human living can be organised according to the frequency of human use and plant or animal needs. Frequently visited regions (elements of the design) are located close to the house in zones 1 and 2. Less frequently visited or manipulated elements, and those that benefit from isolation (such as wild species) are farther away and assigned higher zone numbers.

Zone 0

> The house, or home centre. Here, permaculture principles would be applied in terms of aiming to reduce energy and water needs, harnessing natural resources such as sunlight, and generally creating a harmonious, sustainable environment in which to live and work. Zone 0 is an informal designation, which is not specifically defined in Mollison's book.

Zone 1

The zone nearest to the house, the location for those elements in the system that require frequent attention, or that need to be visited often, such as salad crops, herb plants, soft fruit like strawberries or raspberries, greenhouse and cold frames, propagation area, worm compost bin for kitchen waste, *etc*. Raised beds are often used in zone 1 in urban areas.

Zone 2

This area is used for siting perennial plants that require less frequent maintenance, such as occasional weed control or pruning, including currant bushes and orchards. This would also be a good place for beehives, larger scale composting bins, and so on.

Zone 3

The area where main crops are grown, both for domestic use and for trade purposes. After establishment, care and maintenance required are fairly minimal (allowing that mulches and related devices are used), such as watering or weed control maybe once a week.

Zone 4

A semi-wild area. This zone is mainly used for forage and collecting wild food as well as timber production.

Zone 5

A wild area. There is no human intervention in zone 5 apart from the observation of natural ecosystems and cycles.

Zone 00

A quick search of the internet will reveal additional mention of "zone 00" in reference to permaculture, and it may seem incongruous to list it at the end of the description of the other zones. However, zone 00 is the entirety of the "self" – the physical, the conscious and the spiritual. The idea is, in part, that in order to "people care" one must first take care of one's own health, spiritual wellbeing, emotional balance, in order to establish a connection with others, and with nature. Thus, the zonal mapping process becomes entirely holistic, and addresses all levels of existence, particularly the connections between all elements (zones), including the deepest recesses of our own identity.

12.7. Animals

Whether animals should be part of the design or not is controversial. Some practitioners introduce them deliberately as an element, while other projects avoid the use of domesticated animals entirely. There seems no fundamental violation of the permaculture principles *per se*, in using animals to provide eggs and milk and indeed in killing them for food and leather. From a pragmatic perspective, the choice simply depends on the kind of lifestyle to be supported.

13. Farming without oil; using practical permaculture.

"The flocks of gulls and crows squabbling behind the plough for worms and beetles is just a childhood memory for me. Today, the birds don't follow the plough because the soil is dead and there is nothing for them to eat.

"The only way modern agriculture can get away with killing the life in the soil is through the another use of fossil fuel – by turning it into chemical fertilizer containing nitrates, phosphates and potash."

Rebecca Hosking (Environmental Campaigner)[48].

The UK imports 40% of its food and, whether imported or home-grown, it is transported around the country. Thus the entire food production and distribution system is highly dependent on crude oil, as may be judged from the following values estimated from published figures for CO_2 emissions[33], and assuming the fuel to be n-octane:

- UK Farms use 800,000 tonnes of oil/year for fuel to run tractors *etc.*
- Transporting food within the UK uses 2.9 million tonnes of oil/year. 650,000 tonnes of that is for car journeys to shops.
- Importing food from abroad uses 2.1 million tonnes of oil/year.
- Growing the food to be imported uses 580,000 tonnes of oil/year.
- Grand total of oil to feed Britain: 7 million tonnes of oil/year.
- Food sector in total uses 17% of our total energy, in terms of farming, processing, transport, packaging, refrigeration *etc.*
- Total oil used in UK for transport is 60 million tonnes/year. 13 million tonnes of that is for aviation.

Practical permaculture, involves the reconstitution and preservation of natural habitat, including hedgerows, where there is biodiversity and interacting "layers" of flora and fauna, that pass down nutrients between levels, and bugs and earthworms that naturally till the soil. The result is a fertile and high-yielding crop ecosystem, in which the soil food web has been restored. This can be more productive than conventional agriculture, and maintained with minimal inputs of oil and other kinds of energy, fertilizer and pesticides. It is claimed that one day a week's worth of harvesting, and around 10 days a year of maintenance, is all that is necessary to keep such a system going, rather than the drudgery that farming was in the days before cheap oil and mechanization. Moreover, the farm could, at maximum production, feed ten people per acre, or roughly double the number that can be fed from an average acre of conventional arable farmland. The transitional phase from farming a field using artificial inputs of fertilizer, pesticide and herbicide to the "natural state" would involve an initially reduced yield, until the soil food web had been re-established.

Monoculture crops will probably always be produced in lower yield using "organic" methods, than through industrialized farming, but it is through mixed cropping, and the symbiosis of biodiversity, that a high fertility is obtained. The environmental campaigner, Rebecca Hosking, notes that she had always thought of hedgerows as being simply divides between fields, and indeed that was my view too. I remember my first flight in a plane, and seeing the English countryside as though someone had drawn lines of division between the different fields, as their various individual hues and shades seemed to confirm; almost like a watercolour patchwork. However, the hedgerows not only provide habitat for birds, which add a contribution of nitrogen to the ecosystem (through their droppings), but are crop-productive entities in their own right – a kind of vertical field. I tend to think of the majority of arable land in the sense of flat fields, with occasional trees here and there, almost as a kind of garnish; yet in reality, the greatest fertility is found when the landscape is effectively a forest (as most of Britain once was, until the trees were cut-down to make ships and charcoal for smelting iron) with occasional clearings cut through it. One lifetime famer, Arthur Hollins, recognised that the woodland on the farm was much richer in wildlife than the fields he cultivated, leading him to believe that ploughing destroys essential nutrients in the soil by exposing them to sunlight[48]. Field is naturally restored to forest, and occurs by a
process known as "succession". Left wild, a field becomes a meadow, with grasses, weeds and wildflowers growing from wind-blown seeds, and if left untouched, shrubs and trees begin to grow under the canopy of the grasses. As the shrubs and trees grow, they begin to block the sunlight from reaching the grasses and other plants, which die-off, and the system is described as "scrub". As the trees continue to grow, a thicket is created, with many young trees growing close together. As the trees become taller, they block out the light from the shrubs which correspondingly begin to die-back. Then the stronger trees out-compete the weaker ones, and

finally a forest is formed. The shrubs rebuild the soil, helping the tree roots to grow. The process of conversion of field to meadow, to thicket, to forest can take 40 years[9].

Farming has undergone a revolution in its practices, driven mainly by cheap energy in the form of oil-based fuel, chemical fertilizers and pesticides, and this has profoundly changed the shape of the countryside. Life on a small farm prior to WWI was indeed a life of drudgery. Even organic farms depend on oil, and for the reasons of an imminent shortage of cheap oil, and the effect of burning fossil carbon fuels on climate change, alternative approaches to food production must be sought. In 1981, humanity began to use more oil than it found new oil, and indeed, less and less new oil has been discovered during the past 40 years. Humanity now consumes four barrels of oil for every single new barrel of oil that it discovers. It has been estimated that the production of conventional crude oil will decline by around 3.4%/annum[49], and this might be worsened by a lack of development in new oil infrastructure. Our dependence on oil and gas may be illustrated by the familiar "ham sandwich", as is now normally provided in a pristine plastic wrapper. There is diesel needed to run the tractors that harrow the land, and dig seed in, so that grain may be grown to feed the pigs on. Then there are chemical fertilizers and pesticides, herbicides and insecticides, all of which are made from oil and natural gas. Once the grain is harvested, it is dried using large, energy-intensive heaters, most often powered by electricity made from natural gas, or they are gas-heaters themselves. To make the ham, the pig eats around half a tonne of grain per year, and to complete the sandwich the salad is either flown-in from elsewhere in the world or produced in a heated greenhouse. It is then driven many miles in a refrigerated lorry. The plastic package is made from oil and takes further fossil energy to produce.

Currently, it takes 10 calories of energy to produce 1 calorie of food energy. The Green Revolution (Section 20), that has confounded the Malthusian predictions that world population would outstrip our capacity to grow enough food to feed it, is underpinned by cheap energy, particularly from oil. Genetically Modified (GM) crops depend as much on oil as any other crops: although more can be grown on the same area of
land, a commensurate increase in the input of fertilizers, pesticides and fuel for farm machinery is necessary. If there is an energy famine, the United States and Australia could collapse as food exporters. This would cause a world famine, and a huge increase in the price of what food is available. Most of the skills attendant to farming without fossil fuels are forgotten: a good example of this is the television series, "Victorian Farm", shown on BBC 2 recently[50]. Here a team of three (two men and a woman) spent a year living and farming as Victorians would have done, and their roles are rather traditional. The woman attends to the cooking, the housework - it

takes practically the full week to do all the washing and ironing - and the poultry, including killing the birds when they need to be eaten; while the two men learn to plough with a heavy horse, build a pig-sty, harvest the crops and hay, and between the three of them they do everything using, at best, hand-operated technology which was an innovation of Victorian engineering, hugely labour-saving than without them, but still all heavily manual.

I watched this series in wonder, but with the simmering sense of fear that we might have to return to this way of life, and if so, the question arises of how could we cope with relearning so many forgotten skills, and indeed all the hard manual work? It is work for young men, at best, and the average age of a British farmer is now 60. The Victorian equivalent of a tractor was the "heavy horse", so called because they weigh up to one tonne and are powerful but amiable beasts.

A modern tractor has a power equivalent to 400 horses, while in pre-oil times a small farm had at most (if they could borrow another for very hard work) two horses. Indeed, the present level of energy consumption around the world, from crude oil, is equal to 22 billion slaves (the world population is 7 billion) working 24 hours a day[51].

The farming industry has declined in the UK, and the country imports around 40% of its food - brought in using oil-powered transport. The cost of such carriage can only increase and ultimately fail, as oil prices rise inexorably. There are only 150,000 farmers left in the UK, and as noted, with an aging population. Animals normally need to be taken indoors during winter, otherwise they destroy the pasture. To feed them, hay needs to be harvested, and this is the biggest use of energy on a small farm. At Fordhall farm in Shropshire, the cattle are kept out all though the winter, where they graze with very little in the way of additional feed being needed for them. This rendered the brother and sister team, Charlotte and Ben Hollins who run the farm, almost immune to the recent oil price shocks that provided severe stresses to the industry overall. The approach is to use a range of grasses, natural to the area, and which, in combination, make the land surface tough, so that it is something like a wild prairie and able to withstand the constant pummelling by the animals' hooves during the winter. Choosing the best kinds of grass is an empirical matter, and whichever type works best for a given region is the one to select. Other kinds of grass may be most appropriate for another area: again, local knowledge is likely to prove indispensable, probably to be found in old farming records. At least 96% of all food grown in Britain relies on farming methods that use synthetic fertilizer, without which the soil lacks sufficient microorganisms/nutrients for healthy plant growth, and without ploughing, it is inadequately aerated[48]. This seems both a stalemate situation and a conflict with nature. However, lessons may be drawn for practices that act in harmony with the natural world, which was lush 10,000 years ago, before humans began ploughing fields. That earthworms are able to till and aerate soil was known to Charles Darwin[52], and that they have done so for millions of years. Forests are able to flourish without the agricultural impact of humans, because they rely on a natural fecundity which is created by billions of microbes (soil food web), animals, birds and plants. This is the importance of biodiversity: an interconnected, holistic symbiosis of living organisms. Before the fifteenth century, most of Britain was forest land, and most of the energy expended in preserving modern agriculture is to hold it in an artificial bubble; from returning to its natural forested state. On a permaculture smallholding ("forest garden") in Snowdonia, it has proved possible to produce all the fruit and vegetables needed for two people to live there, and even the fuel to cook it. The site is effectively a set of small clearings in a mass of woodland, in reverse of what we normally now think of as the layout of a farm, with clumps of trees surrounded by fields. A natural woodland is like having half a dozen fields stacked one on top of the other. It works on different levels: shrub, *etc.*, fruit trees, tree canopy, and the whole symbiotic arrangement recycles nutrients, *e.g.* nitrogen in leaf litter, beneficial fungi and root systems. It is reckoned that 10 people can be fed per acre (25 per hectare), or about double the number fed by conventional (industrialised) agriculture. Cereals cannot easily be grown in a permaculture garden, and so it will be necessary to adapt our diet to other foods. For example, nuts grow on chestnut and hazelnut trees at a yield of 2 tonnes/acre, which is a similar yield to field-grown wheat, although from a nutritional standpoint, nuts are similar to rice.

For the UK to become self-sufficient, we need to eat less meat. Gardening with hand tools is more energy effective (and labour intensive), but raises five times as much food on a given area in a small garden than is produced on the same area of open field. It is likely that a preponderance of small plots will take the place of fields, as the latter decline in the face of a loss of oil and natural gas supplies. There are just 150,000 British farmers left now, and we will need around 11 – 12 million[48], *i.e.* every family will be involved, not merely those running a collection of industrial-scale farms. Rather than asking the question, “could permaculture feed Britain?”, it is more salient to ask whether conventional agriculture can. In the longer run, the answer to the latter is, no, because it depends so utterly on oil and gas, and so the only course of action is to try permaculture. It takes a long time for soil to regenerate, but if left to the actions of nature, it does. Every plant is important in some way: *e.g.* bracken collects potash and birch encourages phosphate recycling through the ecosystem. Nitrogen, potassium and phosphorus are all circulated through the system by nature – animals, including worms – and so no energy input is necessary.

Some creatures help with pest control, while others control drainage and others pull up nutrients from the soil; all are important in this symbiosis of biodiversity. Birds, that eat insects and seeds, accumulate phosphates which are returned to the soil in their droppings, thus eliminating the need for rock phosphate fertilizers, world supply of which is thought may peak around 2033[53]. It seems probable that the dominant demographic trend of the 21st Century is going to be re-ruralisation (or de-industrialisation). That is not to say that the cities will disappear, but the proportion of people involved directly in food production will, of necessity, increase, in either rural or urban environments.

14. Greening the desert: using practical permaculture

My initial interest in permaculture was profoundly stimulated by watching a video-clip, entitled "Greening The Desert", featuring the life-long permaculturist (and former student of Bill Mollison), Geoff Lawton[54].This remarkable, short documentary describes a field-study that was undertaken in Jordan, strategically sited in the desert lands near the Red Sea, and said to be the region on earth with the lowest rainfall. He demonstrated the dryness of the highly saline soil there, by picking up a handful of it, and letting it fall through his fingers, to the ground, as dust. On a 10-acre site, by a combination of mulching and other permaculture techniques, within 3 years olive groves and other plants were flourishing there, and using only 5% of the water that would normally be required to grow plants in that region. Remarkably, although the greening of the desert site has received no serious funding or management for 6 years (there is a lack of money for projects of this kind, which despite their obvious importance, do not yield immediate and significant fiscal returns on investment), many of the plants seem to be thriving, and the soil seems to be regenerating itself through the system of swales – a form of rain harvesting trench –that the original team put in.[55]

14.1. Demonstration permaculture projects

Worldwide. there are literally thousands of permaculture projects in action[56,57], of which the following is a somewhat illustrative and highly incomplete list. Nonetheless, it is clear that the principles of permaculture can be applied in various and subtly different ways, according to the exact terrain, and area available. Sustainability and resilience are key features in all cases, with a minimisation of energy and other inputs, particularly of freshwater, since the re-use of water (*e.g.* "grey water", that has already been used for washing, but is clean enough to water plants) is emphasised. In some cases, there is a deliberate focus on environmental regeneration, in areas that have been affected adversely, *e.g.* by urban development. Many of the projects are situated on sizeable areas of land, but there are also, *e.g.* roof gardens, and vegetable plots on railway stations, which maximise the productivity of urban space. Educational and societal/community aspects are implicit to most of these projects (with associated outreach activities), many of which run courses on permaculture and sustainability. There is a belief that involvement (reconnection) with nature can prove therapeutic to people suffering from depression and other mental disorders, and in the rehabilitation of young offenders. It has been said that modern society is suffering from “Nature deficit disorder”, a term coined by Richard Louv in his 2005 book, “Last child in the woods”, in which he claims that, because children spend less time outdoors than they did, they have lost contact with nature, resulting in a range of behavioural problems[58]. The evidence for this has been reviewed. http://www.childrenandnature.org/downloads/CNNEvidenceoftheDeficit.pdf

14.2. Australia

The development of David Holmgren's home plot at Melliodora, Central Victoria, has been well documented on his website and details of it are published as an E-book. (www.holmgren.com.au)

Geoff Lawton's *Zaytuna farm* in northern New South Wales, Australia, is a 66 acre medium-farm scale example of permaculture implementation, started in 2001, and is also the home base for the Permaculture Research Institute of Australia. The site is off-grid, and has multiple food forest systems; animal systems; a kitchen garden and main crop areas; a large network of water-harvesting earthworks, for passive hydration of the site; composting toilets; rocket stove-powered showers; straw bale, natural buildings, *etc*. A video tour of the farm is available (http://permaculturenews.org/2012/06/01/zaytuna-farm-video-tour-apr-may-2012-ten-years-of-revolutionary-design/).

Crystal waters is described as “a socially and environmentally responsible, economically viable rural subdivision”, and is situated north of Brisbane, Queensland. Crystal Waters was designed by Max Lindegger, Robert Tap, Barry Goodman and Geoff Young, and established in 1987 (www.crystalwaters.org.au). The project received the 1996 World Habitat Award for its "pioneering work in demonstrating new ways of low impact, sustainable living". Eighty-three freehold residential and two commercial lots occupy 20% of the 640 acre (259 hectare) property. The remaining 80% is arable land, and has common ownership. It can be licensed for projects in sustainable agriculture, forestry, recreation and habitat.

City Farm Perth is an example of community permaculture, and is situated in an inner suburb of Perth, Western Australia. The farm was constructed on a brownfield site in 1994, and is a focal point for permaculture education, along with community music and art (www. perthcityfarm. org.au).

14.3 Africa

In Zimbabwe, there are 60 schools designed according to permaculture principles, with a national team working within the schools' curriculum development unit. The UN High Commissioner for Refugees (UNHCR) has produced a report on using permaculture in refugee situations after its successful use in camps in Southern Africa and in the Republic of Macedonia. The biofarming approach used in Ethiopia can be considered as permaculture, and is mainly promoted by the non-governmental organisation (NGO), BEA, based in Addis Ababa.

There are permaculture farms in other nations too, *e.g.*, *Badilisha Eco Village Trust Foundation* is a permaculture farm that integrates sustainable agriculture with community development on Rusinga Island, in rural Kenya (www.badilisha.net).

14.4 United Kingdom

There are various permaculture projects in the UK, including:

- *Agroforestry Research Trust* managed by Martin Crawford is a not-for-profit organisation based in Dartington, Devon that runs a 2-acre (8,100 m^2) forest garden and publishes the journal *Agroforestry News* (www.agroforestry.co.uk)
- *Chickenshack Housing Co-op* is a fully mutual housing co-op established in 1995 using permaculture design principles, and is based in rural North Wales (www.chickenshack.co.uk). The community has four dwellings and six residents on a 5-acre (20,000 m^2) site. Among its features are a biomass and solar district heating scheme, a half-acre forest garden and various wildlife conservation and habitat creation strategies. There are connections with other regional sustainability projects such as the Machynlleth Transition Towns initiative. It runs occasional courses in permaculture design and regularly receives visits from interested parties. The Centre for Alternative Technology (CAT) is also based near Machynlleth (www.cat.org.uk).
- *Middlewood Trust* is a permaculture-based farm located in North Lancashire which runs courses in permaculture, crafts, forestry and sustainability (www.middlewood.org.uk).
- *Plan-It Earth Eco Project* offers a variety of Environmental Education Programs, Courses and Events, and Eco Holidays at a traditional smallholding near Penzance, Cornwall.
- *Plants for a Future* is a vegan-organic project based at Lostwithiel,

Cornwall, that is researching and trialling edible and otherwise useful plant crops for sustainable cultivation. Their online database features over 7,000 such species that can be grown within the UK (www.plan-itearth.org.uk).

- *Prickly Nut Woods* is a 10-acre (4 hectare) woodland near Haselmere, Surrey, managed by Ben Law (www.earthcentrenetwork.org.uk). He uses a "whole system", permacultural approach, involving a wide variety of woodland products and documenting a complex web of relationships, and managed to build a house almost entirely using products from the woodland – this was featured on Channel 4's Grand Designs television series.
- *Ragmans Lane* is a 60 acre (24 hectare) farm in the Forest of Dean, Gloucestershire (www.ragmans.co.uk).
- The RISC Roof Garden (Figure 9) is a fine example of urban permaculture, and is on top of the Reading International Solidarity Centre (RISC), which is a Development Education Centre close to the heart of Reading's town centre. It 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. The garden is composed of dense plantings of over 180 species of edible and medicinal plants and is fed by rainwater and composted waste from the centre (see section on Urban agriculture–urban permaculture) (www.risc.org.uk).
- *Tir Penrhos Isaf* is near Dolgellau (North Wales), developed by Chris and Lyn Dixon since 1986 (www.konsk.co.uk).
- *The Sussex Roots Society* is a community permaculture garden inaugurated by Mischa Nowicki and Integralpermanence at Sussex University, which collaborates with the Student Union as part of the country's first "Eco Uni" initiative (www.aliveincreation.com).
- *Eastside Roots* is a (not-for-profit, worker co-op) community garden centre and hub which evolved from the Bristol Permaculture Group. They have leased "waste ground" from the railway company First Great Western, and converted it into a flourishing garden centre with ongoing education and social projects and out-reach into the wider community. The project promotes principles of sustainability and permaculture (www.ecojam.org).
- An allotment has been created on the platform of Kilburn Underground station, in London. Members of Transition Kensal to Kilburn, a sustainable living group that organised the plot, said they hoped the project will encourage the thousands of people who use the station to grow their own fruit and veg. Michael Stuart, from the group, said: "We want people travelling on the tube to see the plants, and help themselves to the fruit. We hope to show people that if we can grow fruit, vegetables and flowers on a busy tube platform, then

they can easily grow the in their gardens, on their windowsills or in their front drives." (www.ttkensaltokilburn.ning.com).

14.5 South America

14.5.1 Cuba

Cuba has transformed its food production systems by means of low-input, or organic agriculture and, in part, permaculture. Currently, Havana meets around 50% of its food requirements from production within the city itself, much of it produced by people in their own homes and gardens and in municipal spaces.

14.5.2 Nicaragua

Project Bona Fide (www.projectbonafide.com) has been under development for almost a decade and is a 43 acre (17 hectare) site on the island of Ometepe, Nicaragua, which has two volcanoes, one of which (Volcán Concepción) remains active. There are natural buildings built with local materials, terraced and medicinal plant gardens, an extensive nursery, seed bank, developing fruit and nut orchards, food forests, native timber forestry, timber bamboo plantings, water-catchment, drip irrigation and ferrocement technologies, renewable energy systems, and composting toilets. The term "ferrocement" usually refers to a mixture of Portland cement and sand which is applied over layers of woven or expanded steel mesh and closely spaced small-diameter steel rods (rebar). It can be used to form relatively thin, compound curved sheets to make hulls for boats, shell roofs, water tanks, *etc.*

Ostional Private WildLife Reserve ("O") is a 46 acre (19 hectare) privately owned nature reserve on a historic site nicknamed La Colina ("the hill") in Rivas, Nicaragua. Project "O" is a relatively recent innovation and is scheduled to open to the public in 2012, with plans to become a centre for education and community development (www.opwr.org).

14.5.3 Brazil

Fifty years ago the city of Brasilia was designed and then built from scratch to become the new capital city of Brasil, currently with a population of 2.5 million people. Surrounding Brasilia is the Chapada Highlands – savanna traversed by sandstone mountains. In the dry season, there is no rain for 5 months, and along with the environmental consequences of rapid urban development, the area is in severe need of sustainable and regenerative solutions.

Oca Brasil is an NGO which hosts an agro-forestry system, recycled paper production facility and an education program in the local Alto Paraiso community. They spread environmental awareness through many different programs. One good example is the project "Quintais Verdes" (Backyard Landscapes), where they help families of young delinquents to plant fruit trees and vegetable gardens in their yards as a means of improving the home. Besides teaching techniques of land use and generating greater self-sufficiency in food, the program helps to create an environment of love and healthy relationships within the families. (www.ocabrasil.org).

IPEC (Institute of Permaculture and Ecovillages of the Cerrado) is a demonstrative ecocentre in Pirenopolis, 2 hours from Brasilia, specialising in bio-construction and natural building. on-site, IPEC hosts many educational groups to learn permaculture design, natural building techniques, and ecovillage design. (www.ecocentro.org)

IPOEMA, Instituto de Permacultura, Ecovilas e Medio Ambiente (Institute for Permaculture, Ecovillages and the Environment) is an umbrella organisation that features a diverse range of ecological projects, including four permaculture villages in development around the city of Brasilia (www.ipoema.org.br).

14.5.4 Chile

The Permaculture community in Chile is relatively new. Its development has been driven largely by a small group of dedicated permaculturists building a learning community. The community has rapidly expanded in the last two years following a tour by David Holmgren in 2007, the work of Eluwn, the delivery of Permaculture Design Certificate courses by El Manzano, and the formation of the Instituto de Permacultura en Chile. The broad network can be found at www.permacultura.cl, where specific links can be found to the principal organisations.

15. How many people can the Earth support?

It is claimed[59] that "a population density of 6–10 people per acre might be supported through permaculture, and this is greater that our current cereal-based food economy can sustain". Since our ability to grow cereals in the quantity we do depends on industrialised agriculture, with its considerable inputs of oil- and gas-based fuels, fertilisers and pesticides, the practice is not sustainable and so the comparison is not strictly valid. We are then left with the question of how many people might be supported by the earth, if permaculture methods were widely introduced. If we assume the lower limit, this means that 15 people can be fed per hectare. Thus, to feed the

human population of 7 billion, we would need 467 million hectares of land, or 4.7 million km^2. Since we have 150 million km^2 of dry land, and around 14 million km^2 of arable land, it would appear there is no problem in sustaining the present global population, and that to supply even 9 billion by 2050, or 12 billion by 2100, is feasible. Toby Hemenway, regarded as one of the gurus of permaculture, is less optimistic, and believes that the maximum carrying capacity of the Earth is nearer 2 billion[60].
[This is also the number arrived at by Pimentel *et al.*[61], on the basis of the limited resources of energy, water and food available to us, and it seems most likely that it is failing supplies of these key inputs, particularly freshwater, that will reduce and finally limit our population. One is reminded of the "four horsemen of the apocalypse": pestilence, war, famine and death, each rider being perceivable in a guise of resource shortages. Since the consequence of consumption is pollution, this too must prove a determinant to the numbers of humans that can live sustainably on "Spaceship Earth", as the visionary Buckminster Fuller termed[62] our existence]. Other permaculturists are far more sanguine than Hemenway about what might be achieved, in terms of sustaining the global population, and point out that predictions of food shortages are based on limits of the resources that are necessary for modern agriculture, whereas permaculture is based on the interacting and holistic mechanisms of nature, where nothing is wasted and everything is recycled, all elements being returned to the ecosystem, by death, and from which new life can flourish. David Blume claims to have fed up to 450 people on two acres (0.8 ha) of land for 9 years, by the end of which the soil contained 22% SOM, with a CEC of >25 (a measure of its humus content). This amounts to *ca* 18 m^2/person, which might be understood to imply that the current world population of 7 billion could be fed on just 120,000 km^2 of land. The key to this success is polyculture, which benefits from the growth of mycorhizal fungi (Section 10) and less solar saturation (www.permaculture.com/node/1344). Blume has described this technique as "restorative agriculture", and he believes that there is, correspondingly, no immediate limit to the number that can be fed on Planet Earth, and that ethanol fuel, produced on the local scale could meet all our energy needs – including electricity production – and obviate the need for crude oil.

Hemenway has spoken[63] on the subject of: "How permaculture can save humanity and the earth, but not civilisation," which may initially sound like an oxymoron. It is in fact a rather more subtle proposition to the effect that while permaculture cannot sustain the present global economy and global civilisation with a population of 7 billion people, it might support a lesser number of up to 2 billion, but, of necessity, its practices mean living in small communities. Thus, the civilisation that permaculture could sustain is not of the global kind, but a village of globes, rather than the global village. The principles of permaculture are central to the growing community-based Transition Town movement[64], the aims of which might been summarised in the following working definition, written by me for Transition Town Reading:

"Transition recognises both the inevitability and challenges of declining fossil fuel use. We have built a global economy and civilisation rendered fragile through its underpinning and dependence on cheap carbon-based fuels and materials.

Transition is the process of breaking that dependency through localisation and community self-reliance. By so doing, we become far less vulnerable to prevailing external forces, *e.g.* global warming, a liquid fuels crisis caused by peak oil, resource constraints of all kinds, and global economic instability.

As far as is possible, such communities provide for themselves in terms of food, energy, clothing, materials, transportation, culture, information, entertainment, security, healthcare, skills and employment.

The credit crunch and recession have provided us with a foretaste of some of the challenges that will confront us, though the future remains uncertain. Through Transition, as individuals, families and communities, we may weather the storms, and lead happy and meaningful lives. Thus, we aim to use our collective wisdom to turn this potential crisis into an opportunity to thrive and create a positive future for all of us."

16. Urban agriculture – urban permaculture

Urban agriculture[65] is the practice of cultivating, processing, and distributing food in or around a village, town, or city, and contributes to food security and food safety, firstly by increasing the amount of food available to people living in cities, and secondly, it allows fresh vegetables, fruits, and meat products to be made available to urban consumers. The idea of supplemental food production beyond rural farming operations and distant imports is not new, and has been used during times of war and in the Great Depression, when there were food shortages. During World War I, President Woodrow Wilson called upon American citizens to utilise any available open space to grow food, since the war in Europe curtailed food supplies to the USA. By the year 1919, over 5 million plots were growing food, and over 500 million pounds of produce was harvested. A similar practice emerged during the Great Depression, so providing a purpose, a job, and food to those who would otherwise have none of these things, and in addition to providing economic growth, morale was raised among an otherwise dispirited population. During World War II, the War/Food Administration set up a National Victory Garden Program that set out to systematically establish functioning agriculture within cities. It is thought that 20 million Americans took part in the victory garden movement, and over 9 million tonnes of fruit and vegetables were grown annually, which accounted for 44% of all the produce then grown in the USA. In Britain, the slogan was, "Dig on for Victory." Since World War II, human civilisation has become more industrialised and urbanised, and the following facts[65] now apply:

Figure 9 *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, R.B.A. Information Services.*

- In 2010, 50.5% of the world population lived in cities, a figure projected to reach 70% by 2050.
- 800 million people are involved in urban agriculture worldwide.
- Urban residents on low incomes spend between 40% and 60% of their income on food.
- It is thought that by 2015, the populations of probably 26 cities will exceed 10 million, each requiring a daily import of 6,000 tonnes (6,600 tons) or more of food.
- 250 million hungry people in the world live in cities.

Urban permaculture comprises our own relationship with our environment, as much as it focuses on the physical surroundings themselves. It is an effort to bring nature back into the cities, and to dissolve the barriers of action and perception that have been raised between our the way we live and the natural world. Cities are highly consumptive of resources, and, accordingly, they excrete vast quantities of waste and pollution, which needs to be removed and disposed of, to the extent that we are beginning to run out of landfill space. Valuable nature corridors, agricultural land, and open spaces, are being increasingly encroached upon by urban sprawl. Against this backdrop, urban permaculture aims to create sustainable, productive landscapes that require minimal external inputs of energy, water, artificial fertilisers, pesticides and herbicides, and to create an enhanced local capacity to sustain human populations within the limits of natural resources.

Within a large town or city are unused areas where food might be grown, that are not immediately obvious, probably because we tend to think in ground-level terms. As a deliberate and practical example that there is more space available in an urban setting than we realise, an edible forest garden has been planted on the roof of the *Reading International Solidarity Centre (RISC)*[66], in the town of Reading, in the south east of England (Figure 9). The garden explores the origins of plants and their different cultural and culinary uses, but also highlights global justice issues, such as unfair trade rules and intellectual property rights, that have a detrimental effect on some of the poorest farmers in the world. It also provides practical information, on alternative energy, composting, water harvesting and urban food production. In the present global setting, we take the things we use for granted, and are mostly unaware of our connection to and dependency on other nations, through complex international trade mechanisms, as was put by Martin Luther King[67]:

"All men are interdependent. Every nation is an heir of a vast treasury of ideas and labor to which both the living and the dead of all nations have contributed. Whether we realise it or not, each of us lives eternally "in the red". We are everlasting debtors to known and unknown men and women. When we arise in the morning, we go into the bathroom where we reach for a sponge which is provided for us by a Pacific Islander. We reach for a soap that is created for us by a European. Then at the table we drink coffee which is provided for us by a South American, or tea by a Chinese, or cocoa by a West African. Before we leave for our jobs we are already beholden to more than half the world."

That our inextricable links to other peoples of the world, and our daily actions, can affect the livelihoods of people elsewhere, is well illustrated in terms of food. The history of the RISC roof garden began when the flat conference hall roof was in desperate need of repair, but the premises also needed heat and sound insulation, in order to keep its public entertainment licence. Applying the permaculture principle, that “the problem is the solution”, these separate “problems” presented the ideal opportunity to give the roof a complete overhaul. Soil provides a perfect material for both thermal and noise insulation, and, naturally, is an ideal medium in which to grow plants. After gaining planning permission, a Community Fund grant was obtained to pay a company to mend the roof and install a special drainage system, before placing 30cm (1ft) of soil on the roof. A further Creativity Seed Fund grant from the National Lottery, along with grants from the Environmental Agency and the Environmental Trust for Berkshire, enabled the design and implementation for the garden to be carried out. In the middle section is a forest garden and is planted exclusively with edible perennials from around the world, permitting awareness of the origins and also the culinary, religious and cultural significance of different plants. The arrangement of plants emphasises the aspect of "layers", there is a "three sisters" plot, and most of the soil is covered by the leaves of ground-level plants. Apparently, it requires just 3 hours a week by one person to tend it. The far end of the garden is designed for annual vegetables (and is situated near the water source to accommodate a more intensive growing system). The latter is a huge water reservoir which collects all of the water that drains from the main roof and from adjacent roofs. Attached to the south-facing wall are solar panels, and on a nearby chimney is a wind turbine. These provide a combined electricity supply, which, in the summer, pumps the collected water around the garden using a drip feed irrigation system. In the winter, when the water is in excess, the water system is diverted to the café which is two floors below and therefore uses the natural force of gravity alone to flush the toilets.

The practical principles of urban permaculture have been espoused in a book[68] by David Watkins, with a particular emphasis on making the most of available space, *etc*., within the apparent restrictions of an urban setting. For example, even without a garden, it is quite feasible to grow edible plants in window boxes, pots of herbs and smaller plants on windowsills, and to germinate shoots and sprouts in jars. Balconies can also provide growing space. Vertical surfaces can allow trellis, *etc*., for climbing plants, and a conservatory or glazed door may be shaded in summer by a deciduous vine, while evergreen foliage on walls acts as an insulator in winter – this is in addition to the crops that the plants produce. A garden, or other ground, near a roadside suffers from pollution, *e.g.* by lead and cadmium, but it may still be used to produce bamboo for bean-poles, and willows, rushes, sedges or reeds for basketry. If a small garden is available, it is recommended to concentrate on high-yielding plants, and to use available vertical surfaces, while stacked logs can yield crops of edible fungi, and a vertical tyre stack can be used to produce a good crop of salad potatoes. Hedges are highly productive, and are far more than a simple divide between gardens or fields. In fact, as is noted in Section 13, they are a forest garden in miniature. An actual forest garden can produce crops throughout the year – although it takes some time to establish, once it has done so, the amount of maintenance is relatively low. Edible ornamental gardens offer another possibility, in which those plants grown are pleasing to the eye, but may also be eaten. A medicinal herb garden can be grown too. Wild food may also be gathered, particularly berries. Thus, there is much that can be achieved in the typical urban setting.

As a final example, both of urban permaculture, and the principle that "the problem is the solution", we may consider the "problem" of algae in swimming pools[69]. Now, the technological solution is to treat the water with chlorine (probably generated *in situ* from dilute hydrochloric acid and sodium hypochlorite). The permaculture way is to recast the problem as not having too much algae, but too few fish. By adding fish to the pool, they eat the algae (solving "the problem"), and their excrement falls to the bottom of the pool and becomes high quality (anaerobic) soil, which can be recycled through composting, and added to the garden as a fertiliser to grow food. In this "solution", not only is the pool kept clean of algae, but soil is produced, the fish can be eaten, and humans may still swim there, with the fish. Perfect!

Since more than half the population of the world lives in urban settings, it seems likely that strengthening the resilience of these environments, using urban permaculture, may be critical to ensuring that a slower energy descent is achieved, rather than an abrupt collapse of civilisation.

17. Sustainable cities

The term "ecocity" was first coined by Richard Register in his 1987 book[70], *Ecocity Berkeley: building cities for a healthy future.* The definition of what a sustainable city should be and what elements should feature in it, has yet to be agreed upon. It is normally thought that a sustainable city should meet the needs of the present generation, while avoiding any according sacrifice for future generations. To be sustainable, a city should be able to feed itself with minimal reliance on the surrounding countryside, and provide sufficient renewable energy for its purposes. This should hence result, in the smallest possible ecological footprint, with minimum pollution, and an efficient use of land. Waste materials should be composted, recycled or converted to energy, so marginalising the overall contribution of the city to climate change. The close proximity of people and resources means that energy can be used more efficiently, *e.g.* for mass transit and food transportation.

The following devices, by which ecological cities may be attained, may be emphasised[71]:

- Different agricultural systems, such as agricultural plots within the city (suburbs or centre). This reduces the distance that food has to travel "from field to fork". This may be accomplished either on small scale/private farming plots, or through larger scale agriculture (*e.g.* farm scrapers).
- Renewable energy sources, such as wind turbines, solar panels, or bio-gas created from sewage. Cities provide economies of scale that make such energy sources viable.
- Various methods to reduce the need for air conditioning (a massive

Figure 10 *Green roof church at Hof, Iceland.Credit Ira Goldstein. upload.wikimedia.org/wikipedia/commons/9/98/Church_at_Hof.jpg*

energy demand), such as planting trees, natural ventilation systems, an increase in the number of water-features, and green spaces, to equal at least 20% of the city's surface. These measures counter the "heat island effect", caused by an abundance of tarmac and asphalt, which can make urban areas several degrees warmer than surrounding rural areas – by as much as 6 ^{o}C during the evening.

- Improved public transport, and an increase in pedestrianisation, to reduce car emissions. It also relates to dealing with the loss of cheap liquid transportation fuels, as a result of Peak Oil. This requires a radically different approach to city planning, with integrated business, industrial, and residential zones. Roads may be designed to make driving difficult.
- Optimal building-density, to make public transport viable, but to avoid the creation of urban heat islands.
- Green roofs (Figure 10)
- Zero-emission transport
- Zero-energy building
- Sustainable urban drainage systems.
- Energy conservation systems/devices
- Xeriscaping – garden and landscape design for water conservation
- Key Performance Indicators – development and operational management tools providing guidance and Measurement and Verification for city administrators.

17.1 Individual buildings (LEED)

LEED, or Leadership in Energy and Environmental Design, is an internationally recognised certification system for "green buildings". A sustainable design for an entire building is recognised by identifying key areas, *e.g*: sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, locations and linkages, awareness and education, innovation in design, regional priority. In order for a building to become LEED-certified, sustainability needs to be prioritised in all features of its design, construction, and use. One example of sustainable design would be including a certified wood like bamboo, which is fast growing and has an impressive replacement rate after being harvested. The optimisation of energy requirements has earned the most credits under the LEED scheme by far, thus encouraging innovative thinking about alternative forms of energy and its more efficient use.

17.2. Eco-industrial park

In an eco-industrial park, a community of businesses decreases its collective environmental impact, while maximising its economic performance, by cooperating in the use of resources such as energy, water, and materials. The landscaping of the building will include native trees, grasses, and flowers, and its design will further act as a climate-shelter for the facility. To decide upon the most appropriate materials to build an eco-industrial park, a life-cycle analysis must be made for each material used in the building, to assess the true overall impact on the environment. Waste-streams from industry can provide heating for homes in the area, while renewable energy, such as wind and solar power, should be used as far as possible. The companies in an eco-industrial park may have common waste-treatment facilities, and means for transporting by-products from one plant to another. Alternatively, resource recovery companies may be recruited to the location, or established in the park at its inception. To ensure a more efficient use of water, the treated water from one installation can be reused by another, and a collection system for run-off and storm water can be implemented, so that less externally supplied water is needed.

17.3. Urban farming

As already noted, urban farming (agriculture) is the process of growing and distributing food, as well as raising animals, in and around a city. According to the RUAF Foundation (www.ruaf.org), urban farming is different from rural agriculture because, "it is integrated into the urban economic and ecological system: urban agriculture is embedded in - and interacting with – the urban ecosystem. Such linkages include the use of urban residents as labourers, use of typical urban resources (like organic waste as compost and urban wastewater for irrigation), direct links with urban consumers, direct impacts on urban ecology (positive and negative), being part of the urban food system, competing for land with other urban functions, being influenced by urban policies and plans, *etc*". There are many motivations behind urban agriculture, but in the context of creating a sustainable city, the approach reduces the energy used for food-transportation, minimises imports of food, renders the supply of food more reliable and lowers costs.

17.4. Urban infill

Many cities are currently undergoing a demographic change, from the suburban sprawl model of development, and back to urban dense living. An increased number of residents, per unit area, increases demand in many sectors, and this is reflected in the architectural fabric of the city, *e.g.* in terms of housing. More accommodation can be supplied by new build, or by historic rehabilitation ("retrofit"). Retrofit is to be preferred to new build, both on grounds of cost, and speed of implementation. Such higher density populations are more effective, in terms of economies of scale, and also that a more efficient infrastructure can be established.

17.5. Walkable urbanism

Walkable urbanism is a development strategy that opposes the seemingly chaotic nature of suburban sprawl. The notion advocates housing for a diverse population, a full mix of uses, walkable streets, positive public space, integrated civic and commercial centres, transit-orientated development and accessible open space. The most clearly defined form of walkable urbanism is known as the Charter of the New Urbanism set out by the Congress for the New Urbanism which is the leading organisation that promotes walkable, mixed-use neighbourhood development, sustainable communities and healthier living conditions. As set out in its Charter, some of the hallmarks of new urbanism are:

- Liveable streets arranged in compact, walkable blocks.
- A range of housing choices to serve people of diverse ages and income levels.
- Schools, stores and other nearby destinations reachable by walking, cycling or transit service.
- An affirming, human-scaled public realm where appropriately designed buildings define and enliven streets and other public spaces.

17.6. Transportation

Sustainable transportation attempts to reduce the environmental impact of vehicles in a city, by an increased use of public transport, and better access to such means of transit for all citizens. Transportation accounts for a significant proportion of the energy used in a city, and hence, in the past 10 years, there has been particular emphasis on energy efficient, lower carbon-emitting, sustainable transportation. Worldwide, almost one third of total energy consumption, and carbon dioxide emissions, is the result of transportation. In order to reduce the environmental impact caused by transportation in metropolitan areas, sustainable transportation relies on three generally accepted principles:

17.6.1. Emphasis on proximity

The concept of urban proximity is the product of eco-friendly urban planning, and an essential element of current and future sustainable transportation systems. The principle requires that cities be built and retrofitted, with an appropriate population and landmark density, so to reduce transit times to particular destinations. The result is that less fuel is used, and shorter distances encourage fuel-free alternative means of transportation, *e.g.* walking and cycling. A reduction in time spent commuting, by placing residential areas closer to major landmarks, enhances the quality of life for those who choose to live in these cities, by allowing them more leisure time.

17.6.2. Diversity in modes of transportation

Another key feature is to employ a diverse range of vehicles, that are fuel-efficient but also use a variety of different fuels. This strategy renders the transportation infrastructure of a city more resilient to the vagaries of price shocks for particular fuels, and to inconsistent fuel supplies. The employment of alternative energy vehicles, and a plentiful provision of refueling points, is an essential aspect of this theme. Centralised cycle-ways and footpaths are another key feature.

17.6.3. Transportation access

Since the costs of cars and fuel are often beyond the reach of lower income urban residents, efficient and accessible public transportation, to all levels of society, is a crucial factor. Thus, to make public transportation more accessible, the price of each journey must be kept low, and pick-up/put-down stops must be placed within walking distance, across the city.

This has many benefits, for example, by allowing lower income residents cheap and accessible transportation, it becomes possible for them to look for employment throughout the urban centre, rather than being confined to that area in which they live. This, in turn, reduces unemployment, and various associated social problems, such as crime, drug use, and violence.

18. Transition cities

"Resilience is, in a nutshell, the ability of a system, whether an individual, an economy, a town or a city, to withstand shock from the outside. Resilience is about building-in the ability to adapt to shock, to flex and modify, rather than crumble. You can think of it as being like building surge protectors into an electrical system." Taken from: Transition in action, an energy descent action plan[72].

We have already alluded to the Transition Town movement (Section 15), and given a working definition for one such Transition Town Reading[64], in the south east of England. The concept of resilience is central to Transition. The first Energy Descent Action Plan[72] was devised successfully, for Totnes, on the River Dart in Devon, which is a market town of some 7,000 people. Reading has made several attempts to become reclassified as a city, given its population of around 250,000 (in fact greater than that of many UK cities), though these, so far, have foundered. Clearly, Totnes and Reading are rather different in their requirements to achieve resilience. Reading is a well established commuter town, from where some 70,000 workers commute into London daily. What is less commonly understood is that an almost equal number of workers commute daily into Reading – many from London – to do high-tech jobs in the town, while the majority of the Reading-to-London commuters are office workers. Due to limits in the capacity of public transport (mainly rail), most of these journeys are made by car, and it would save a great deal of fuel if the Reading-based workers were re-skilled to do high-tech jobs in Reading while the London-based workers could do the jobs there. Since transportation is acutely vulnerable to peak oil, such re-skilling should be seen as critical to the process of Transition, by which means people may earn their living more locally. Many of the necessary implementations for a Transition City have been alluded to already, (Sections 16 and 17).

While no oil-free and self-sufficient, "transition town" exists as yet, there is some belief that such an entity is possible[64]. In contrast, there is much speculation as to whether a city can be made fully resilient, and provide for itself through non-mechanised agriculture and non-fossil energy sources. Probably it cannot, or not as an evolution of a city in its present form, unless far less energy is used to run its essential functions, and it is becomes markedly less dependent upon imports. Thus, a strong element of resilience can be built-in by local food production, *etc*., which acts as a buffer against any actual loss of external supplies, and their rising costs. The above example, of Reading, emphasises the aspect of transportation, which is a major use of energy in any city; hence, any degree of relocalisation must reduce energy inputs overall, and particularly the demand on crude oil, which is our most vulnerable energy source.

It is those cities that have a highest oil consumption[73], *per capita*, that are particularly vulnerable to the effects of peak oil, being highest in the USA (Atlanta 103 GJ, New York 44 GJ), followed by Australia, Canada and New Zealand (30–40 GJ), Europe (< 20 GJ), Eastern Europe (5–10 GJ), and this reflects, principally, their use of transportation. As noted earlier, Cuba managed to survive the *special period*, when supplies of fuel were severely curtailed by the collapse of the USSR, its main benefactor through urban farming and permaculture. Due to the shortage of fuel and therefore severe deficiencies in the transportation sector, a growing percentage of its food production takes place in urban agriculture. In 2002, 35,000 acres (14,000 ha) of urban gardens produced 3,400,000 short tons (3,100,000 t) of food. In Havana, 90% of the city's fresh produce came from local urban farms and gardens. In 2003, more than 200,000 Cubans worked in the expanding urban agriculture sector.[74] The Cuban capital city of Havana has a population of 2.1 million at a density of 2,932 persons/km^2. The population of Havana can be compared with, say, the West Midlands urban area (which includes the cities of Birmingham and Wolverhampton, and some large towns) with a population of 2.3 million, at a density of 3,808/km^2, though it is noteworthy that the mean population density of Cuba is 105/km^2 and that of the UK 258/km^2.[75] Many cities in the World, though less populous, have far greater population densities[76] than is typical for Cuba or the UK, and for whom the transition is likely to be considerably more difficult.

Opinions as to whether it might be better to achieve transition in an urban/city environment or a rural setting, lie in different camps. On grounds of resource limitations of all kinds, one view[77] is that the cities will descend into barbarism, expecting a fairly rapid collapse of an industrial society that is so completely underpinned by hydrocarbons. It is stressed that hydrocarbons form a mutually dependent triad with metals and electricity, *i.e.* to have any one of these elements depends on the availability of the other two. Other outlooks are based on a slower depletion of resources, and emphasise the efficiencies of scale that are possible in a city, in terms of "wire, pipe, pavement", growing food using urban permaculture, and being far less dependent on imported coal, fertiliser, medicine, clothes and fuel for transportation, as when living relatively isolated in the countryside[78]. The amount of food that can be grown in an urban environment is also emphasised. Undoubtedly, both urban and rural landscapes offer their own advantages, as is espoused by another commentator[79]. While rural areas may be better in the longer term, in the early phase of transition they may fare worse economically, because there are fewer jobs. It is most likely that there will not be an abrupt societal disintegration, but a long emergency, where there is enough commercial food, yet insufficient money to buy it. Many rural areas have few shops and are at the end of supply and distribution lines. Thus, if fuel becomes expensive and/or resource shortages ensue, it is these hinterland regions that may go without. Living sustainably in a city may offer the advantages of better infrastructure, scavenging and bartering for essentials, building diverse communities, a reestablishment of local manufacturing, and meeting cultural needs. It may prove that a general re-skilling of a population is far more practical to achieve, within the networks of an urban population. All of the latter depends on cooperation between individuals and communities, and here is where the idea of transition and resilience begins to take root.[72]

19. Scientific research into permaculture

The positive results of permaculture are widely documented, and evidence for its many beneficial outcomes abound. Nonetheless, there has been little hard, rigorous scientific research and few peer-reviewed papers published on the subject[80]. The method is based on the principles of ecology and is one based on experience. It is very much underpinned by observations of nature, and arriving at an optimal design that is based upon, and works with, natural processes, in terms of optimising efficiency and doing "what works best". The processes that occur in nature are complex, both in themselves and because they involve holistic interactions between many different components, *e.g.* it is thought that there are more than one million different species of microbe in some soil samples. Clearly, applying the conventional reductionist approach, as we are familiar with in the physical sciences, to comprehend such an inordinately complex system, is likely to be of limited benefit. That noted, there are clearly demonstrable facts that can be determined by direct measurement, for example the way that soil fungi extract and mobilise phosphate from soil minerals, and at greater depth than would be allowed by the degree of penetration of the primary root systems of plants. In some cases, there appears to be a symbiosis between the fungi and soil bacteria[81], which are able to solubilise insoluble forms of phosphate in a soil such that it becomes accessible to the fungi. Soil science itself is a mature discipline, but deals with complex systems, and so tends not to fathom the depths of simple, often isolated, components, as do the physical sciences.

An exact study of permaculture is perhaps hampered by its own philosophy, and runs counter to it, since it extends beyond pure observations and measurements, and enters the consciousness and perception of each of us, our interactions with others and with the environment, and even our very beliefs and faiths. In this sense, it evades being pinned-down. Nonetheless, given the enormous potential of permaculture for providing food and materials, decontaminating the environment, and with minimal energy and other inputs, in the face of resource limitations of all kinds[82-86], for these reasons alone, its practices deserve serious scientific study and investment[87]. It would be a tragedy should we not take advantage of such a critical opportunity, while sufficient existing resources remain to do so.

Bill Mollison is famously quoted[9] as saying: *"If every university on Earth was destroyed we would lose nothing. If we lose the forests, we will have lost everything."*

I take this to mean that without proper care for the Earth we will lose our civilisation and hence our universities, but there is a deeper context, which is that the most important knowledge for us is that derived from observing nature, to urge humanity on to take practical actions that are in harmony with the natural ecosystems, rather than rarefied academic learning. Without such a universal perspective, we may not survive. Before, however, we do lose our universities, we might use their resource to create a resilient future for life on Earth.

20. The Green Revolution

The origins of the Green Revolution[88] are often attributed to Norman Borlaug, an American agricultural scientist who, in the 1940s, began conducting research in Mexico, and developed new disease resistant, high-yield varieties of wheat. These are plants bred specifically to respond to fertilisers, and produce a greater amount of grain per acre 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 Green Revolution methodology. In the early 1960s, India was facing mass starvation, because existing methods of food production were insufficient to match 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 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 productivity of a crop.

20.1. 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 fertilisers, which cannot grow without their application. Prior to the Green Revolution, substantive agriculture was largely confined to areas where the rainfall was appreciable, but though widescale 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.

20.2. Negative aspects of the Green Revolution

A major criticism of the Green Revolution is that its success has led to world overpopulation – 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, which has now passed 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[85]. 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, as alluded to in

Section 7. Ironically, large numbers of people who have been rescued 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 considerable 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.[89,90] Maintaining the Green Revolution has required a continuing, and possibly increasing, use of pesticides and fertilisers which have proved hazardous to the environment and toxic to humans and animals. The necessity to reduce these inputs, such that agriculture becomes more sustainable, is likely to once more reduce levels of food production, and at the time of greatest ever population. The situation is problematic, to say the least.

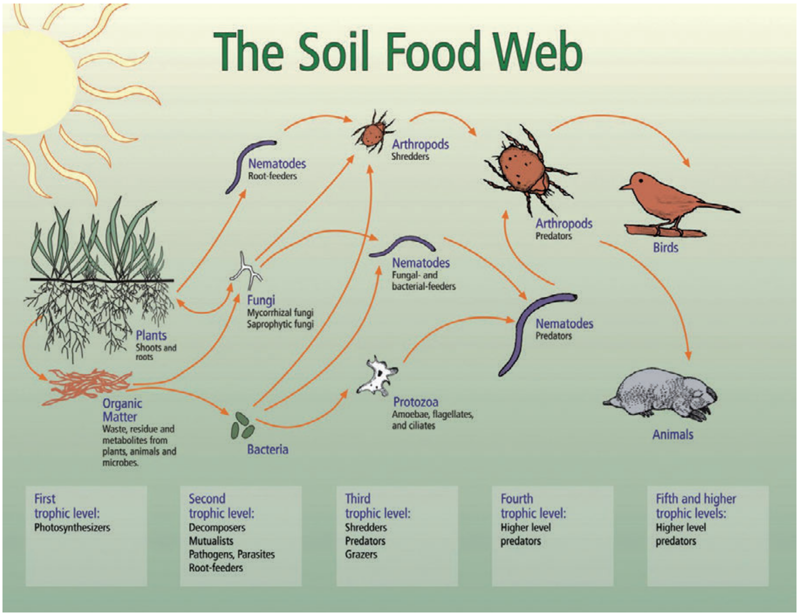

Figure 11 *The soil food web. Credit USDA.*

21. The soil food web

The term "soil food web" was coined by Dr Elaine R. Ingham, President of Soil Foodweb, Inc. (www.soilfoodweb.com) in Corvallis, Oregon. The soil food web[81,91] refers to the relationships between the wide range of living organisms found in soil, and is similar to the food chain, except that a typical food chain is linear. In contrast, the soil food web accepts the premise that a cyclical relationship exists between all flora and fauna, in the consuming by each of other species, or being consumed themselves

(Figure 11). As is discussed in Section 2, there are essentially two components of soil: minerals, which provide the the nonliving framework of the soil, and the food web, which includes minute creatures (soil biota), by whose agency the soil is converted to a living system. There are many forms and many roles for the soil biota: some (described as beneficials) contribute to the health of the soil and aid good plant growth; others (pathogens) can cause such undesirable consequences as root rots, blights, moulds, and mildews. Both beneficials and pathogens exist symbiotically and contribute to the natural growth/decay cycles in soil. Nonetheless, in a garden, the aim is to enhance the growth of the beneficial biota and suppress pathogens as far as possible. By increasing soil tilth, texture, aeration, drainage, and nutritional content - by feeding compost and other amendments to the soil, so that the soil food web functions smoothly – beneficials are encouraged, and the garden thrives.

A well-populated and properly functioning soil food web has the following consequences:

(1) Humus is created by the decomposition of organic matter.

(2) Soil structure is improved by binding soil particles together, with the creation of micro-aggregates.

(3) Plant roots are protected from diseases and parasites.

(4) Phosphorus, nitrogen and other plant nutrients are retained in the soil.

(5) Following point (4), a slow-release of nutrients to plants is provided.

(6) Water is retained in the soil.

(7) Enzymes and hormones are manufactured, which assist the growth of plants and aid their resistance to disease and to stress.

(8) Pollutants in the soil are decomposed, including herbicides and pesticides applied during "conventional" gardening practices.

The food web contains, and depends on, the following organisms (biota):

21.1 Bacteria

A teaspoonful of ordinary garden soil may contain billions of bacteria with thousands (in some cases perhaps a million) of different species, many of them specific to a region. Among their beneficial roles are that they aid the movement of water through the soil, recycle organic matter, and help avert soil diseases. Of the most important types of bacteria are those that fix nitrogen. Bacteria feed on humus, and produce a waste product called bacteria manure, which increases the organic component of the soil.

Many plants absorb nutrients highly efficiently from the bacteria manure, and hence the nitrogen-fixing bacteria are a primary source of nitrogen for them. Bacteria and their waste products are also consumed by many other soil life-forms, and thus the soil food web is nourished, as well as the plants that are grown in the soil. Lawns, flower beds, and most vegetables will flourish in soils dominated by beneficial bacteria – bacteria tend to become abundant in alkaline soils.

21.2. Earthworms

A soil that is teeming with earthworms is a healthy soil. However, these creatures are sensitive and may be killed by many commonly used pesticides and herbicides. Worms mix-in amendments, such as compost, when layered onto garden soil, and form tunnels through heavy soil which allows air to access the plant roots. Earthworms derive their nutrition from the many forms of organic matter that are present in soil, including decaying plant components, decomposing remains of animals, and living organisms such as nematodes, protozoa, rotifers, bacteria, and fungi. Thus, a worm can produce its own weight in castings (excrement) every 24 hours. During the digestive process, many insoluble minerals are solubilised and long-chain molecules such as cellulose are partially broken down by bacteria in the worm digestive tract. It has been demonstrated that fresh earthworm casts are several times richer in available nitrogen, available phosphates and available potash than is the surrounding topsoil. The abundance of beneficial bacteria in the ejected worm casting, is much higher than in the material ingested by the earthworm, and there are also beneficial enzymes present. The castings promote strong root growth and feed many soil biota. While an overpopulation of worms poses no real problem, soils rapidly lose their fertility when there are too few worms present.

21.3.Fungi

Contrary to popular wisdom, fungi are vitally important to soil health, and beneficial strains are found in virtually every kind of soil on this planet. Fungi break down organic matter by digesting and excreting humus, thus recycling nutrients through the soil food web, much as bacteria do. Probably the better known fungi are the Mycorrhizae, which attach themselves to the roots of plants and create a mesh of fine feeder "rootlets" (hyphae). Through osmotic and other gradients, the hyphae are able to deliver nutrients and water to the host plant's root system, vastly expanding the functional surface area of the roots (Section 10). Fungi tend to flourish in acidic soils. Soils in forests are dominated by fungi, over bacteria, a balance that must be maintained by leaving the leaves that fall to be absorbed by the soil. Common practice is to remove the leaves, to give a neater appearance to the ground, but the soil is deprived of important nutrients in this way. To help the leaves to decompose more quickly, and also to avoid their smothering other plants as they try to grow, they should be shredded and returned to the forest floor as mulch.

21.4. Arthropods

Arthropods are invertebrate creatures with an exoskeleton (external skeleton), a segmented body, and jointed appendages. Arthropods are members of the phylum Arthropoda (from Greek *árthron*, "joint", and *podós* "leg", which together mean "jointed leg"), and include the insects, arachnids, and crustaceans. Arthropods feed on bacteria, fungi, and earthworms, along with plant particles. They include microarthropods — very small organisms such as mites — and larger organisms, such as sow bugs, springtails, spiders, and centipedes. Microarthropods tend to remain in the soil, consuming debris and facilitating the availability of nitrogen and other nutrients to plants and other soil biota. Arthropods control the population of other organisms in the soil, helping to maintain a natural balance of species in the soil food web.

21.5. Nematodes

Along with fungi, nematodes are commonly assumed to be pathogens. The truth is that fertile garden soil contains a substantial population of beneficial nematodes, which feed on many other creatures, from bacteria and protozoa to other nematodes, including the pathogenic varieties (Figure 12). Nematodes support root growth, and *via* their manure, pass vital nutrients along to plants. Pathogenic nematodes consume plant tissue and impair the healthy growth of roots. In a well functioning soil food web, beneficial nematodes help to keep the number of their pathogenic counterparts in check.

Figure 12 *Whiplike larva of root-knot nematode, "Meloidogyne incognita", magnified 500x, shown penetrating a tomato root. Once inside, the larva establishes a feeding Site, which causes a nutrient-robbing gall. Photo by William Wergin*

21.6. Protozoa

Soil-dwelling protozoa are single-celled organisms which consume bacteria, and help to keep down the population of pathogenic bacteria.

They produce manure which is rich in available nitrogen and can be taken up by plants. Nematodes and other soil fauna consume protozoa, and release nitrogen and other nutrients back into the soil in their excrement.

21.7. Stability of food webs

Mathematical modelling of food webs has raised the question of whether complex or simple food webs are more stable[92]. Until the last decade, it was believed that soil food webs were relatively simple, with low degrees of connection and omnivory (consumption at more than one trophic level, sometimes referred to as intraguild predation) between different elements. This notion was derived principally from mathematical modelling studies which predicted that food webs were destabilised by complexity. These models used community matrices, in which species were randomly linked with random interaction strengths, and seemed to show that local stability was inhibited as the degree of complexity (measured as connectance) increased, by diversity, and a greater average interaction strength between species[92].

However, it was recognised in other fields of ecology, that the food webs used to construct the "random" models were grossly oversimplified, and did not represent the complexity of real ecosystems. Indeed, actual soil food webs do not function according to these predictions, and it was discovered that omnivory in food webs is common, and that food chains can be long and complex, yet still be resilient to the effects of drying, freezing, and fumigation of the soils in which they function. There are probably a number of reasons why complex food webs are associated with stability. Complex food webs may be more stable if the interaction strengths are weak, and real soil food webs seem to comprise many weak interactions and a few that are much stronger. The structure of the soil can act as a buffer medium, by keeping different organisms separate, and thereby prevent strong interactions between them. Bacteria, among other soil organisms, have an intrinsic resilience mechanism, in that they can remain in a dormant state during periods of external stress, but reproduce rapidly once conditions improve. It is important to note that the stability of the system is reduced by the use of nitrogen-containing inorganic and organic fertilisers, which raise the acidity of the soil to the detriment of its biota. Despite their limitations, food webs are a very convenient way of describing ecosystems, and the interactions between soil organisms and their influence on decomposition processes – soil maturation – are the subject of serious investigation[92]. Lacking, however, is information about the long term stability of soil food webs, and their temporal evolution, which is key to understanding food webs as the principal determinants of soil fertility.

22. Effects of biochar on soil biota.

Biochar is charcoal, and the alternative term specifies the particular use of the latter as a soil amendment, intending to improve soil fertility and mitigate climate change by locking-up carbon captured from the atmosphere by photosynthesis, in a relatively stable form in soil. By means of pyrolysis, the biomass is converted to biochar (charcoal), which may be buried in soil, where it is thought to be stable over hundreds of years. Thus, the method constitutes a carbon capture and storage (CCS) technology. However, there is more to biochar than this, since although it is stable to decomposition in soil, it is not entirely inert in this environment, where it provides an active amending agent. This is a consequence of various factors, including cation- and anion-exchange, direct physisorption and chemisorption. The properties of the biochar are altered by ageing in the soil, which appears to be mostly due to surface oxidation of the biochar particles. It has been proposed that the tiny pores in the biochar might provide "condominiums", where soil microbiota – principally bacteria - can live, thus encouraging their growth, although actual proof of this case is little more than circumstantial. In any event, it is of considerable interest to know how the prevailing biota react to the intrusion of this foreign material. However, from the results available for scrutiny, the phenomenon is extremely complicated and does not lend itself readily to overview. This is illustrated clearly from a review[93] by Lehmann *et al.*, from which few generalities and predictions can be made. In many cases, the data are too limited to draw firm conclusions as to what is going on, and this is particularly true of attempts to determine the influence of biochar on soil fauna populations, other than earthworms. In general, it can be said that the presence of biochar increases the abundance of bacteria, *e.g.* in soil and wastewater, and also in bidigesters for producing methane. In general, too, the presence of biochar raises populations of mycorrhizal fungi, but there are exceptions. There are published investigations of the use of charcoals as soil amendments (before the word "biochar" had been coined): for controlling pathogens, for delivering inoculants, or for sorbing signalling-compounds and toxins. Absent from the soil biology literature are direct investigations that address the large variations in the physico-chemical properties of biochars, and accordingly there is little to draw upon from which to elucidate the mechanisms by which biochar influences soil microorganisms, fauna and plant roots. Furthermore, the sorptive properties of biochars confound the standard extraction procedures used to determine the biomass of soil microbes and enzyme assays; a situation that is further complicated by the varying quantities of minerals present. It has usually been found that when biochar is added to soil, the microbial abundance increases, and it appears that changes in the nature of the microbial community and enzyme activities may account for

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the influence of biochar on elemental cycling, plant pathogens, and crop growth. However, practically nothing is understood regarding the mechanisms by which biochar are able to affect the abundance and types of microbes in soil. Other than several studies of its effects on earthworms, the influence of biochar on soil fauna is quite unkown. Nonetheless, such phenomena as sorption, pH and various physical properties of biochars, including pore structure, surface area and mineral composition provide important determining factors in the interaction between biochar and soil fauna; the co-concentration of various resources (*e.g.* nutrients) in and around biochars is likely to play an important role. An increased abundance of soil biota is probably due to the sorption of growth-inhibiting substances by the biochar.

There have been a few reports that mycorrhizal fungi are inhibited by biochar, but rather than any direct effect of the material, it is more probable that by increasing the concentration of nutrients, by release from biochar particles, the normal symbiotic plant–root–fungus hyphae system is inhibited, since the plant roots are already nourished by this external nutrient input. As a corollary to this observation is the experience that heavy use of fertilizer (*e.g.* phosphate) may discourage or damage the growth of fungi[93].

23. Will "fracking" render the "peak oil" concept obsolete?

In a nutshell, the answer to the question posed in the sub-heading is, "no". Similarly, the media message that "peak oil is over", on account of alleged large new finds of conventional crude oil, is also misleading. However, the issue is critical, since whether peak oil[86] is a real and impending event, or a phantom, determines implicitly whether or not humanity needs urgently to break its dependence on crude oil.

Leaving aside for the moment the issue of climate change, and that transportation is culpable for one third of human emissions of CO_2, if we are to be spared an imminent decline in the production of crude oil, we can expect fuel supplies to remain plentiful and continue with business as usual for the foreseeable future, and that includes continuing to produce our food using contemporary, high-input, farming practices. In which case, who needs permaculture? The issue of declining rock phosphate fertilizer is one nail in the coffin of industrialised agriculture, irrespective of the oil situation (albeit that, as noted, the two are connected), but let's look a little more closely at fracking for shale gas and shale oil, which has led to a promise of energy independence for the United States, if not the rest of the world.

The process of hydraulic fracturing (called frac'ing in the industry but fracking in the media) has been used since 1947 to fracture impermeable rock so that oil and gas may be recovered from it[83]. A hydraulic fracture is formed by pumping a fracturing fluid into a borehole drilled into the source-rock so that the downhole pressure exceeds that of the fracture gradient of the formation rock. The pressure causes the formation to crack, whereupon the fracturing fluid enters and extends the crack more deeply into the formation. To keep the fracture open once the injection is complete, a solid proppant, commonly a sieved round sand, is added to the fracture fluid. The propped hydraulic fracture then becomes a high permeability conduit through which the formation fluids can flow to the well. For the extraction of shale gas, wells are dug vertically into the ground and then branched off horizontally into the shale, making the gas far more accessible. The wells are sunk vertically (ftp://ftp.eia.doe.gov/natgas/usshaleplays.pdf) to depths of typically up to 1,000 m (or more than twice that for the Marcellus Shale) and drilled out horizontally to distances of up to 3,000 m.

Natural gas is the cleanest-burning hydrocarbon fuel, and North America has vast reserves which, it is claimed, could replace petroleum products from overseas. The development of techniques for horizontal drilling has made it economical to extract the gas from shale seams that were previously considered to be inaccessible[83].

Since the fracturing (fracking) fluid contains various toxic materials, including hydrocarbons, benzene *etc.*, there are fears that these may leak out, along with methane, and contaminate *e.g.* aquifers from which drinking water is drawn. However, two studies, one from Duke University and another from the University of Texas found no evidence for any leakage of fracking fluid into the water supply. In respect to methane leaking into the groundwater, there is a video (http://www.youtube.com/watch?v=PRZ4LQSonXA) on YouTube showing tap-water so heavily contaminated that it can be ignited. Hence, there is cause for concern, and while the Texas team is of the opinion that fracking is not the cause, the earlier study by Duke University found a build-up of methane in water near fracking drills. There are issues of high natural levels of methane in the groundwater in the Marcellus Basin and inadequate disposal of wastewater from gas-drilling operations. The matter is therefore complex and remains to be fully resolved[94].

So, can the USA become energy independent through fracking? US domestic gas production is predicted to fall by 20% over the period until 2035. This reflects a –29% fall in conventional gas production and –4% in coalbed methane, and other than a +9% increase in offshore gas production, shale gas would need to compensate for this shortfall, even before any expansion of total gas production output could be achieved with it. An increase of +26% is expected for total gas production in the

USA by 2035, which falls far short of the amount necessary to deliver all the promises made for shale gas[95]. There is no doubt that the reserves of shale gas are very high, and thus it is claimed that the USA has "100 years worth" of gas, all told[96]. Even assuming the EIA forecast for growth in shale gas production can be achieved; there is little chance of a wholesale replacement of coal for electricity generation or oil for transportation by shale gas. Replacing coal by gas would require a 64% increase of gas production from the quantity produced in 2009, and to use gas to run heavy vehicles a further 24% and light vehicles yet another 76%[97]. Any such lifetime for a reserve is determined as the R/P ratio, which is defined as the known economically recoverable amount (R) divided by the current rate of production (P) of it. The R/P ratio analysis is of course a gross approximation, since a given amount of a resource/year cannot be produced constantly, right up to the bitter end. Rather, as has been demonstrated for the production of all kinds of materials, a peak is found, and beyond which (P) declines, in reflection of falling Energy Returned on Energy Invested (EROEI), *i.e.* the material becomes increasingly hard to get. But even accepting the R/P "100 year" reserve lifetime, that timescale refers specifically to current rates of use, and as growth in demand increases, the time before it is exhausted closes sharply, *e.g.* to 37 years for a 5% growth[95]. Moreover, the production decline rates from shale gas wells are very high, of the order of 65 – 80% within the first year, and a substantial further decrease over the following year. Accordingly, outputs tend to fall far short of the initial production of a well very quickly. For this reason, continuous drilling is required to maintain an overall gas-output from a field, and to achieve actual growth in production, new drilling installations must be implemented rapidly and relentlessly – "Drill, baby, drill". This situation has been compared with trying to run up an escalator that is moving downwards, and fast. To establish an increase in the overall rate of production, a rapidly rising (exponential) concentration of new wells must be drilled. It is thought that around one million new wells will need to be drilled by 2035, to achieve projected production of shale gas across the world. The upshot is that rig fleets of enlarging capacity must be inaugurated on a continuous basis, and so the effort *en mass* becomes increasingly capital-intensive, and ultimately, growth must plateau according to limitations of the number of skilled workers and investment available. Since this will be offset by a loss of conventional gas production, an overall production decline must finally ensue – "peak gas". Moreover, the "100 years worth" figure has been disputed, and known proved plus probable reserves sum to a supply of nearer 21 years[96], again at present rates of use for gas. If a wholesale switch from coal and oil to gas were to occur, to replace fuel for power production and for heavy vehicles alone[97], the gas would be used up

88% faster, *i.e.* in about 12 years. Shale gas has become an increasingly important source of natural gas in the USA over the past decade, and interest has spread to potential gas shales in the rest of the world. In 2000 shale gas provided around 1% of US natural gas production, but this has increased to > 20% by 2010. The US government's Energy Information Administration (EIA) predicts that by 2035, 46% of the American natural gas supply will be provided in the form of shale gas[98]. In the light of the above considerations, this does remain speculative, and unlikely should a massive increase in the production of gas become necessary to replace coal and oil-refined fuels. The world situation for shale gas is less clear, both in the quantities that may be finally recovered, and indeed in its quality: *e.g.* a recent exploratory well drilled in Poland produced a gas so heavily contaminated with nitrogen that it wouldn't burn[99]. While feasible technology exists to clean a gas containing say 6% N_2, the Polish gas contains nearer 50% N_2, hence the overall EROEI would probably be less than unity and the gas useless as a fuel source. The
gas samples also showed levels of hydrogen sulphide that are appreciable given its toxicity.

What about the situation for actual crude oil, rather than gas? One must be careful to distinguish between shale oil and oil shale. Oil shale is neither oil nor shale, but is organic marlstone (porous rock) containing kerogen (a complex, primordial, solid material) that requires considerable inputs of energy (heat) and water to decompose it into a material resembling crude oil – a process that has yet to be performed successfully on a commercial scale. Shale oil is also known as tight oil, and is actual crude oil trapped in an impermeable rock, which must be pulverised by fracking to get the oil out of it. But how substantial are the reserves? For the world situation, the likely recoverable quantity is unknown, but according to the US Energy Information Administration (EIA), the total technically recoverable resources of oil from deep shale amount to 24 billion barrels[100]. While this measure of a "resource" tells nothing about how much of it will actually be economically recoverable (the "reserve"), we may deduce that at a world consumption of around 30 billion barrels of crude oil per year, this is enough for about 9 months, or 3 years for the US alone. It is thought that this tight oil will be produced at a rate of 1.3 mbd by 2030. Similarly to the case for shale gas extraction by horizontal drilling and fracking, the wells deplete by around 80% of overall production during the first two years, and so a continual drilling programme will be necessary, with a new well being drilled every couple of years to maintain output. Since the total oil consumption by the USA is expected to remain close to 15 mbd until 2030 (the US exports over 3 mbd, making total oil use around 19 mbd), and its own oil production (conventional crude, plus tight oil) to peak in 2020 at 6.7 mbd, and decline thereafter[100], clearly America will be importing crude oil throughout this entire period. Other large oil "finds"[101] offer little more comfort, since a similar calculation indicates the amount of time "bought" for each: Jubilee Field (Ghana, 1.8 billion barrels, Gb), 22 days; Chicontepec Basin (Mexico, 10 Gb), 122 days, but this is heavy crude and at present too expensive to extract; Kashagan Field (Kazakhstan, 11 Gb), 134 days; (Supergiant fields in Iraq's southwest desert, 45-100 Gb), 3.3 years, at best; Santos and Compos Basins (Brazil, 123 Gb), 4.1 years; Orinoco Belt (Venezuela, 513 Gb), 17.1 years. There are massive environmental costs too, and strip-mining the ultra heavy Venezuelan oil will effectively leave a huge swathe of the country polluted and barren (*c.f.* Canadian oil sands). The EROEI will be relatively low too: 3 – 5, *e.g.* as compared with 10 – 20 for conventional crude oil. Even if all of this new oil could be extracted, it adds up to a total of 25 years worth for the world, and assuming the normal behaviour of oil wells, production, if started simultaneously for all these oil fields would peak in 12.5 years. Finally, we must mention the oil sands (tar sands) in Canada that are also proposed could make the US energy independent. [The term "tar sands" is more accurate than "oil sands", since the material does not contain oil as such but bitumen, which saturates naturally occurring mixtures of sand, clay and water, present in loose sand or partially consolidated sandstone. The bitumen is washed out of the mineral using copious quantities of very hot water, and so is very demanding in both energy and water].

Production of oil sands was projected to increase from 1 mbd in 2006 to 2.8 mbd in 2012, and yet it is still only 1.6 mbd. The EROEI for oil sands "oil" production is estimated at 7.1 but this drops to 3.1 once it has been "upgraded" into fuels.[102] Other analysts put the EROEI as low as 1:1, implying that the process overall barely breaks-even, if it does at all. Since it takes one fifth of Canada's natural gas demand to provide heat to extract the process the bitumen from oil sands, and to produce each barrel of "oil" requires between two and four tonnes of oil sands plus between two and four barrels of water, the process is extremely wasteful of resources, and probably not worth the effort.[103]

The US imports a total of around 9 mbd of petroleum products from other nations, including OPEC. US domestic production of oil is claimed to be 10.1 bbd, but this breaks down to 5.7 mbd of actual oil, including lease condensate production (56%), another 2.2 mbd of natural gas plant liquids (22%) plus 1.1 mbd of corn ethanol (11%), with refinery gains accounting for another 1.1 mbd (11%)104. While total "oil" use in the USA is down in 2012 at 19 mbd from 21 mbd in 2007, it seems likely that the nation will be importing crude oil and petroleum products for the foreseeable future.

Indeed, oil production statistics are somewhat confounded[104,105] by the reference to "liquids" rather than "oil", which includes hydrocarbons that are recovered, sometimes in great quantity, from oil-and gas-wells: they are in the gas-state at the high temperature of the reservoir, but condense in liquid form once the temperature drops below the dew-point at the well-bore. The latter are called lease condensates, and to their volume may be added natural gas plant liquids NGPL: hydrocarbons that exist in fields as constituents of natural gas but which are recovered separately as liquids, including ethane, propane, butane and pentane – refrigeration is necessary to liquefy ethane and propane. Thus, while the production of crude oil (including lease condensates) per se may have flattened worldwide at around 74 mbd at the end of 2004, total liquids increased to 90.7 mdb in the first quarter of 2012. The volume of total liquids is increasing because of a rising production of natural gas plant liquids and to a far a lesser extent, biofuels. Taking crude oil, lease condensate and liquids extracted from natural gas alone, the 2011 total world output of "oil" was 87 mbd.

According to the US Energy Information Administration (EIA)105, "the

NGL Attribute Summary eia

Natural Gas Liquid	Chemical Formula	Applications	End Use Products	Primary Sectors
Ethane	C_2H_6	Ethylene for plastics production; petrochemical feedstock	Plastic bags; plastics; anti-freeze; detergent	Industrial
Propane	C_3H_8	Residential and commercial heating; cooking fuel; petrochemical feedstock	Home heating; small stoves and barbeques; LPG	Industrial, Residential, Commercial
Butane	C_4H_{10}	Petrochemical feedstock; blending with propane or gasoline	Synthetic rubber for tires; LPG; lighter fuel	Industrial, Transportation
Isobutane	C_4H_{10}	Refinery feedstock; petrochemical feedstock	Alkylate for gasoline; aerosols; refrigerant	Industrial
Pentane	C_5H_{12}	Natural gasoline; blowing agent for polystyrene foam	Gasoline; polystyrene; solvent	Transportation
Pentanes Plus*	Mix of C_5H_{12} and heavier	Blending with vehicle fuel; exported for bitumen production in oil sands	Gasoline; ethanol blends; oil sands production	Transportation

C indicates carbon, H indicates hydrogen; Ethane contains two carbon atoms and six hydrogen atoms
*Pentanes plus is also known as "natural gasoline." Contains pentane and heavier hydrocarbons.

Figure 13 *Different uses for Natural Gas Plant Liquids (NGPL).*

term ‘liquid fuels’ encompasses petroleum and petroleum products and close substitutes, including crude oil, lease condensate, natural gas plant liquids, biofuels, coal-to-liquids, gas-to-liquids and refinery processing gains.” Since the major gains in production have been in the form of NGPL, it is a matter of some importance to consider the exact properties of these materials in comparison with conventional crude oil, particularly in relation to providing liquid fuels. As the following data[106] show, a barrel of these liquids contains far less energy than a barrel of crude oil (6.12 GJ), natural gasoline (4.87 GJ), iso-butane (4.19 GJ), n-butane (4.56 GJ), propane (4.05 GJ), ethane (3.25 GJ) – data from original source converted from Btu to GJ. Moreover, they are far from being “close substitutes” for crude oil, in terms of their molecular and physical composition, and are mainly used for other purposes (Figure 13). The major single component of NGPL is ethane (42%), which is converted to ethylene mainly to make plastic from. Roughly 28% of NGPL is propane, which is mostly used to run small heating appliances, e.g. barbecues. It is claimed that there are 17.5 million road vehicles worldwide that run on propane, which amounts to 1.7% of the total number of just over one billion. Clearly, a vast number of vehicles would need to be retrofitted to run on propane, rather than liquid fuels refined from crude oil, to make any real difference. The caveat is that propane only constitutes around 5% of all raw natural gas production and so there are limitations on its supply.

In the USA, more oil is used as “heating oil” to run boilers/heating systems in buildings than is the case in Europe, and so switching these systems to run on natural gas would indeed save oil for vehicular fuels and other purposes. That said, the implementation of new natural gas fired infrastructure would be staggering. Similarly, oil and its derivatives provide half the electricity used in Saudi Arabia, and at a growth in demand of 8%/year it has been predicted that the Kingdom will become a net oil importer by 2030. Saudi already uses all its natural gas production for domestic purposes, and is seeking to develop nuclear and solar power on a grand scale, in order to preserve precious crude oil for export, which provides 86% of its national income[107].

Overall, the procedure of combining NGPL and crude oil, in the same tally, seems a little disingenuous and rather misleading against an expected decline in actual conventional crude oil production by 3.4% (3 mbd/year)[49], since the two are not the same thing at all or even “close substitutes” in terms of what they can be used for. Globally, NGPL provides around 9 mbd, biofuels, coal-to-liquids and a very small amount of gas-to-liquids altogether provide another 2 mbd[105]. Another 2 mbd is due to “refinery gain”, which is not real additional oil (or liquids) production, but measures the increase in volume of the total products obtained *e.g.* from cracking heavy oil[105]. Indeed, it can be considered as a measure of the energy expended to "refine" crude oil. Biofuels are highly limited by the available area of worldwide arable land, as noted earlier, in competition with food production. Since it will be necessary to bring more land into production to feed a rising world population, biofuels are unlikely to rise in volume above their present 2 mbd, even if that level can be maintained. In short, whatever the hype about accessing new energy sources through fracking, peak oil and its consequences remain with us.

24. Conclusions

Curbing our demand for energy, and using energy more efficiently, are the cheapest and most practical means for cutting carbon emissions and enhancing resource security. To implement energy sustainability, we must devise ways to reduce our demand for energy and make the best use of the fuels that we cannot avoid burning. Critically, there are zero emissions from hydrocarbons that stay in the ground. Costly and energy-intensive "solutions" such as carbon capture and storage (CSS) and methods of geo-engineering are not sustainable in energy terms. Nonetheless, to refer to an umbrella "energy crisis" or "energy crunch" is misleading.

What humanity is most immediately confronted with is a "liquid fuels crisis", which will be the most strident heralding that peak oil has arrived. Quite simply, we need to travel and move goods around far less than we have become used to, as our world has become increasingly global.

However, to implement energy supply limits and demand reduction in the use of energy runs counter to vigorous economic growth, and will be understood by some as "ruining the global economy". For this reason, very probably, a large cohort of policy makers, energy analysts and environmentalists avoid espousing explicitly the nature of our predicament. While this may save political face, and not discourage voters at the next election, it is the far longer future that is at stake. Although the problems facing us are unequivocally daunting, there are many courses of action available to us, with which to construct a resilient societal and natural environment, and largely through the process of localisation. Yet, we will be blinkered from taking the correct and necessary path while we labour under false pretexts about the amount of resources and energy likely to be available to us now and in the immediate future.

It makes little difference if the peak in conventional oil production is 10 years away, rather than right now. If that date could be pushed ahead to 20 years distant, *e.g.* through fracking, it would still make little difference. If we really did have 100 years worth of hydrocarbons, oil and gas, or even 50 years, then it would matter, because it might buy us enough time to transition to a resilient, carbon-free society. But, human nature being what it is, such a seemingly far off event would persuade us to carry on with business as usual, and we would leave any actions for future generations to take, meanwhile pouring carbon dioxide into the atmosphere, as a further compounding of a legacy they are already unlikely to thank us for. The 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, are unconvincing in the face of proven reserves, rather than estimated resources. Resources are optimistic quantities, including all that might be theoretically possible, whereas reserves are those whose recovery is economically realistic. Thus, even if there are vast amounts of oil and gas in the ground, it is the rate of recovery that is crucial to meeting demand.

Furthermore, because of the rapid depletion rates of flow from gas wells that are accessed by fracking, it will be necessary to drill continuously and relentlessly to maintain output, and this is limited by the level of investment, equipment, technology and trained personnel required to do this. In terms of averting or postponing peak oil, how much shale gas there is to be fracked out is a red herring, since it would be necessary to convert vehicles to run on natural gas rather than liquid fuels refined from crude oil. Clearly, it would take a considerable time to so convert anywhere near the around one billion vehicles that run on the roads of the world. 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. Beyond oil and gas, there are limits to other resources of all kinds, and which are tied-in with peak oil since the whole extractive system, of mining, processing and transporting final products of metals and fertilisers is underpinned by oil-refined fuels. Water too is a fragile resource, and along with a lack of rock phosphate and synthetic nitrogen fertilisers, will set a decline in industrialised agriculture. 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. Thus these methods offer the means to feed and heal the World, and create a truly resilient and meaningful future. That said, the path we choose to attain these objectives is critical.

" It is good to have an end to journey towards, but it is the journey that matters, in the end."

Ursula Le Guin.[109]

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