What is the Role and Importance of Soil Biology and the Soil Food Web in Sustainable Agriculture?

by Martin Parsons

1. Introduction

Agriculture has been with us for around 12,000 years and, when practiced sustainably, it has enabled human population increases to levels that would otherwise have been impossible. But it is within the last one hundred years that farming, certainly in western world countries such as the UK, has undergone change at a rate never previously seen. In the last century, we have moved away from farming with horses, to farming with mechanical tractors that could be maintained and repaired by a competent mechanic with using hand tools, and on to today's tractors that have electronic control modules for managing engine and machine systems, and can be guided by GPS systems to an accuracy of +/-2cm. At the same time field sizes, machine sizes, and tractor powers have increased significantly. Today the average power for tractors sold in the UK is well over 150bhp, and tractors with 400bhp or more are not uncommon. All this has taken place in a little over one generation.

2. Current Achievement

Here in the UK, agricultural production is now worth £5.3bn annually[1]. Every day, worldwide agriculture produces 23.7 million tonnes of food, uses 300,000 tonnes of fertiliser, and 7.4 trillion litres of water for irrigation[2], whilst covering 38% of the Earth's surface[3]. During this time total world population has grown from less than 2 billion to over 7 billion.

3. Issues Arising

However, there are issues arising from many of today's farming practices. These include emissions of climate changing greenhouse gases (GHG), eutrophication, excessive extraction of ground freshwater, soil degradation, soil compaction, and loss of biodiversity. Soil degradation is perhaps the most under-reported of these issues, but it is now a critical problem around the world[4]. In 2015 the UN secretary-general Ban Ki-moon noted 'We degrade 12 million hectares of productive land every year….. More than half our farmland is degraded. Through land degradation and other inappropriate land use, we release about a quarter of the greenhouse gases. Climate change and unsustainable land use, particularly by agriculture, are contributing to the decline in freshwater resources in all regions of the world'[5].

In 1982 it was estimated that the USA was losing over 3 billion tonnes of topsoil annually from its cropland[6,7]. In the latter half of the twentieth century, nearly one-third of arable lands worldwide were lost to erosion and taken out of production. In Asia, Africa and South America, annual soil loss was about 31 tonnes/hectare[8]. In the UK, Cranfield scientists estimate that soil degradation is now costing us between £900 million and £1.4 billion per year[9,10]. This loss of soil results in loss of food production services, reductions in soil carbon sequestration, loss of organic matter and nutrients, loss of soil biota, reduced water infiltration and reduced water holding capacity[8,9,11]. The significance of this loss was recognised by F.D. Roosevelt, who in 1937 wrote, 'A nation that destroys its soil destroys itself'[12].

Soil degradation is part of land system change, and is one of the nine planetary boundaries identified in 2009. Others include i) atmospheric CO_2 loading, ii) biosphere integrity, iii) biogeochemical nitrogen and phosphorous cycles, and iv) global freshwater use. Farming and agriculture contribute to and hence impact these parameters. Hence the way that we practice agriculture impacts the space within which we live. The objective of this paper is to investigate how healthy soil biology can contribute to sustainable farming and reducing the impact of agriculture on planetary boundaries.

4. Early Agriculture, Old Testament and the Land

In its twelve millennium history, agriculture has sometimes it has been practiced in a sustainable manner, and for example, in some parts of China the same fields have been farmed for over 4,000 years[13]. In other cases farming practices have been unsustainable, leading to either the abandonment of the land, or even the collapse of society[13,4].

In the early days of agriculture, the Promised Land given to the Israelites was a small and fragile land, only marginal for agriculture. The picture of a land flowing with milk and honey suggests goat herding and wildflower meadows for bees. Moses, a great preacher of land care, acknowledges their land was unlike that of Egypt, with the Nile and its well-watered flood plains. Instead Israel has to rely on rainfall. Nearby were the great agricultural empires of Egypt and Mesopotamia, yet the abundant writings of these empires lack the keen sensitivity to matters of land care that pervades Israel's scriptures[8]. But Israel is a land over which the Lord keeps watch, and agriculture becomes a central theme running through the Old Testament.

The Israelites were given guidelines to ensure the land had it's rest, so that it did not become farmed out[14] (Lev26 v34). They were also given laws to ensure that land ownership was retained within families, and did not end up being bought up by the rich, leaving the poor without a means to grow food (Lev25 v28). They were also warned against joining field to field (Isa 5 v8), perhaps not just as a warning against greed and controlling food supply to others. Large fields would mean less trees and hedgerows, both of which provide habitat for wildlife, and are known to reduce the risk of soil erosion. Trees are also important for drawing up essential trace minerals from deeper in the ground and making them available to plants and crops[15]. In addition, trees can increase the amount of rainwater that the surrounding soil can absorb, and by a factor of up to 67 times[16]. Britain is now one of the least wooded nations in Europe, with just 13% of woodland cover.

Later in the Old Testament many of the ancient prophets spoke against an exploitative agricultural economy, one that they recognised to be destructive to human communities and the land itself. These prophets preached that a society which misuses land, and abuses those with the skill and passion to care for it, stands in fundamental opposition to God (Micah2 v1-3).

In total, the Bible speaks of 'land' and 'soil' over 1800 times. Scripture sees land as very precious, and reminds us it is not ours to do with as we please. Even pre-fall, eating from the tree of knowledge was forbidden, so there was no moment in human history when we could obtain our food safely without observing limits. This theology and awareness should surely influence how we practice agriculture in the 21st century. But today we are losing not just our soil, but also our biodiversity at a rate that represents a crisis[17,18].

5. Fertile Soil and the Soil Food Web

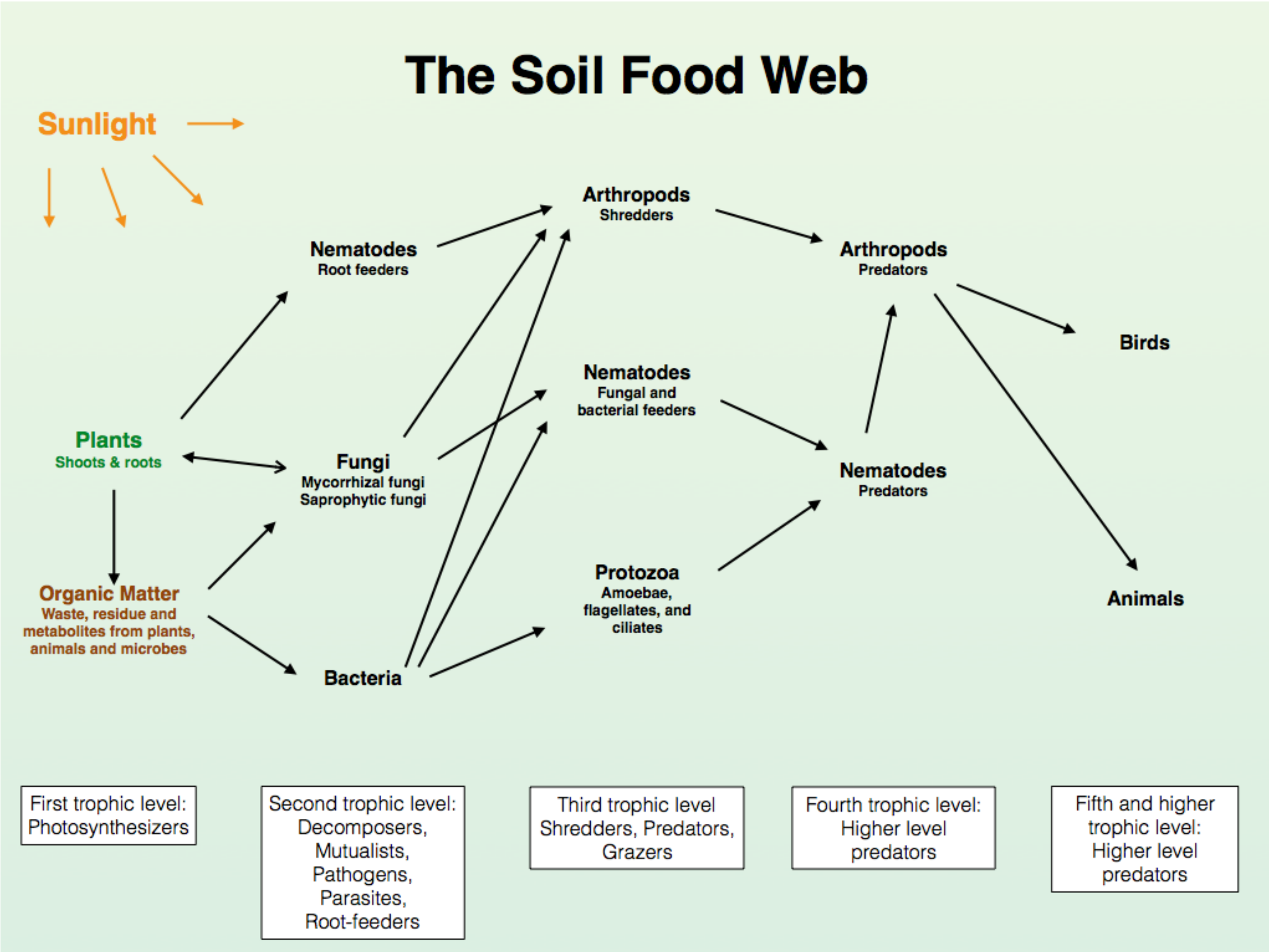
How do we define fertile, healthy soil? There are three aspects to consider - the physical, chemical and biological characteristics[19].

Physically, healthy mineral soil is generally made up of about 45% mineral material, 25% water, 25% air, and up to 5% organic matter[20,21]. Heavy machinery such as today's large tractors and harvesters can result in significant soil compaction, which reduces the amount of air available in soil, and the ability of soil to absorb moisture and rainwater.

Chemically, a fertile soil will also have a whole range of different elements present. It is now accepted that in addition to carbon, oxygen and hydrogen, healthy plants and crops need circa nineteen mineral elements, to carry on life processes[22]. These include
- macronutrients such as nitrogen, phosphorous, sulphur, potassium, magnesium, and calcium
- micronutrients such as iron, manganese, zinc, copper, boron, molybdenum, chlorine and nickel
- beneficial elements such as sodium, silicon, cobalt, iodine and vanadium

But in order to be available to plant life, it is important that these mineral elements are present in a suitable form that the plant can absorb. The biological life in healthy soil (the 'Soil Food Web') plays a vital role in facilitating this.

The Soil Food Web and its biological life can be represented as below. It is crucial for soil fertility.



The Soil Food Web

(based on work by the United States Department of Agriculture)

The start of the soil food web is the input of organic matter - the food for the bacteria, fungi and nematodes at the bottom of the food chain. The arrows in Fig.1 represent a series of conversions of energy and nutrients, including organisms eating other organisms. The role of the soil food web is to break down nutrients until they become temporarily immobilised in the bodies of fungi and bacteria and then mineralized. It is this mineralization process that makes the minerals available in a form that the plant can use. Governed by its chemical make-up, a healthy fertile soil typically will have a pH level in the range of 6.2 - 6.8, which is close to 'ideal' for most arable soils and crops.

Achieving and optimising all these physical, chemical and biological factors helps maximise the 'Cation Exchange Capacity' (CEC) of a given soil type, which is a measure of how many nutrients a soil can supply to the crop, and is therefore a fairly good indicator of a soil's fertility[23]. It should be noted that the CEC of a soil will also vary depending on the ratios in which clay, silt and sand size particles are present, with clay soils having the highest capacities.

6. How Nature Farms

Achieving fertile soil and hence healthy plant growth in a sustainable manner, is something that nature manages on her own without any input from humanity. Observing nature reveals much that should inform our approach to sustainable agriculture. Wendell Berry summarises it as[24]:

- Mother Nature never attempts to farm without livestock
- She always mixes her crops
- Great pains are taken to preserve the soil and prevent erosion
- The mixed vegetable and animal wastes are converted to humus, there is no waste
- Growth and decay balance one another
- Ample provision is made to maintain large reserves of fertility
- The greatest care is taken to store the rainfall
- Both animals and plants are left to protect themselves against disease

These principles from the natural world give important clues to sustainable farming. They were particularly noted by Sir Albert Howard[13], (1873-1947), an agricultural scientist who regarded nature as the supreme farmer. Howard sought to learn how nature manages her kingdom, in order to apply the same principles to farming. He became one of the pioneers of sustainable organic farming.

The principles of Farming God's Way[25], as Brian Oldrieve believed were revealed to him by the Lord in Zimbabwe in the 1980's, have many similarities with how nature farms, and were pivotal for Brian, and many others, in restoring degraded land, building soil fertility, and increasing both crop yields and crop quality.

7. Organic Farming

Prior to the 20th century, almost all farming was organic (i.e. free of man-made chemicals), although not necessarily sustainable. For many engaged in early agriculture, gradual loss of soil fertility from farmland had been regarded as an inevitable outcome. Howard, who worked for many years in India as a British government scientist, noted that some Indian peasant farmers had kept the same fields fertile for two thousand years. He studied the Indian peasant farmer's methods, and realised that returning all waste to the land was pivotal. Through careful field trials he became convinced of the need to return to the soil everything taken from it, by using manures, and by composting all plant, animal and human waste. His theory was that healthy soil, where all required elements are present, would grow healthy plants, capable of rearing healthy animals.

Howard saw disease and pest outbreaks as indicators that something was amiss with the soil / plant / animal health, and even conducted an experiment to illustrate his belief that vulnerability to foot-and-mouth disease was linked to malnutrition. He allowed his cattle, which had been fed on healthy crops growing on healthy fertile soil, to have 'over-the-fence' contact with infected cattle. His herd remained disease free. Howard became convinced that mixed farming, with crops and animals, was essential to maintaining soil fertility and hence sustainable farming.

There are many detractors of organic farming[26], and some farmers are giving up[27]. However, there is also much evidence to show that organic farming, with soil that is well managed for fertility, can not only produce high quality crops, but also match the yields of intensive farming methods[28,13]. A recent paper by the Worldwatch Institute[29] asking 'Can Organic Farming Feed Us All?' concludes that it could have an important role to play.

8. Tillage and Soil Structure

The way that soil is tilled and cultivated has a huge impact not only the physical structure of soil, but also on the soil biology within. Whilst wild boar and tree-uprooting elephants do disturb and break up soil to some extent, nature has no equivalent to the mould-board plough, or the power harrow. Both of these implements treat soil very violently, and can lead to significant damage to the soil food web. In addition, they can cause a large loss of soil carbon through oxidation of soil organic matter, followed by erosion of the soil (particularly a problem with peat soils, which can contain up to 95% soil organic material). Worldwide, soils contain 1,500bn tonnes of carbon, compared to 720bn tonnes of atmospheric carbon[30].

However, crops still need to have the crop residue or manures incorporated into the ground to allow soil organic matter content to increase, and to make way for the next crop. Consequently, there has been much work to explore minimum and reduced tillage systems[31], where the plough and harrow are replaced with an implement such as serrated disc-harrows[32] that can work the crop residue into the surface of the soil. As ever, there are no quick answers to identifying the optimum tillage solution for a given farm. Instead, timeliness of cultivation, careful observation, understanding, and openness to new ideas are key[20,22]. The rewards can be very significant. The optimum choice of tillage system can have a major influence in both increasing the soil food web and reducing soil loss through erosion.

The quantity of carbon contained in the atmosphere increases by 4.3 billion tons every year. The world's soils contain 1,500 billion tons of carbon in the form of organic material. If we increase in 0.4% per year the quantity of carbon contained in soils, we can halt the annual increase in CO2 in the atmosphere, which is a major contributor to the greenhouse effect and climate change [4p1000.org/understand].

9. Man-made fertilisers

The significance of nitrogen for plant growth was understood in the 19th century, and the traditional sources of plant available nitrogen are from manure, and the breakdown of protein from dead organic matter. Soil nitrogen levels can also be boosted by growing legumes and green manure crops such as clover and alfalfa. After World War 2, man-made nitrogen fertilisers became readily available as a quick way of boosting crop growth. These fertilisers are manufactured using natural gas, and their production is energy intensive. To produce 1 tonne of artificial nitrogen produces between 3.3 and 6.6 tonnes of CO_2 equivalent. Fertiliser production now accounts for 1.2% of global GHG emissions. Of particular concern are emissions of nitrous oxide (N_2O), a GHG with 298 times the warming potential of CO_2. N_2O makes up 54% of the UK agricultural sector's GHG emissions[33].

Soluble artificial nitrogen is prone to leaching from soil, and can also alter the breakdown of soil organic matter, leading to reduced carbon storage in soils. Therefore understanding and knowledge is needed as to how best to present this nitrogen to the plant, in a form that it can use, at the time it is needed. Finding ways of reducing dependency on man-made nitrogen fertiliser is very important for reducing GHG emissions, and the imbalance in the nitrogen cycle[34].

Another key element that we are heavily dependent upon is phosphorus, and the associated phosphates. Like nitrogen and nitrates, phosphates also need to be presented to the plant in a form that it can use. (Zimmer has demonstrated that the presence of calcium in good quantities can be a key factor[20] in facilitating this). Phosphate supplies are reliant on geological deposits, and are still available to be mined[35,9]. But reducing phosphate run-off, and recycling of phosphates needs urgent attention if the anthropogenic imbalance in the phosphorus cycle is to be reduced.

10. Man-made insecticides, herbicides and fungicides

After World War 2, new biochemicals became available to help agriculture deal with unwanted pests and weeds. One of the most infamous, DDT, was initially heralded as a tremendous breakthrough. However, in the 1960s Rachel Carson drew the world's attention to the devastation caused by DDT[36]. Today, fierce debate surrounds other pesticide and herbicide products, such as neonicotinoids, and glyphosate (Monsanto's Roundup). Glyphosate is a particularly emotive issue at present[23], with Monsanto tabling evidence to show that it is 'safe' and farmers declaring that they cannot make a profit without it. Meanwhile Friends of the Earth[37,38], the Soil Association[39], the Soil Fertility Service[40] and others[41] all express grave concerns over possible side effects, including destruction of beneficial mycorrhizal fungi, locking up of trace minerals, and the impact on the health and fertility of livestock. The benefits and necessity of these chemicals is staunchly defended, but there is much evidence to suggest that their side-effects are not properly understood and may be very harmful. Meanwhile much of our biodiversity is facing worrying decline[17,18], and for reasons that are not properly understood.

11. Can we reconcile man-made fertilisers, herbicides and insecticides with healthy soil biology?

Across agri-business, governmental, and organic organisations, there is often broad agreement regarding the importance of soil organic material, the soil food web, reduced tillage, and crop rotations. But then there are a range of views regarding the use and necessity of artificial fertilisers, herbicides and insecticides. Key differences of opinions are usually focussed on the risk of potential side-effects, the length of time herbicides and pesticides stay active in the environment, and the impact they may have on the soil food web. It is outside the scope of this paper to draw specific conclusions on this topic, other than to say that as stewards of creation we have a duty to ensure that our activities sustain or enrich creation, rather than degrade or deplete it.

12. Biological Farming, Principles of Sustainable Farming

The issue of how to maximise soil health and hence crop and livestock health is one that has been extensively investigated by Gary Zimmer, the son of a Wisconsin farmer, who trained in animal science and dairy nutrition. He went on to become a pioneer of 'biological farming'[22,20,42], a method of farming that focuses on ensuring that the soil is balanced with all minerals present in suitable quantities. This is achieved through regular soil testing, with soil correctives being added as necessary, usually in the autumn. Zimmer has developed the 'Six Rules' of biological farming, summarised:

i) Test and balance soils, plus feed the crop a balanced supplemented diet.
ii) Use fertilisers that do least damage to soil life and plant roots, with a balance of soluble and slow release nutrients.
iii) Use pesticides, herbicides, biotechnology and nitrogen in minimum amounts and only when absolutely necessary.
iv) Create maximum plant diversity by using green manure and tight rotations.
v) Use tillage to control the decay of organic materials, and to control soil air and water.
vi) Feed the soil life, using carbon from compost, green manures, livestock manures as well as crop residues. Apply calcium to help with mineral availability.

Using these principles, Zimmer has had considerable farming success, producing high quality, high yielding crops, and also regenerating 'farmed out' land. Zimmer is now President of Midwestern Bio-Ag[43], lectures around the world, and is the author of two bestselling books[22,20]. Here in the UK the same principles of Biological Farming are championed by Soil Fertility Services (SFS)[44,39].

13. What is the Role and Importance of Soil Biology and the Soil Food Web in Sustainable Agriculture - Conclusions

In this paper, I have attempted to outline the crucial role played by soil biology (the Soil Food Web) in maintaining soil fertility, recycling nutrients back into the soil, replenishing soil organic matter, and maintaining soil structure, as a basis for producing health crops in a sustainable manner. To achieve healthy soil biology and enable sustainable farming, there is much evidence that principles of biological farming and organic farming appear extremely relevant, whilst the principles of Farming God's Way are also compatible with these objectives.

In the 'Book of Words' the Lord created a world full of all types of creatures, plants and trees, and creation was teeming with life. He declared his creation was 'very good'. The Lord then tasked us with being good stewards of it all, and gave us instructions concerning how to look after the land. In the 'Book of Works' observance of nature can give us knowledge and wisdom to help us understand the mysteries of the ecosystems around us, and inform us as to how to live as part of the community of creation, rather than trying to master and conquer it. The Soil Food Web is a vital part of creation and many of its ecosystems, but as yet we have only limited understanding of how it works, and how to work with it in order to produce the food that we need, sustain soil fertility, and rejuvenate farmed out land.

How we approach our agriculture in the coming decades will significantly impact the world that we live in, and our ability to respect many of the identified planetary boundaries. The importance and potential role of the Soil Food Web in this should not be underestimated.

Biography

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Martin grew up on a small dairy and arable farm in Hampshire. He studied Mechanical Engineering at Southampton University, before joining a leading diesel engine manufacturer. He has over thirty-five years experience in the field of engine development and reducing engine exhaust emissions. He has a strong interest in the natural world, is a former CRES graduate, a supporter of The Wildlife Trusts, and honorary secretary of a local countryside trust.

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Inspiration for JRI is taken from John Ray (1627-1705), English naturalist, Christian theologian and first biological systematist of modern times, preceding Carl Linnaeus.

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