A Nuffield Farming Scholarships Trust Report

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Above and below the ground: building resilient, productive and profitable soils

David Walston

June 2015

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Date of report: June 2015

"Leading positive change in agriculture. Inspiring passion and potential in people."

Title	Above and below the ground: building resilient, productive and profitable soils
Scholar	David Walston
Sponsor	The Worshipful Company of Farmers
Objectives of Study Tour	To discover why some soils are more productive than others, and learn about the best ways to improve them.
Countries Visited	Argentina, Australia, Brazil, Canada, Denmark, New Zealand, Uruguay, USA
Messages	Many farmers are degrading the soil, their greatest asset The more we use artificial fertilisers and pesticides, the more we need to use them again next year Conventional soil testing metrics must be treated with great caution We need more livestock in our fields; both above and below the ground

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DISCLAIMER

The opinions expressed in this report are my own and not necessarily those of the Nuffield Farming Scholarships Trust, or of my sponsor, or of any other sponsoring body.

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1. About me

I grew up on an arable farm just south of Cambridge, that my family has owned for about a hundred years. We traditionally grow mainly wheat, but also oilseed rape, sugar beet, peas and beans. Although I grew up on the farm, I never actually had any interest in it at all, apart from earning a bit of money in the summer working at harvest time. I went off to boarding school at 13, and ended up at university in London reading biology. I didn't follow the normal career path, but instead started a photography business in my second year. By the time I graduated it was ready to employ me full time. I stuck at that for the next 7 years, by which time the novelty of going to fifty weddings a year had worn off. My business partner was still keen, so he bought me out. This was a great relief, except I now had nothing to do.

At this point my dad, who had been farming for about forty years, said to me: "*Why don't you come and work on the farm for a year or two and see what it's like*". Well, without any better ideas, I said yes. I'd managed to get by without a real job so far in my life, and saw no reason to change.

Apart from driving trailers and combines, I had basically no experience at all with how the farm worked. I had never ploughed, planted a crop, or even set foot in the most important machine on the farm – a sprayer. So I started from scratch, and tried to learn as much as I could. It was fun, and I still enjoy doing it – one of the best things about being a farmer is the variety of work that I get to do - every day is different. It must be obvious that I enjoy it, as that was over 5 years ago, and I'm still here now.

About a year after I started working on the farm I got married, and spent some time in Japan on honeymoon. Something I had always wanted to do was to eat Kobe beef, or Wagyu as the breed itself is called (the one which is supposedly fed on beer and massaged with Sake). We were near the city of Kobe, so it seemed like a good opportunity. I won't bore you with the details, but it was delicious. So good in fact that I thought it would be a great idea to have some of this beef at home. There was a pretty large problem however: my knowledge of arable farming was limited, but compared to what I knew about cattle it was encyclopedic. It turned out that while I couldn't go out and just buy some Wagyu animals, I could import frozen embryos from America, that could then be implanted into surrogate mothers. At this point you say a few prayers and hope that a little black calf pops out 9 months later. A lot of the time it doesn't.

I thought it would be a good idea to buy some books about cows, and try to figure out what on earth I was going to do. One of them was about keeping cattle on grassland, and how to manage the whole system. Although I didn't realise it at the time, it was quite a radical book, but it all seemed to make logical sense to me. It talked a lot about building soils through natural plant growth and how this would increase fertility whilst at the same time reducing the amount of artificial fertiliser that was needed. It was really the nucleus of an idea that got me wondering about why some soils are more fertile than others, and what we can do about it.

2. Why I applied for a Nuffield Farming Scholarship

Fifty years ago our farm was not just arable; there was also a pedigree Jersey dairy, a pedigree Charollais beef herd and, for a short time, over a thousand breeding sheep. Over time, as the animals went, more and more fields were converted from grassland into crop production. It's the modern way.

Figure 1 : The author, David Walston

After each harvest we rank all our fields using yield data from the last 20 years or so. The worst field will normally yield around 20% less than average, and the best around 20% more. We have a group of three fields, right next to my house, which all share the same physical soil type. Two of the fields in this group yield in the mid range, but the other one is the best field we have, and will produce an extra 20% with the same inputs. Isn't it incredible that directly adjacent fields can differ so much? The question then was: why was it happening? The answer is simple – the better field had been pasture land used for grazing animals until around 25 years ago, and the others were converted 25 years before that. This was a revelation to me, but if you ask almost any farmer they will already know that the best fields on their farm are the ones that have been in grass most recently. It seems strange, but most farmers just accept that. Wouldn't it make more sense to try and make all your fields as productive as the best ones? We have a demonstration on our farm of how we could potentially increase our yields by 20% - that's a massive number that would transform our business, or that of any other farm for that matter.

There was a reason though that all the animals went from our farm, and from almost all the others farms within 100 miles. People realised in the 1970s and 1980s that if they went to pure arable cropping, not only did they make more money, but their lives were a lot easier; plants tend not to die, escape, or need feeding on Christmas Day. Being able to go skiing every winter was another bonus.

The problem with our best field is that the benefits all accrued from having it in long term pasture, so I needed to find out how to get these benefits without it taking decades, and while still being able to make money at the same time. So I applied for a Nuffield Farming Scholarship.

3. Where I travelled

I went on four main trips, as well as a few quick visits in the UK, and one in Europe.

1. March 2014	**New Zealand:** I felt the climate here is, in some parts, as similar to the UK as I would be able to find in a different country. I also suspected that the farmers here may be more open minded to new ideas because they had been weaned off the subsidy safety net several decades ago.
2. June 2014	**USA & Canada:** There is a small but significant movement gaining momentum in some parts of the USA where farmers are starting to think about how they can farm more efficiently and in tune with nature. Both of these countries also have long histories of no-till farming.
3. November 2014	**Australia:** Possibly the most dissimilar place to farm compared to northern Europe, but these challenges mean that they are people thinking of totally new ways to grow crops and raise livestock. I wanted to see what happened when they went against conventional wisdom.
4. March 2015	**Argentina, Uruguay & Brazil:** These are countries with a strong history of mixing crop and animal production, and they were also amongst the first to switch to no-till.

I prepared this report in the spring of 2015 but I have also included extracts from my blog, www.ooofarmer.com, which I wrote and posted whilst actually on my travels.

4. What makes some fields better than others?

My plan to begin with was simple and, I hoped, effective. I would first set out to show that by being considerate, careful, and taking good care of your soil then your farm would make more money. After showing that, I could move on to the details of what was the best way to achieve it in principle. Pretty quickly it became obvious that this was not going to work as I had intended.

The first problem was: how do you define whether a farm is in good condition or not? and the second one was: how do you show that a farm makes more money in one system than it would in another? Both of these were fundamental problems which made my tactic unworkable.

After travelling for weeks, and reading on the subject, the term which cropped up again and again was *Soil Health*. Almost everyone uses it, and says they are trying to improve their own Soil Health, or that farmers should really start paying more attention to it.

The problem really came when I asked a) how do you define Soil Health? and b) how can I measure it? Answers were always very unsatisfying for the first question, and usually non-existent for the second.

> *"Healthy soils are high performing, productive soils" – USDA Leaflet*

> *"Soil health is a combination of physical, chemical, and biological properties that impact the function and productivity of the soil" – USDA Leaflet*

The quotes above are representative of what most people would say when asked for a definition, which to my mind is too unspecific to be of any real use. This trend continued until I spoke with a French farmer called Frederic Thomas. His definition was:

> *"The health of soil can be measured by its capacity to grow a crop with no inputs at all"*

The problem remains that it is very difficult to measure, but it does link the concept with one all farmers were familiar with before Soil Health was invented: fertility. For a time I dismissed the entire concept of Soil Health from my mind, and considered it a meaningless buzzword used only by ignorant journalists or snake oil salesmen. Instead, I would tell people that I was learning how to increase the fertility on our farm.

I realise now that I was wrong. To me fertility means, in a simplistic manner, the nutrients in the soil, and how lush a plant looks. Conventional farming systems add fertility to their land every year from a bag or a bottle. What I was trying to do was improve not only the nutrients a plant could take up, but also how resilient it was to diseases, pests, floods, droughts, compaction, temperature variations - everything. These benefits would not only accrue from changes in the plant, but also changes to the soil, both physically and biologically, but in a non-measurable manner. Vets, and indeed doctors, will talk about healthy populations having fewer problems with diseases, and having increased productivity, even though there is no magic number that can show how healthy an animal (or person) is. So isn't it in fact reasonable to try and strive for better Soil Health after all? I think so. I apologise to those I have lambasted in the last year for using the term.

4a. What is in a healthy soil?

At the most basic level, all a plant needs is chemical nutrients. Carbon, which makes up the bulk of all plants, is freely available from the air in the form of CO_2, as is oxygen. All the other chemicals, nitrogen, phosphorus, potassium, hydrogen, iron, molybdenum, boron, copper, manganese, sodium, zinc, nickel, chlorine, aluminium and cobalt, will generally come in through the roots. It is obvious that we can feed the plant directly with all these nutrients, as hydroponics is an established technique. However, hydroponics is not suitable for large scale food production, so we must use soil to grow most of our plants.

Soil is made up mostly of minerals, which were formed over millions of years by the erosion of whatever base material was present in a particular location. As well as the relatively inert, inorganic compounds, there is also a huge amount of life in the soil: bacteria, fungi, protozoa, nematodes, arthropods, and larger invertebrates such as earth worms. Most of these organisms will have no direct impact on a plant, but some will be beneficial, and some will be harmful. The key concept is to try and maximise the beneficials, whilst minimising the impact of the undesirables.

It is critically important to realise that all these creatures are living in a complicated ecosystem, which when functioning properly, gives each of them a niche, but not enough room to get out of control. Unfortunately I feel this is a concept that has become forgotten in modern agriculture. By growing crop monocultures, we produce conditions that suit specific organisms over others. This becomes a problem when those conditions favour something harmful, be it a fungus, insect or a weed. The standard way of dealing with that now will be to kill it with a pesticide, but this does not just control the harmful organism, but also all the other similar ones it has been competing with. Afterwards, it all looks good for a short while, but the original conditions still exist. The problem organism can now return, but in the disrupted ecosystem there is now much less competition, and a vicious cycle is started.

So a healthy soil is a diverse soil, but it is not all about stopping disease. There are several ways that the soil life can actively help plants.

Bacteria: The most widely known beneficial bacteria are those which fix nitrogen from the air and turn it into a form which is available to plants. These can either be free living in the soil (such as Azospirillum) or living in root nodules (Rhizobia). Different bacteria convert the other micronutrients which are originally present in the soil minerals.

Fungi: Mycorrhizal fungi develop symbiotic relationships with many different types of plants (although not brassicas). They actually grow into the plants' root cells, and facilitate the absorption of water and nutrients. In some cases a single mycorrhizae can span different plant types, and experiments have shown that they can move nitrogen fixed in the roots of a legume into a neighbouring grass plant.

Worms: The benefits brought by worms are largely structural in the soil. The channels they create increase drainage efficiency, which reduces the likelihood of flooding and therefore anaerobic conditions which are bad for soil life. They can reduce compaction by physically breaking through it, and at the same time bring down plant material from the surface to provide food for microbes. Their excretions are rich in plant-available nutrients, particularly nitrogen, phosphorus and potassium.

In general, the more life there is in the soil, the healthier it will be. But we can also consider specifics, and the ratio between the biomass of bacteria and fungi can be interesting. Older and more developed ecosystems, such as forests, tend to have much higher levels of fungi to bacteria ratios: normally between 5:1 and 100:1. Native grasslands are lower, usually around 1:1, and this is the level at which our agricultural crops tend to be the most productive. Unfortunately, our long term agricultural soils are almost always strongly dominated by bacteria. This lack of fungi could be reducing the efficiency with which the plants we grow are able to use nutrients, and increase our dependency on artificial inputs.

It is possible to measure all of this - but the tests are expensive and unreliable. Hardly any farmers use them, and consequently it is not really possible to determine whether "good" results correlate to productive and profitable farms. What I really needed was a simpler metric.

4b. Soil Organic Matter

This is another of those words that crops up a lot in farming magazines, but for good reason. Soil Organic Matter (SOM) has a deceptively simple name; in fact it is a catch-all for many different types of material in the soil that were once part of something living. As these dead materials decompose they form into more and more stable compounds, which as a rule are also increasingly beneficial to the soil. So what are the benefits?

Physical - Organic matter is literally like a sponge; think of the difference between pure sand and compost that you buy in bags to put into a vegetable garden. The sand is 0% organic matter, the compost nearly 100%. This physical characteristic helps in exactly the way you might think. It will hold weight from machinery more effectively without becoming compacted, as it can spring back into shape. And, again just like a sponge, it can both hold more moisture and also drain excess water in very wet periods.

Chemical - SOM acts as a buffer for soil nutrients, allowing plants to absorb them more readily.

Biological - SOM is a food source for microbes, so higher levels support higher microbe populations. This encourages greater and greater cycling of nutrients, as after the microbes die, they in turn become SOM and are eaten by the next generation. Each cycle releases more nutrients for plants to use.

If we consider the above points in relation to the USDA leaflet I quoted at the beginning,

> *"Soil health is a combination of physical, chemical, and biological properties that impact the function and productivity of the soil"*

it is clear that SOM levels and Soil Health may potentially be linked.

▪USDA: "Research at Michigan State University indicates that a 1% increase in SOM offers a 12% increase in crop production potential". This is a massive number, but does tally roughly with our farm, where adjacent fields with differences in SOM levels of ~2% can vary in yield by 20%.

▪USDA: "Using 1% SOM as a baseline level, the total long term value of a 1% increase could be estimated at $24/acre for the nutrient value and available water holding capacity". This is data from South Dakota, and so not necessarily applicable to other areas. But if you consider $24 is currently around 6bu of maize, then a 3% rise in SOM levels would be worth 18bu, equivalent to raising yields by perhaps 20%.

4b.i. An important lesson in Kansas

Near the start of my trip around the USA I visited a farmer in the middle of Kansas called Josh Lloyd. He lives in a beautiful, but very exposed, house looking out over the wheat belt. Not surprisingly his main crop is wheat, with soybeans a close second. He also grows maize and sorghum, and there is a small cattle herd grazing the old stubbles and some native grassland. In front of his house is an area which for decades was used to keep the cattle on over the winter period when there was no grazing available. Although this practice stopped some years ago, it is still very easy to trace in the crops where this area was:

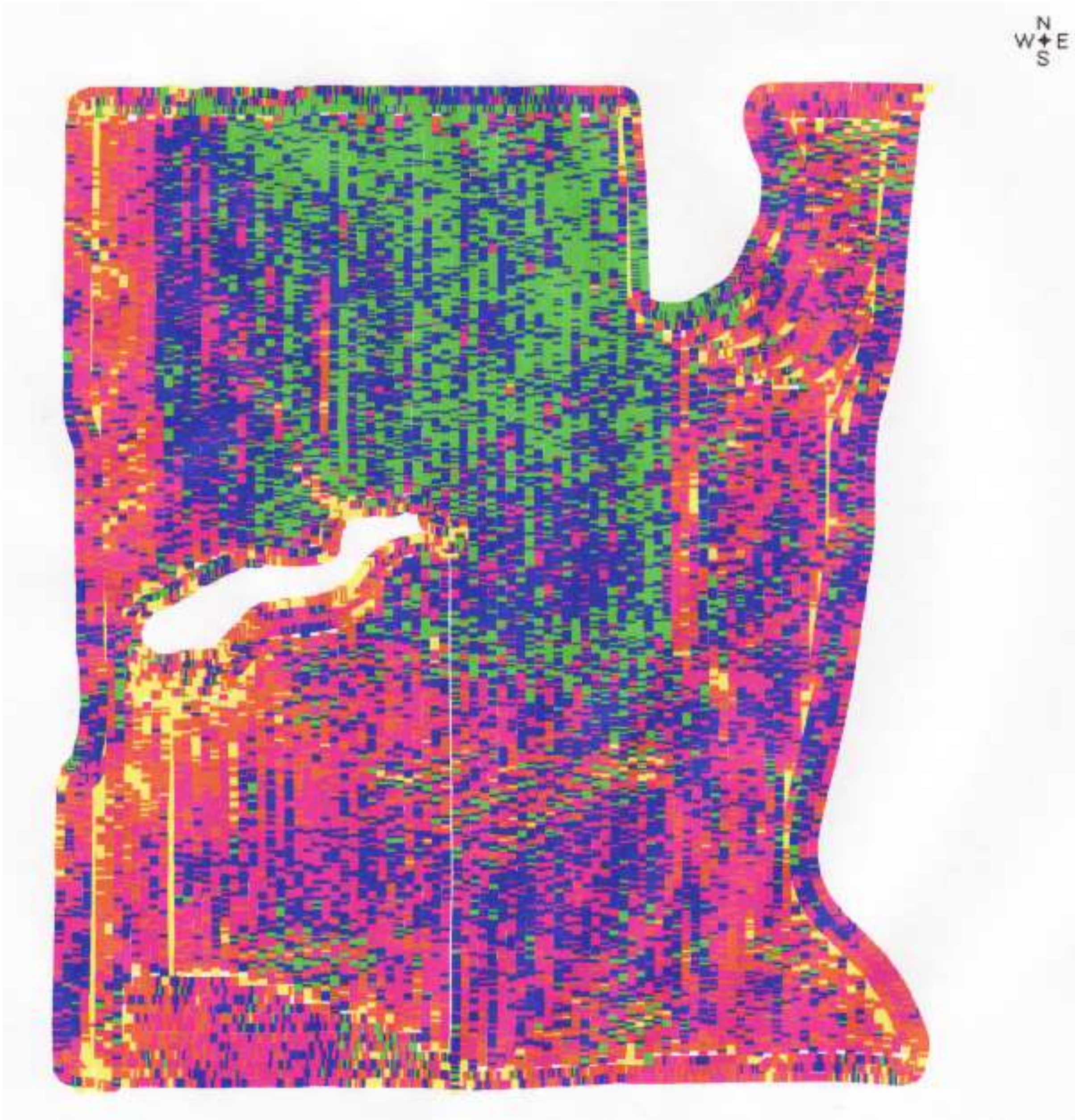

Figure 1 Combine yield map

This is a wheat yield map from 2010, and the old cattle holding area is very clearly visible as the blue & green square in the top/centre. That year, which was apparently representative, the wheat yielded around 25-30% more in this area. What makes this scenario even more interesting is the soil sampling that Josh has had carried out on his farm.

Many of the fields have been grid sampled for a whole range of different factors: nutrients levels like phosphorus, potassium, magnesium, zinc, as well as pH and SOM. Out of all the different maps that were produced for this one field, only two results correlated with the yield maps.

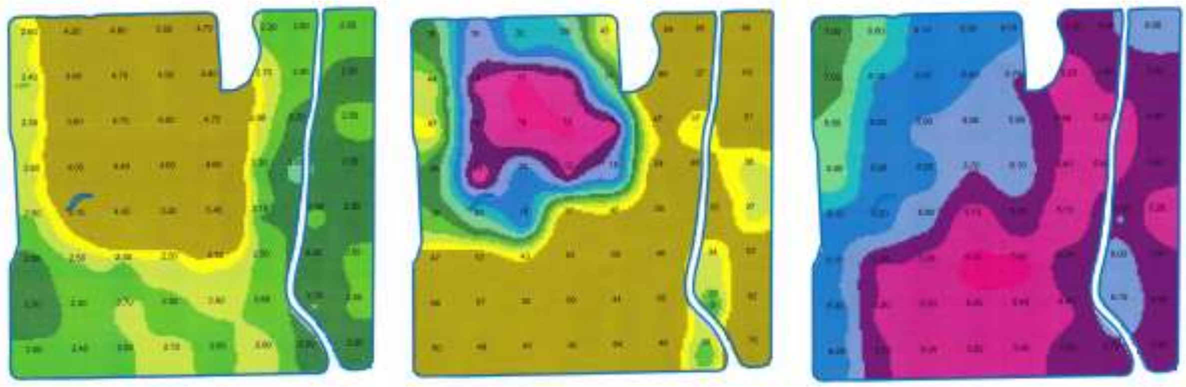

Figure 2. Left: SOM% in the soil. Centre: Available phosphate levels. Right: pH levels for comparison

On the left is the map for SOM. In the high yielding areas it is between 3.1 and 5.5%, compared with 2.1 to 2.7% in the rest of the field. This is not surprising. The map in the centre is available phosphorus - the normal test used to determine whether we need to apply a phosphate fertiliser such as TSP or DAP. We can see from the map however, that the high yielding areas of the field are showing significantly less phosphorus than the rest. In fact, they are technically very deficient: a fertiliser salesman would no doubt use this result to increase the size of his order book.

It is obvious to me from this that we must be very careful when using conventional soil tests. The results are not as straightforward as people would like to believe, and it throws real doubt on the current application of precision agriculture, which often relies heavily on this sort of sampling.

The common method for measuring SOM is to perform the “loss on ignition” test. This involves the following steps, or a variation thereof:

1. Heat soil to 105C for 90 minutes
2. Weigh soil
3. Heat to 500C for 2 hours
4. Weigh soil. The carbon will have burnt off, and so the difference in weight is considered to be approximately the weight of the organic matter that was present.

Now if we consider the following USDA quote, there is a bit of a problem.
“It takes at least 10 pounds of [plant] residue to decompose to 1 pound of organic material”
If you test a soil sample with 10 pounds of residue and 1 pound of organic material in it, the result will show 11 pounds of organic matter, or something close to that anyway. This begs the question, how do you measure true soil organic matter?

from my blog: www.ooofarmer.com

The Haney Test - better than SOM?

The Haney test has some overlap with conventional soil tests, but it is designed to determine more precisely how much nitrogen and phosphorus will be made available to growing plants through biological activity, not just what is physically present. One of the ways this is accomplished is by using a weaker acid solution to extract the nutrients, which is supposed to be closer to the conditions roots grow in, compared to conventional tests, like Olsen P.

Total carbon, nitrogen and phosphate are measured, as well as their inorganic fractions. When you subtract inorganic from total, you end up with the organic fraction. Inorganic nitrogen is easily leachable, and so if there are high levels they would recommend grass based cover crops to try and capture some of it.

The ratio of organic carbon to organic nitrogen is important, as if it is above 20:1 then no nitrogen or phosphorus will be released through microbial activity. In this situation they would recommend cover crops with higher proportions of legumes to bring the ratio down to between 15:1 and 8:1.

Another novel part of this regimen is the Solvita CO2 burst test. This measures the amount of CO2 produced by 40g of soil in a 24hr period. The idea is that more CO2 = more microbial activity & biomass. They claim that this is highly correlated with overall soil fertility.

All these tests are combined to come up with a "Soil Health Calculation" score. For completeness, here is the formula:

Solvita CO2 / organic C:N + (organic carbon/100) + (organic nitrogen/10)

The score goes from 0 upwards. A conventionally tilled soil with little or no crop rotation, cover crops, livestock etc may score as low as 2. At the other end of the scale, farms with cover crops, companion crops and livestock integration can be in the high 20s or even low 30s. The printout for each sample includes what the results would have been from a conventional test, which in the case of nitrogen is usually less as it has not accounted for the organic forms. This should supposedly allow the application of less nitrogen (if your soils are fertile), and therefore save money.

Interestingly, they claim that with cover crops, the scores are significantly increased as the mixes become more diverse. It does make sense, as presumably different root exudates will feed different microbes, and the total quantity will increase. They also warned that there is normally a 6-12 month lag in seeing improvements after cover cropping, as it takes this long for the biology to work its magic, and make the nutrients available.

Does is work? Rick Haney, who invented it, is currently analysing yield data from farmers all over the US and trying to correlate it to actual crop performance.

from my blog: www.ooofarmer.com

4c. How quickly can we build organic matter?

I've written above about the ways in which some soils may be better than others, but how easily can we make these changes ourselves?

The scientific evidence is in strong contrast to the anecdotal evidence I found on many farms. Technically it should not really be possible to increase SOM by more than about 0.1% per year. This contrasts with several farmers who are claiming five or ten times this rate of increase. I have no real explanation for the difference, although it could be due to different measurement or sampling techniques, or perhaps cherry-picked results from farmers. I feel that the systems are too complicated for us to understand properly, and so evidence which goes against what is theoretically possible should not be discounted quickly.

USDA: "A typical acre of soil 6 inches in depth weighs about 1000 tons. One percent organic matter equates to 10 tons of organic material…it takes at least 10 pounds of residue to decompose to 1 pound of organic material". If we want to increase our SOM levels by 3%, then it will take 300 tons per acre of residue, or in real money, 670t/ha (Don't forget, these are short tons – 2000 lbs - they talk about, not metric tonnes which are 2204 lbs). That is A LOT, and something doesn't add up.

One Ohio farmer I visited claims to have increased SOM levels from 0.5% to 5% on his farm. He started farming in 1971, so in 40 years he must have added 25t/ha of plant residue to the soils every year. In actual fact he says he can make that change in about 7 years, which is 140t/ha/yr. Neither of these scenarios seems plausible to me if you consider that a wheat crop may produce 14t/ha of above-ground material, double that when you include roots too.

from my blog: www.ooofarmer.com

The two soil samples above were taken from neighbouring fields in Ohio. The field on the right has been farmed for 40 years in a no-till and cover crop system, compared to conventional tillage on the left. The SOM levels are around ten times higher on the right. At the time I was incredibly impressed with this demonstration. However, the samples were taken from around 50m apart, and I have seen many examples since of soil types changing in shorter distances, so there is now doubt in my mind as to how much of this difference is due to human influence.

5. How we might improve our soils

5a. Protecting vs improving

The soil on almost every arable farm in the UK, and probably the world, is significantly degraded. This is easy to check by comparing the SOM level of fields that are used for production to native vegetation in the same area, or even just under a hedge, or at the side of the field in some grass. It is almost certain that in the non-farmed areas there will be significantly higher levels of SOM, which will likely manifest as a darker-coloured soil with more roots, worm holes, and better structure.

Figure 3. These samples are taken from within 10m of each other on a farm in Brazil. On the left is a continuously no-till cropped arable farm. In the middle is the neighbouring field, which is also farmed using no-till, but two years out of four every field is planted with grass and grazed by cattle. The two fields are separated by a track, and along the verge is permanent grass; the right hand sample is taken from this grassed area. I did not test SOM levels, but it is clear that the soil gets darker going from left to right - a reliable indicator of increasing SOM levels when all else is equal

The first step in improving our soils should be understanding how we have caused the damage to them in the first place. Unfortunately, like the frog being slowly boiled, these changes have happened over the course of many generations, and often go unnoticed. Indeed, where we find ourselves now is considered normal by a lot of farmers, and so there is no apparent need to change.

The reduction in SOM levels can be fairly easily traced to modern farming methods. By cultivating the soil with a plough, set of discs, or anything else, we are oxidising organic matter. In this process, which is effectively the same as burning, we are releasing the stored carbon from the SOM into the atmosphere as CO_2, but at the same time that leaves the nitrogen part behind in the soil. Because nitrogen is often a limiting factor in plant growth and yield, cultivating soil can result in higher yields as we eat into the bank of nutrients that we started with. How quickly we deplete these stores depends very heavily on local conditions. In the damp and cool UK, we still have easily measurable benefits from old pasture land that was converted to cropping 25 years ago, with continuous cultivation in the meantime. Compare this to Brazil where it has been shown repeatedly that it is possible to go from native bush with 5% SOM to less than 0.5% after 5 years of cropping. This may help to explain why more conservation-minded farming techniques tend to be more popular in regions where any damage done is seen much more quickly.

Farming without cultivations, variously called no-till, zero-till or direct drilling, has been used successfully for decades in much of South and North America, and Australia, and has been studied in several long term experiments.

One interesting study carried out in New Zealand by FAR (the Foundation for Arable Research) over the course of 13 years compared what happened when they converted pasture into cropped land. The trial had three treatments, ploughing, min-till (using discs to cultivate) and no-till. Although the cultivated systems lost SOM quickly at the beginning, by the end all the plots had reached the same level. This would suggest that by itself no-till may not help with improving SOM levels, but by cultivating you will be taking much larger backwards steps, which may undo good work in other areas.

Figure 4. A cultivation trial in New Zealand clearly shows the difference between the techniques. On the left is no-till, in the middle min-till and on the right ploughing & power-harrowing

In Nebraska I visited Paul Jasa who runs the Rogers' Memorial research farm for the University of Nebraska. They have an ongoing experiment, now in its 35th year, also comparing cultivation systems. The difference in yields is small but significant, with higher production coming from the no-till sites. They put this down to higher SOM levels (around 0.5-0.75% more than in cultivated plots), but also to the increased amount of plant residue left on the soil surface. Like SOM, plant residues have many benefits. They can act as a physical mulch, which stops moisture from evaporating, but also keeps the soil cool on a hot day. [It is worth nothing though that whilst this may be desirable in Nebraska, the same effects may be deleterious in climates where limiting factors come from being too cold and too wet]. Soil erosion will be lessened by the residues as they protect from wind, and also make heavy rains less likely to wash fine particles into rivers. Finally, in the same way that SOM provides food for microbes, surface residues do exactly the same thing, either directly by surface living organisms, or after they have been pulled underground by worms.

I wrote earlier about the benefits of soil fungi and also earth worms. Both of these are affected negatively by tillage. Fungi are made up of many very long and thin strands called *hyphae*. These are slow growing and very fragile - the action of moving the soil with steel easily destroys them and seriously hampers the ability of fungi to grow. This may be one reason why modern agricultural soils have a shortage of fungi compared to bacteria, which are much less sensitive to tillage. Earth worms are disrupted in the same way, as their burrows are easily destroyed and any worm caught by a machine is likely to be killed. Equally the reduction in SOM and general soil life means the worms, which live at the top of the soil food chain, have less food, so their populations will become smaller.

One farmer I visited in Australia recounted how when he started farming 40 years ago, the cultivators would come out of the ground wrapped in huge worms up to 30cm long; he now never sees anything that size. This might be due to the tillage itself, or perhaps the type of pesticides which are now commonly used. His land was, compared to some parts of the world, only recently in native vegetation, and so he knows what changes have happened. Here in Europe, these type of changes probably happened many generations ago, and so we take the current condition of the farm as normal and acceptable. Maybe we should also have foot-long worms?

5b. Leaves for show, roots for a pro

If we believe that natural soils are the most fertile, then it is logical to try and design a farm system that is as close to them as possible. One of the key characteristics of those systems is diversity - how often do you see a monoculture growing in nature? As farmers we have done a good job of removing as much diversity as possible from our land, to the point where whole regions sometimes grow a single crop continuously for years, or even centuries, on end.

This lack of diversity has knock-on effects for the soil. From a physical perspective each different type of root has its own unique way of changing the soil. Grasses have a mass of very fine roots, which are good at breaking up surface compaction and quickly increasing SOM when they die off. Other plants, such as chicory, will have very deep single tap roots. These have little effect on the soil to the sides, but will go very deep and with great force, so they can break through hard layers further into the soil profile.

As plants photosynthesise, they convert carbon from the air into a sugar: glucose. Most of this is then used for the plants' own respiration, to live and grow. However, a large proportion (up to 25%) goes underground, where it and other chemicals are exuded into the area around the roots, called the *rhizosphere*. This space is colonised by huge numbers of microbes of all types - bacteria, fungi, nematodes, protozoa - which live off the exudates. As discussed earlier, the more diverse an ecosystem, the less chance a pathogen can become dominant and cause a plant disease. Because every plant will secrete a different blend of exudates, the more different types of plant growing in one place, the healthier a soil can become. Although there is not a lot of hard proof of this, the circumstantial evidence is incredibly strong. Why else would plants have evolved to give away a quarter of their energy if they were not receiving a massive benefit from doing so?

Figure 5. The different rooting types can be seen with these plants dug out of one of our cover crops. From left to right: stubble turnip, fodder radish, sunflower, oat

5b.i. Rotation

The traditional way of getting more diversity of roots into a farming system is to grow a rotation of different crop types. This practice is around 8,000 years old, but until the introduction of artificial fertilisers one part of the rotation was usually left fallow, growing nothing. Rotations help by not allowing pests and diseases to build up, but they still have the problem that usually it is a rotation of monocultures, so the benefits are limited. Economics can also play a large role - if only one crop can be grown profitably then starting a rotation is, as Sir Humphrey Appleby would say, a courageous decision.**

** "Oh, yes! 'Controversial' only means '*this will lose you votes*'.
'Courageous' means '*this will lose you the election*'!"

Figure 6. There are two signs of bacterial life on this bean root. The first is in the round nodules where nitrogen fixing bacteria are living in symbiosis in the plant. The second is the furry layer of soil which sticks to the roots. This is evidence of the root exudates and the microbes that feed on them

5b.ii. Cover crops

Although it is difficult to grow cash crops that are not in a monoculture, there is often a period of time in a rotation where fields are left bare. Depending on the crops being farmed, and the climate, it may be possible to plant a cover crop in this period. The concept here is not new either, as farmers with livestock have long used this time to grow feed for their animals to eat over winter. Sheep may perform very well on a field of stubble turnips which have been fertilised and had several pesticides applied, but the benefits for Soil Health will be limited. That is not to say though that yields in the following crops will not be better. In the New Zealand FAR trial mentioned earlier, they found that cash crops always yielded higher after a cover crop than after fallow. The cover crops were scavenging nutrients that might otherwise have washed away, which the sheep then grazed and turned into a highly plant-available form of fertiliser.

The current trend is to grow multi-species cover crop. (*See picture on next page*). This is happening on many farms that I visited, but the epicentre seems to be in the USA - in particular the areas in North and South Dakota which are influenced by Dr Dwayne Beck, Jay Fuhrer, Gabe Brown, and all the people who are visited each year by hordes of Nuffield Farming Scholars, including me. Mixes can vary from two species, such as rye and vetch, up to over fifty for those people really pushing the envelope. There are several benefits to having multiple species in one cover crop:

Root diversity means increased soil life diversity, with all the benefits already discussed above. It also should improve soil structure due to the differing root profiles of each species.

Growing conditions can vary greatly between seasons, and it is inevitable that in a given year the weather will suit some species more than others. The larger the diversity in plant types, the more likely it is that there will be at least one which will thrive.

Some people advise not to grow any plant type in a cover crop that is also grown in the main cash crop rotation. This is to stop a "green bridge" of similar plant types which could cause diseases to persist in the soil. A competing theory is that by having no one plant type dominate a cover crop, the disease problems will be eradicated because there is no monoculture to allow the pathogen to get a foothold.

Mixing legumes and non-legumes together allows the mixes to be fine tuned for a particular field. In a field with high carbon levels, it may be preferable to grow more legumes to provide extra nitrogen to the following cash crop. On the other hand, if there is a lot of free nitrogen in the soil, then high carbon plants, such as grasses, will efficiently utilise it, stopping the chemical from leaching into water courses.

Picking exactly which species to use in the cover crop can be complex, as every plant will have pros and cons. For example, grasses are very good at using residual soil nitrogen, and will grow well in cooler soil temperatures. However, they also will make that nitrogen unavailable for following crops, and their root exudates can inhibit other plants' germination and growth (this effect is called *allelopathy*). Brassicas such as forage rape or stubble turnips are very quick to grow, and provide good animal feed. They can potentially shade out other, slower growing, components of the cover crop though if they are too successful. There is also a possible problem with root diseases if growing other brassicas like oilseed rape in the main rotation. Legumes are a very important part of any cover crop, as it is an opportunity to get "free" nitrogen from the air, and turn it into plant-available forms, and SOM. There is no perfect species however: clovers are expensive and slow to establish, beans are physically very large seeds and so are very expensive per plant. Vetches offer a good balance between these two, but ideally there would be other options to increase diversity further.

See picture on next page.

Figure 7. A multi-species cover crop growing in Denmark. This one was very rich in legumes, containing vetch, crimson clover, serradella & phacelia

5b.iii. Companion crops

At this point we are starting to get out of the comfort zone for most farmers. Everywhere in the world, the vast majority of arable crops are grown in monoculture - this is easy to see out of the window of a plane, train or car.

The other option is to have multiple species growing in the same place at the same time - a companion crop. This is not an easy way to farm, at least in the conventional sense. With so many crop types in one field, the ability to use herbicides to control weeds is severely restricted, and in some cases totally eliminated. This can be mitigated by choosing companions carefully so that there is some possibility of using a herbicide, or by having a carefully designed rotation so that any problem weeds which occur in a given mix can be dealt with easily in the following crops.

Figure 8 . A field of sunflowers growing in North Dakota, but it has been planted with buckwheat, radish, linseed, clover and oats

Reasons for using companion crops include:

- Unsurprisingly, adding diversity to the system.
- Making use of allelopathy to stop weeds germinating. This should not affect the cash crop it is sown with, as it will have germinated already by the time the companions' root exudates are starting to be produced.
- If the companion is a legume then it may provide some nitrogen to the cash crop, either through sharing via mycorrhizae, or that which becomes available after the companion has died.

The companion's fate can vary dramatically between systems. In some cases when autumn sown, it will die off naturally with the winter frosts, and in others the companion will be killed off with a herbicide after it has performed its function. Clover is sometimes used as a permanent understory, and each year a different crop can be sown into it - this should allow little or no nitrogen fertiliser to be used over the course of the year. Finally, it is also possible to take two or more crops all the way to harvest, where they could be sold together, possibly for animal feed, or else if the seed sizes are different they could be mechanically separated.

Figure 9. In Brazil it is common to grow maize and brachiaria grass together. After the maize is harvested for grain the grass is grazed with cattle

5c. Speeding up the process

So far all the ideas I have discussed have involved letting plants do all the hard work. It is a slow process; even the farmers claiming the quickest results are having to wait years to see them. The scientists will tell you the wait can be measured in decades. Any way that the process can be speeded up would be very helpful.

5c.i. Composts

Every home gardener knows that compost is highly fertile - seeds are often planted directly into it, and every spring whole bags are dug into vegetable patches. In the UK a lot of local councils use composting facilities to turn green waste into something that can be sold, or at least has a productive use. In a traditional chemical analysis this sort of compost does not usually have much in the way of nutrients, but it is often used to try and improve the physical condition of the soil as much as anything else. But there is some evidence that the effect of compost might go far beyond what is shown in a lab test, in the same way as Josh Lloyd's soil maps showed that the traditional results were not what was really affecting his yields.

Figure 10. Cam McKellar's home made compost

On his last farm Cam McKellar was heavily into home made compost. It was such a big operation that he actually had a full time employee just to make it. The ingredients were simple; straw, manure (cattle and chicken) and water. Within 24 hours the mixture, laid out in strips, will reach 70^{o}C. From here on the moisture and CO_2 emissions were measured daily, and it was managed to certain tolerances by either adding water or turning it over. After 3 weeks a special blend of microbes, called EM, is added and then after 10-12 weeks it is done. Simple.

Although the traditional chemical analysis won't show a lot of nutrients in here, Cam is convinced that as it is all in a plant-available form, then it produces a disproportionately large effect. By spreading 4t/ha he could cut bagged nitrogen inputs by 30%, whilst maintaining or increasing yields. Of course, there is a lot more than just NPK in this sort of thing, and these micronutrients could be what is making the difference. I didn't see any trial data, but it is still an interesting idea, especially if you have access to cheap straw and muck.

from my blog: www.ooofarmer.com

Dr Elaine Ingham (USA) is a soil microbiologist who runs a company called Soil Food Web. She is a huge advocate of promoting soil life. They have a test, which I alluded to earlier, which involves checking on the health of soil by manually counting and categorising all the different life forms it contains. This is useful but also slow and expensive. What I find very interesting is her idea that not all composts are equal, and there is a "right" way to make them. This is backed up by anecdotal evidence from some farmers who make their own composts; some years it has an incredible effect on plant fertility and even weed problems, and other years it appears to do nothing. The secret is in using the right ingredients, which are approximately:

10% high nitrogen material, such as animal manure.
30% green material from fresh plants.
60% high carbon woody materials, which are particularly good as fungal food.

Ideally some of the plant or wood will be taken from local native vegetation, as it should then inoculate the compost with whatever microbes are best suited to that location.

The next important step is to always keep the temperature below 70°C, as when it gets hotter the pile will turn anaerobic and very quickly all the beneficial microbes will die. According to Dr Ingham, it is happy coincidence that in 'properly' made compost it is all the beneficial microbes which thrive. To begin with I thought this sounded suspiciously convenient, but then there are parallels in similar processes. For example when making cheese it is possible to culture pathogenic bacteria if the method is not followed correctly, but when done correctly it just so happens that the right organisms prosper and the milk is fermented in a way that is safe (and tasty).

I did visit one farmer in Western Australia who was several thousand kilometres away from a good source of compost. This made the cost of transporting it totally uneconomical. To get around the problem he would buy in a small quantity and then soak it in water to make what is called *compost tea*. The tea can then be placed with the seed at drilling (reducing root diseases and increasing fertiliser efficiency), or applied later to the growing leaf with a sprayer (protecting against leaf diseases by increasing competition from beneficial microbes). Although this farm is in a very harsh climate, with quite low yields, the amount of fertiliser used to grow wheat was tiny: 1kg/ha of phosphorus and 2-10kg/ha of nitrogen. Yields were claimed to be similar to a conventional system, although worse in a particularly good growing season.

One field I saw (see picture below) had been in production since the 1970s. By 2006 the fertility was so low that it was difficult to get anything meaningful from it. Since then it has had several years of all-year cover cropping with plants like oats, peas, millet, turnips and clover. In 2011 the farmer considered the fertility to have been built to a point where maize could be grown. This crop was partly fertilised with nitrogen at three different rates, 90lb/ac, 30 and 0. There was no difference between the three treatments.

Unfortunately we did not have a spade to hand, but I dug around with my fingers. The top inch of the field was pure compost, such as one can buy at a garden centre. I have literally never seen anything like it. Hopefully the photo above illustrates the point. As a rough estimate, if we assume it is half as dense as normal soil, then that inch would weigh about 185t/ha. I think a normal compost application on farm land in the UK is 10-20t/ha? OK, so the field was out of production for several years, but the time has not been wasted.

from my blog: www.ooofarmer.com

5c.ii. From a bottle

Making compost is the difficult way of getting faster results; the easy way is to open a bottle. A different farmer in Western Australia has been trialling a microbe seed dressing for a couple of years with interesting results. The particular blend he has been using contains both bacteria and fungi, which are claimed to perform these functions, not all of which you might normally associate with microbes:

- Fix nitrogen
- Decompose cellulose to release organic carbon
- Improve soil structure
- Increase nutrient uptake efficiency
- Increase nutrient uptake efficiency
- Regulate plant growth
- Protect from diseases

The on-farm trials I saw showed that when seed was treated with this mix, it yielded the same as the conventional system, but showed much less response to fertiliser applications - sometimes none at all. On the next-door plots where normal fungicide-treated seed was used with no fertiliser, the yields were much lower. This would suggest that by using fungicides in the soil we are destroying the helpful fungi, such as the mycorrhizae, and making the whole system much less efficient.

5d. Integrating livestock

If stopping tillage and starting to grow companion crops are alien thoughts to an East Anglian arable farmer, then the idea of getting animals back on the land will send shudders down the spine. Most farms gave up their animals decades ago, because the economics did not seem to work out, and it also made life a lot easier. Even now there is doubt amongst many farmers who are interested in Soil Health as to whether animals are actually useful, or if they just cause nutrients to be lost, and soil structure to be damaged.

Before artificial fertilisers became common in the second half of the 19th century and beginning of the 20th, fertility had to come from natural cycling through fallow or legume rotations, as well as the addition of animal manure. As many farmers know, and I have seen with my own eyes on our farm, land which has supported livestock in the recent past is more fertile than that which has not. As before, I was keen to see if there was any real evidence of this effect, not just anecdotes.

5d.i. Hard data

INIA is the government-funded agricultural research institution in Uruguay, which seems to be well respected by the local farmers for carrying out useful research. Most farms in this country are mixed, so they have both livestock and crops. Because of this, INIA has been running a long term, 52 year experiment on the effects pasture phases have on soil quality.

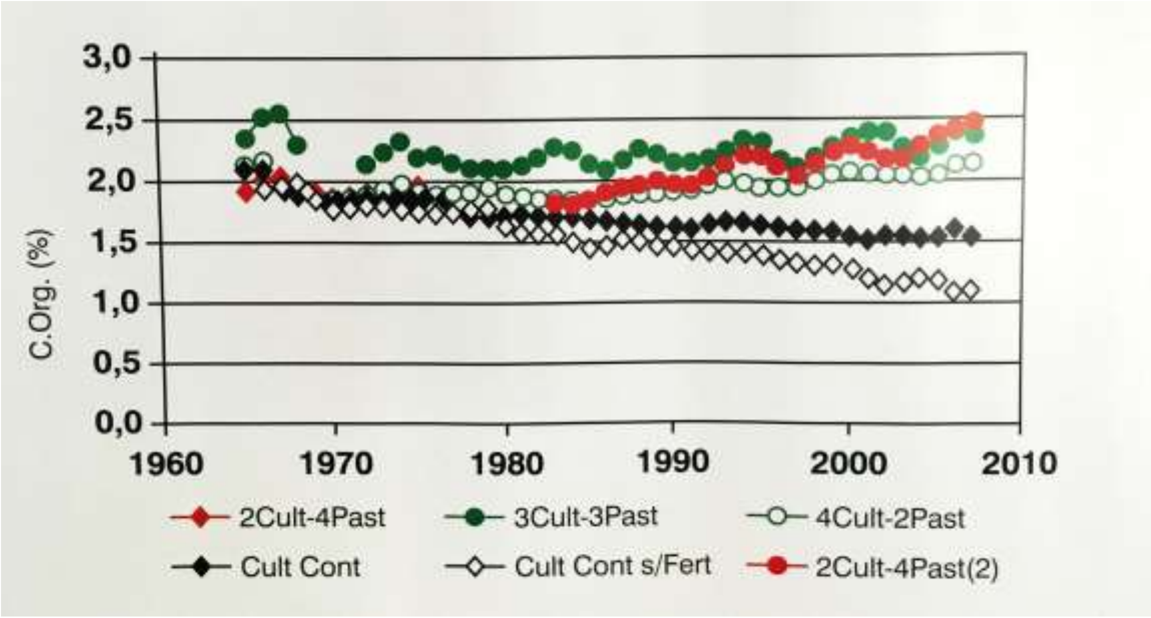

Figure 11. Soil Organic Carbon levels (multiply by 1.7 to get approximate SOM) in different pasture/cropping systems. Green is 50% pasture, red is 66%, white circles are 33%. Black is continuous cropping, and white diamonds are continuous cropping with no fertiliser. Graph courtesy of Dr Andres Quincke/INIA

As is clear from the graph, there is a significant difference between systems which contain pasture, and those that do not; soils under continuous cropping contain roughly half the amount of organic matter - and the trend is for that gap to get bigger in the future. One flaw in this trial is that there are no actual livestock involved, all of the pasture is either cut and mulched, or baled and removed. I would expect this to reduce the positive impact on the soil, because much of the extra nutrients that the plants have used, such as carbon and nitrogen, are not returned to the soil as manure.

Another interesting result from the experiment is the difference between the fertilised and non-fertilised continuous crop rotations. I have been told by many people that inorganic nitrogen fertilisers destroy organic matter. This may well be true in a laboratory. However, it is clear from these results that the opposite is happening in field trials. This is probably due to the fertilisers creating extra plant growth, so there is more residue left over which over time becomes organic matter. The implications of this are potentially large: a practice which is theoretically bad for Soil Health could in fact be better than one which is good, if it stimulates higher levels of plant growth. Possible examples of this could be tillage vs no-tillage, or grazing cover crops vs leaving them intact.

Over the border in Brazil is another state-funded organisation, Embrapa, which has carried out some similar trials. One paper in particular (Integrated crop-livestock system in tropical Brazil: Toward a sustainable production system, *Salton 2014*) was very relevant. It compared four systems:

- **CS** – **C**onventional **S**ystem using disc cultivation, growing soybeans with a winter cover crop
- **NTS** – **N**o-**T**ill **S**ystem, growing a soya and maize rotation with winter cover crops
- **ICLS** – **I**ntegrated **C**rop-**L**ivestock System growing two years of soya & cover crop and two years of pasture
- **PP** – **P**ermanent **P**asture

The results showed that in almost every test carried out for Soil Health & quality, the PP was best, followed by the ICLS, NTS and finally CS. That trend was followed in these areas:

1. Soil structure and aggregate size. This is important because better structure protects some forms of organic matter more effectively.
2. Total quantities of organic carbon. This result was attributed to the root exudates released from grasses when they are grazed. It should be noted however that the carbon levels in the no-till system actually decreased over time, whereas in the conventional tillage system they stayed constant.
3. Total microbial activity, again probably due to root exudates.
4. "Density and taxonomic richness of the invertebrate macrofauna". This means there were more beetles and worms with livestock integration.
5. Weed pressure. Grazing appeared to reduce weed germination, and with conventional tillage there were 87% more weeds than in the next worst system.
6. Yield resilience. In dry years the tillage system yielded up to 60% less than no-till or livestock integration.
7. Tillage systems had much higher nematode pest levels, sometimes as much as 1500x more.

I find the results from Brazil and Uruguay to be particularly interesting, as they suggest a significant benefit from animals that cannot be replicated just by farming with no-till and cover crops. Whether these systems are as profitable is a different matter, and depends on many different factors. It seems that livestock enterprises are more profitable in the Americas and Australia compared to Northern Europe, but this does not take into account positive long-term changes to Soil Health that may be happening at the same time.

5d.ii. Annual vs perennial roots

The reasons why livestock appears to be so beneficial for Soil Health are not always entirely clear. The ability to use annual plant types is probably one of them. Annual plants are useful. They allow rotations to control pests and diseases. They allow flexibility in marketing by growing what is in demand. But the simple fact is that a large proportion of every growing season is spent establishing the plant, limiting the overall system efficiency.

Perhaps the most obvious difference between annual and perennial crops is shown in the roots. By not having to start from scratch every year, the perennial root systems can become massive, both in total weight and also in depth. This means that not only are the perennials much more efficient at collecting water and nutrients, but they are also very resilient to harsh conditions.

All major grain crops are annuals, and so to get perennial types we must grow fruits, nuts or forage. Fruits and nuts generally take a very long time to produce and are very specialised, so do not fit very easily into cropping systems. This opportunity to use perennial plants, such as grasses and clovers, is one reason why animals can have such a beneficial effect on Soil Health. With a larger mass of roots, it stands to reason that there will be more root exudates in total, and also down to a greater depth, both of which have a positive impact. The very act of grazing is also good for soil, as when leaves are eaten some roots die off as the plant metabolises them in order to re-grow. These dead roots form the basis of new soil organic matter.

Figure 12. There is an obvious difference between the rooting and soil structure in perennial grasses (left) compared to annual grasses (right)

5d.iii. Mob grazing

Because soil improvement is driven by perennial plant roots, any system which specifically promotes their growth is likely to have the greatest effect. Mob grazing is a grazing technique which leaves grass to grow for a relatively long time between grazings - perhaps 60 days compared to 25 with conventional rotational grazing. If a plant is grazed too often, its roots will continue to become smaller and smaller as they are used to fuel new leaf growth. Eventually the plant will have none left, and at this point paddocks are often considered to be "tired", and must be re-seeded. With longer rest periods the plant can recover fully and hence have a much more extensive root system. This improves regrowth rates, nutrient-use efficiency, drought resistance and soil improvement through increased organic matter. Another aspect of mob grazing is how a relatively large proportion of the leaves is left un-grazed. Some are trampled into the soil where they will quickly be decomposed into organic matter, and the rest are left intact, which speeds up plant recovery through increased photosynthesis.

There has been very little in the way of scientific research into mob grazing, but it does seem to be able to support large numbers of animals on smaller areas of land, and with a much reduced bill for pesticides and fertilisers. If low profitability is what holds back farms from integrating livestock this may be a solution. What is not in doubt is the huge benefits it can confer to Soil Health, both through the increased rooting, and the ability not to have to use artificial inputs.

Figure 13. After 100mm of rain the soil from Neil Dennis's mob grazed land (right) is very different from his neighbour's conventionally tilled arable field (left). The soil from the arable field would not hold together, and was impossible to walk on without sinking to your knees

Neil Dennis is a grazier who lives just south of Wawota, in Saskatchewan. He farms 1200ac with his wife Barbara, and the occasional helping hand from a summer intern. But Neil is no ordinary grazier. He is an über-mob-grazier [For a very detailed, and readable, explanation of mob grazing, I would suggest reading Tom Chapman's excellent Nuffield Report:
http://www.nuffieldinternational.org/rep_pdf/1348746792Tom-Chapman-2011-report_.pdf].

In brief, it is the practice of grazing cattle in a tight space, but then moving them frequently before all the grass is eaten. Most importantly, and what really differentiates it from standard rotational systems, is that the pastures are left to recover for a relatively long time after they have been grazed. The exact period depends on a number of factors, such as climate, time of year, and what plants are present. It could be as little as 50 days in perfect conditions, or over a year in a brittle climate. Neil will not return within 60 days at a minimum, and preferably 80. The reason is that it takes this amount of time for the ammonia to dissipate from the urine patches, and so the cattle will be happy to eat all the grass.

I've been doing some mob grazing at home, and am pretty sold on the benefits, having compared it myself with more traditional methods. But I am an amateur compared to Neil; I move the cattle once a day, Neil will do it 6 times. If this sounds like a lot, it is. However, the process is pretty streamlined, and normally he will have all the day's moves set up in a couple of hours each morning, and from then on the automatic gate openers do the hard work.

continued overleaf

The two most important factors for Neil are the rest periods, and the amount of animal impact. Longer rests mean healthier plants that grow faster and more efficiently, and recover more quickly. Animal impact is basically the density of cattle at any one point, and the higher the better. Higher stocking densities mean that urine & dung is more evenly spread, and the uneaten leaves are pushed effectively into the ground, which increases soil quality and plant health – a great, positive, cycle. Most farmers will look at this system and see the trampled grass as being "wasted", as it has not gone through a cow. But consider that Neil manages to stock his farm with almost twice as many animals per acre as his neighbour, and to achieve almost the same growth rate. When you're being paid a daily rate to look after cattle, this is a good thing. Bear in mind also that he uses effectively no inputs at all, including any type of fertiliser.

from my blog: www.ooofarmer.com

5d.iv. Grazing cash crops

Although grazing perennial plants is probably going to improve Soil Health the fastest, it is also possible to have livestock on a purely arable cropped farm. The easiest way to accomplish this is to graze cover crops, but there is some debate as to whether this is a good idea. The argument against using animals here is that they will cause nutrient loss, which will undeniably happen. When an animal eats a plant, most of it will pass straight through, but a proportion will be lost as CO_2 from breathing, and the rest is turned into meat. On the other hand, animals may create a benefit by introducing different microbes from their guts, turning plants into more easily accessible forms of nutrients, and they may also decrease allelopathic effects on following crops. If these effects cause the following crops to be more successful, and create more biomass as a result, then it is plausible that nutrient loss could be mitigated or overcome. If we consider that the majority of Soil Health benefits come from the roots of the cover crop, which are not negatively affected by grazing, then it is certainly possible that it is in fact more beneficial to graze than not. The final upside to grazing is that it will earn money, and so pay for the seed and establishment costs, sometimes making cover cropping a no-lose situation.

Figure 14. Wheat grazing trial at Thriplow Farm. This wheat was planted on August 28th, around three weeks earlier than normal, and at the beginning of December it was grazed with sheep.
Left: day before grazing. Centre: day after grazing. Right: early May, five months after grazing

A different technique which used to be used more in the UK but has fallen out of fashion, is grazing cash crops. In Australia I visited a scientist at CSIRO (Australia's national science agency) who had done a lot of research on this idea. They commonly use "dual purpose" crops for grazing and grain production, normally wheat, oats, barley and oilseed rape. Because it is desirable to have as much forage produced as possible, these crops are usually planted earlier than they would be for pure grain production. In theory this will allow more time for root growth, which could potentially give a yield benefit later on. Drilling early can however have big implications for weed management. This technique is almost certainly unsuitable for fields which have problems with grass weeds.

Grazing timing is critical, and animals must be removed before stem elongation starts. The CSIRO research shows an average yield loss of 8% from grazing, but that is well within the standard deviation of 25% - so it is not possible to draw anything definitive from their tests. The possibility of feeding animals for a large part of winter on crops which are otherwise un-used, possibly starting on oilseed rape before moving to cover crops and then wheat, is an exciting one. However it would only take a small amount of yield loss to cancel out profits from the grazing.

When wheat was first being bred into what we use today, the strain that became bread-making wheat (as opposed to noodle-making, or Durum) picked up a gene called Kna1. Without going into details this gene means that the plant uses potassium (K) instead of sodium (Na). This is a useful adaptation to have, because it gives a greater ability to grow in saline soils; however it also means that there is almost no sodium at all in the leaves. This only becomes a problem when wheat is fed to ruminants, because they require a certain level of sodium to allow the uptake of magnesium. So, if they don't get enough sodium, they will develop hypomagnesemia, or grass staggers as we call it. The solution is to give the animals a supplement of a mix of salt and magnesium oxide. This will increase growth rates by around 40%, for very little cost.

from my blog: www.ooofarmer.com

6. The fertiliser addiction

One theme which reoccurred several times in different countries was how healthy soil requires less artificial fertiliser to produce the same amount of grain. Given that nitrogen fertiliser is the biggest single cost to most farming systems, both in terms of money and carbon footprint, this seems like an important point. In the USA I visited a farmer who had grown legume cover crops for five years continuously on one field as its fertility was so low, and in the sixth year he planted maize. Most of the field had a standard rate of nitrogen fertiliser - 90lb/acre. At the same time he tried two areas with 30 and 0lb/acre: there was no drop in yield.

I came across this effect again in Canada, where it had been researched by the Indian Head Agricultural Research Foundation. They had found that the longer a field had been under no-till, the less nitrogen it required for a given wheat yield. Unlike the first example, added nitrogen does give a yield benefit most of the time, but only up to a certain point. The difference may be that this experiment tested only no-till; there were no legumes to actively add large quantities of nitrogen.

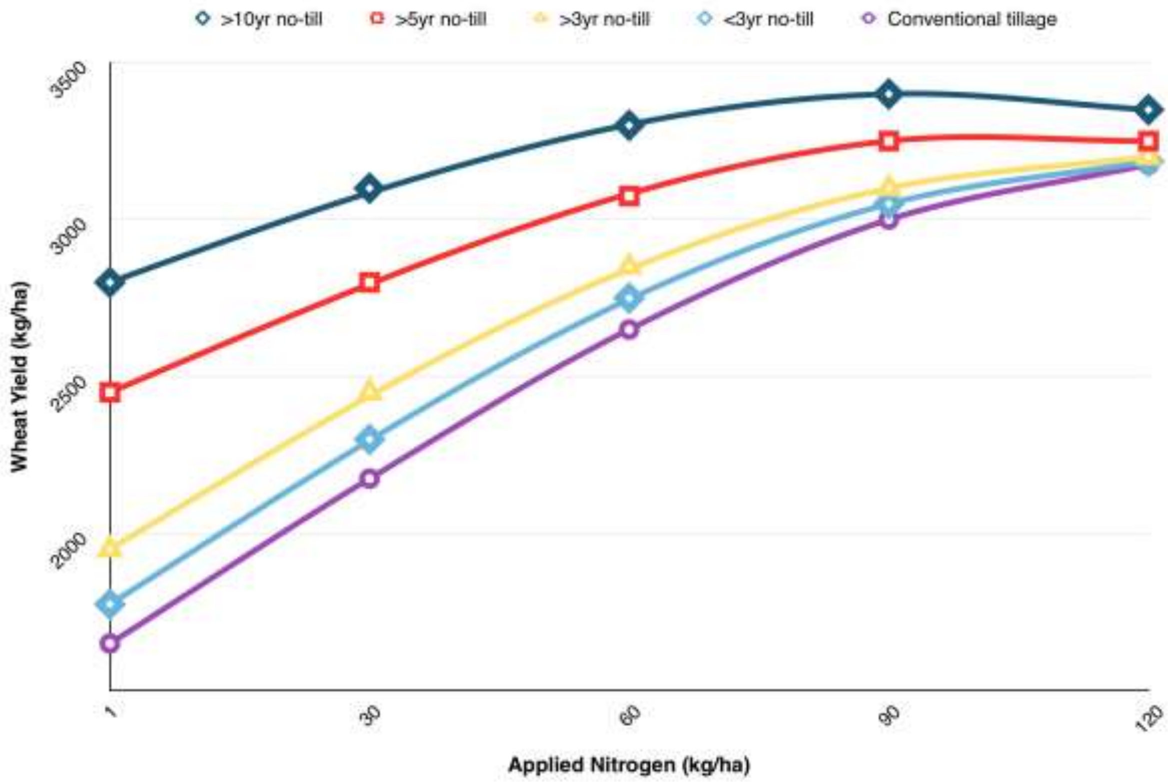

Figure 15. Fields which have been in no-till for over five years yield more than tilled fields, and require less nitrogen to do so. Graph courtesy of Dr Guy Lafond/Jim Halford

The idea of legumes being critical to building up free nitrogen in the soil was backed up by trials carried out by INIA in Uruguay. I mentioned their long-term pasture rotation trials in a previous chapter, but one small experiment within the main plots showed interesting potential. The rotation with 50% pasture was compared to continuous cropping, and the maize crops were given 0, 50, 100 and 200% doses of nitrogen fertiliser. In the continuous cropping plot, anything less than a normal dose resulted in yellow leaves and small plants. In the 50% pasture rotations, there was no visible difference between any of the treatments. At the time I visited the crops were still growing, so no results were available. However, given the undeniable signs of severe nitrogen deficiencies, it is very likely that there will be a yield penalty in the under-fertilised continuous cropping plots.

Figure 16. The left hand picture shows the continuous cropping trial, with 60kg/ha (50% of normal) of nitrogen on the left, and 0kg/ha on the right - these plants are obviously yellower than across the row. The right hand picture is the 50% pasture rotation, also with 60 and 0kg/ha. In contrast, there is no visible difference between the two sides here

Some farmers believe that they do not need to add any artificial fertilisers at all, even though they are taking nutrients off their farms by selling crops or animals. The belief is that by farming with no-till, cover crops, companion crops and livestock, they create new soil, and bring nutrients up from deeper in the profile. I question whether this is a sustainable practice for the chemicals which cannot be replaced out of the air - nitrogen and carbon. One farmer told me "I have enough in my soils to farm for thousands of years without adding anything at all". Could that really be true? The following is taken from a blog post I wrote after having been to a talk by Elaine Ingham.

One of the claims that I was particularly interested in was that "*there are enough nutrients naturally occurring in your soil that you will never need to apply them".* Elaine put up a slide showing average concentrations of nutrients that are found in soil around the world. For phosphorus the figure was 800ppm (parts per million). I don't know if that is what we have in the UK, but let's do some maths.

- An acre of soil 6" deep weighs 1,000t.
- A hectare of soil 6" deep therefore weighs 2,470t.
- A hectare of soil 10cm deep weighs 2,470*10/15.24 = 1,620t = 1,620,735kg
- 1,620,735/1,000,000 * 800 = 1,296kg/ha of P
- According to RB209 every tonne of wheat grain removes 7.8kg of P2O5 = 3.4kg of P
- So a 10t/ha wheat crop will remove 34kg/ha of P
- 1,296/34 = 38 years of P for each 10cm of soil you are extracting from.

continued overleaf

Dr Ingham claims that mature forests store more nutrients as wood each year than we ever take off the land through grain farming, and that they have been going for millennia without any additional inputs. This may be true, and if you consider that tree roots can be found going down to 7m+ in depth, that would be (38*70) 2,660 years of P. This sounds plausible.

Figure 17. A trial in Brazil showed that levels of organic phosphorus are increased in no-till systems. That does not mean though that it is necessarily possible to farm without any fertiliser applications at all. This plot has had no phosphorus for 17 years and is now producing no grain at all

But how deep do we delve in an annual cropping system? Our plants do not have centuries to put down deep roots. Dr Ingham says: "*Wheat, corn, rye, oats, etc can, and should, put roots down to 10 to 12 feet in the first month or two of their life".* I find it hard to believe that this is possible in a lot of situations – roots cannot grow into solid bedrock, and can they get into solid clay subsoils? Having spoken with a range of other scientists and agronomists I believe a more reasonable number might be 1m, which would give us (38*10) 380 years of available P.

But this also assumes that it is possible to extract right down to 0(zero)ppm. According to some soil nutrition researchers, this is not always the case, so that may be overstating what is actually achievable. Of course, on the flipside, we may have 3,000ppm of P in our soils, which would certainly mean there is a lot about. It needs testing.

from my blog: www.ooofarmer.com

7. Is legislation the answer?

From what I have seen and learned on my travels, I am fairly convinced that conventional farming methods in the UK, and most of the world, are leading to the degradation of soils. Sometimes it happens very fast, other times slowly and almost imperceptibly. Soil erosion is a problem that most farmers think does not happen on their farm - but where else does the silt blocking up rivers come from? I used to think we had no soil erosion here, but then I noticed how the high points of fields tend to be very white; this is the chalk subsoil showing through. I'm sure that when the fields were forests or meadows there would have been an even covering of topsoil - so it must have gone somewhere. Physical soil loss is one aspect; the other is the reduction in Soil Health and organic matter levels through over-cultivation, high use of fertilisers and constant pesticide inputs. Unfortunately there seems to be very little appetite for changing behaviours to improve either of these problems. This can be plainly seen when legislation to prevent practices like over-winter ploughing is discussed; even though this clearly can lead to high levels of soil erosion. Many farmers will indignantly shout "no one is telling *me* how to farm".

In Uruguay there is a new system that the government uses to try to limit soil erosion. INIA has modelled many different soil types, crop rotations, cultivation practices, livestock integrations, pasture management techniques, and how each of them interact to effect soil erosion rates. Every landowner must submit a long-term farm plan showing how and what they will farm. This information is fed into the INIA computers, and if the predicted soil loss is less than 7t/ha the plan is approved. If it is over this number then the farmer and landowner will be heavily fined.

Figure 18. Soil erosion in Uruguayan continuous cropping trials

I think that a similar system may be a good idea to implement in other countries, including the UK. An example of similar previous legislation would be the requirement for UK land owners to avoid cultivating two meters either side of a hedge in order to receive our EU subsidies. Before this rule most farms, ours included, ploughed right up to the hedge bottoms, leaving very little area for wildlife, and hence reducing biodiversity greatly.

My main problem with the Uruguayan system is that it lacks ambition. They have found that even native pasture loses 2t/ha of soil each year, and so it is considered impossible to build soils. However, it must have come from somewhere originally, so perhaps they could research how to create soil when farm economics are not important, and then try to transfer those techniques into normal farming practices.

8. "If common sense worked all the time we wouldn't need science"

On one of the very long drives on a straight road through the mid-western USA, I was listening to a Radio 4 podcast of the food programme. One lady on the panel said something that made me think:

"If common sense worked all the time we wouldn't need science"

It is easy, especially in a complex subject, to listen to ideas which sound as though they may work. In my opinion, soil is one of those subjects. It is too complex for us right now - the physics is fairly well understood, the chemistry less so, and the biology is such a web that we have no idea how everything interacts. If something works on one farm, and has an explanation as to why, that does not mean it will work somewhere else. What we need is science to check it out. That doesn't necessarily mean formal replicated trials, but jumping into new techniques without trying them out and comparing to the traditional way is foolish. Wanting an idea to work does not mean it will.

On the flip side, we cannot always wait for trial results, or else we would never try anything new. This is a new area of farming, and outside the interest of many academics, and particularly the input-selling companies who fund most research. So the only way I will know for sure if it works is by trying it myself.

"The best time to plant a tree was 20 years ago.
The second best time is now." - Chinese proverb

9. Conclusions

1. Many farmers are degrading the soil, their greatest asset.
2. The more we use artificial fertilisers and pesticides, the more we need to use them again next year.
3. Conventional soil testing metrics must be treated with great caution.
4. We need more livestock in our fields; both above and below the ground.

10. Recommendations

One thing I have learnt is that everyone has a different farm, and what works in one place may not in another, even if it is only a few miles away. I will not recommend what anyone else should do on their farm, but this is what I plan for myself:

1. Reduce (ideally eliminate) cultivations and soil disturbance.
2. Grow as many different plant types as possible as either cash, companion or cover crops.
3. Try to integrate livestock where economically (and socially) feasible.
4. Be proactive rather than reactive with our farm's Soil Health.
5. Experiment with as many news ideas as possible - and increase the chances of finding something that works.
6. Do not give up when an idea does not work at first, but try to learn from what went wrong, and fix that.

11. After my study tour

At the beginning of my study, I told several people that it would be a shame if I came out at the end with the same views I held at the beginning. That is largely what has happened - but is it a bad thing? I applied for the Scholarship because I could see on our farm what had happened to some fields, and I wanted to know how to improve our soils. If my mind had been changed on this then I would in effect be accepting soil degradation as an inevitable and unchangeable phenomenon.

I do not believe it is.

To reverse the changes will not be easy, or quick. It may also make us less money in the short-to-medium term; to ignore this simple fact would be foolish. This type of farm system does not need the landowner and farmer to be the same person, but they must have the same philosophy. But I am in the privileged position of being both, so I can take the long term view.

The farm will not change radically from what we have been doing before, as we have been moving towards no-till, cover crops and livestock for the last few years. This year we are growing eight different crops, but I hope to try and increase that further. Last year we grew cover crops on almost a third of the farm, and this year it will be an even higher percentage. One of our oilseed rape fields was planted with a companion crop, and I intend to carry on with this, and try out new species for the mixes. Perhaps permanent legume under-stories across many different cash crops will allow us to reduce our nitrogen use significantly.

Pesticide use is an area I hope to change. We will not stop using them, but already we have found that some techniques allow us to reduce or eliminate some applications that beforehand were considered essential.

Perhaps the biggest change I have made is with livestock. We will continue to graze our cover crops with sheep - I am happy that this is probably giving us an advantage over leaving them untouched. In addition we have grazed half a field of wheat, and will try oilseed rape next year. But it all started with the Wagyu, and after returning from my last study trip, to South America, I sold them. I had reached a point where it was crossing from a hobby to a job, and I was not good enough at it to continue. I did not want to give up my cattle experiment so quickly though, and soon after the Wagyu left, 80 Hereford cross yearlings arrived to mob graze our herbal ley for the summer season. I'm hoping this allows me to better manage the grazing, and make it more likely I can turn a mediocre field into a yield topper.

One afternoon in South Dakota, Dr Dwayne Beck scolded me for "thinking incrementally, not transformationally". He was right, but as of yet no one has come up with a transformational system which works in our environment in the UK. I hope that when it does arrive we will be right there.

APPENDIX : Footnote on Organic farming

I am aware that throughout this report I have talked often about the harmful effects of both artificial fertilisers and pesticides. I am not suggesting, though, that organic farming is “the answer”. For one thing, organic farms can still use pesticides - although they are different from the ones we have access to in a conventional system - and these can also have the same harmful effects. The other reason is pragmatic; suddenly stopping all inputs would lead our farm to collapse through massive yield reductions and huge pest problems. It is important though, in my view, to understand the harm that we may be doing to our own soils with the way we now farm. It is only by realising this that we may perhaps be able to wean ourselves, if not totally off chemicals, onto much more efficient systems where our fertiliser comes from the air or subsoil, and our pests are kept in check by the rest of a full ecosystem.

And to prove I’m not too much of a zealot, our farm has just bought a very expensive new sprayer.

Figure 19. The newly arrived mob grazers look innocent, but like to escape.
Sometimes it is obvious why this farm stopped farming livestock

12. Executive summary

After a few years of working on our family farm, I noticed that some fields performed significantly better than their neighbours, even though the soil types were very similar. The histories of these fields were very different, with the better performing ones having been more recently used for growing grass and grazing livestock. In our case, we found that even after 25 years there could be as much as a 25% increase in yields in fields that had been more recently in pasture. Many farmers realise that these areas always grow the best crops, but there is a reluctance to understand why, or to try and harness those characteristics to improve the whole farm.

With my study I aimed to find out how to measure what makes some fields better than others, and then find out the best way to make these changes in an economic way, and in a sensible time frame. To do this I travelled to New Zealand, the USA, Canada, Denmark, Australia, Argentina, Uruguay and Brazil to look at no-till, cover and companion cropping, and livestock integration. I visited farmers which had decades of soil improvement experience and claimed they could increase organic matter levels by 1% every year, as well as researchers who said this was not possible.

I found that although varying climates in different countries meant the effects happened faster or slower, many modern farming methods are contributing to a decrease in productivity and Soil Health. Cultivations carried out by heavy machinery are causing structural damage and organic matter loss at the same time. Many farms in the first world have specialised towards crop-only production, and away from integrated livestock systems. This is causing Soil Health in general to be reduced as plant diversity is diminished, and the lack of perennial pastures means soil organic matter levels are significantly below their potential. The knock-on effect from impaired Soil Health is increased reliance on fertilisers as plants cannot form symbiotic relationships with microorganisms which help them access nutrients. In addition, this lack of soil fauna also allows plant pathogens to become dominant and cause yield-robbing diseases.

Some of the solutions to these problems are easy, such as changing machinery to allow farming with less soil disturbance, whereas altering crop rotations and growing cover crops may require some investment in the future by possibly sacrificing short term profitability. The most valuable change, integrating livestock, will be the hardest to accomplish in scale. Many have moved away from this type of farming in the last century for economic and lifestyle reasons, but it is only now that we are seeing what we have lost in the process.

13. Acknowledgements

When I left on my first month-long trip at the beginning of 2014 I left behind my wife Sabrina and eighteen month old daughter Elyse. Over the rest of the year I spent another seven weeks away, and in January 2015 we had another girl, Madeleine - this was three weeks before my trip to South America. I am incredibly grateful, and lucky, that Sabrina was supportive of my travels. Being left as a single parent for so long is not something I could have coped with nearly as well as she did, so it is to her I owe the most thanks.

Secondly I would like to thank the Nuffield Farming Scholarship Trust, and my sponsor The Worshipful Company of Farmers. It is obvious that without them I would not have had this opportunity.

My father is a Nuffield Farming Scholar from 1978, and I was brought up in the knowledge that, if I was a farmer, I really should try to undertake a Scholarship. Without this inbuilt assumption I might never have applied. However, judging from the amount of grumbling I heard about being away for so long, back in the ‘70s they must not have gone travelling at all. Sticking with the family theme, my mother very helpfully re-arranged the words in this report into readable English.

I also owe a big thank you to Dick Arbon and Grant Anderson, who signed up for an easy life at Thriplow Farms looking after crops, but then got saddled with a small herd of cattle every time I went gallivanting.

Finally, thank you to everyone who has helped, hosted and fed me during my travels. I hope you’re all here in this list, arranged roughly chronologically. I quite literally could not have done it without you.

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