Rotations and their Impact on Soil Health

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Dr Charles N Merfield. MRSNZ

The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

www.bhu.org.nz/future-farming-centre

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"The greedy cultivator is sure to pay dearly in the end for every crop forced from the land unreasonably"

(Society for the Diffusion of Useful Knowledge (Great Britain), 1834)

1. Summary

- This report is based on a literature review of the impacts crop rotations on soil health.
- It has focused on research where it is the rotation itself being compared rather than a component of the farm system, e.g., cover crops, reduced tillage.
- Crop rotations have been a fundamental component of agriculture for millennia, potentially back to the dawn of agriculture.
- There are a multitude of benefits rotations can provide: both on-farm and off-farm; and to the land manager, to wider society and to the environment.
- It only became possible to reduce or stop using rotations with the advent of the agrichemical pesticides (fungicides, insecticides and herbicides) and the widespread uptake of synthetic nitrogen fertilisers, which substitute for some of the benefits rotations provide.
- However, the evidence of negative effects on humans and the environment from pesticides and nitrogen fertilisers continues to grow, such that it is unambiguous that the use of pesticides and N fertilisers must be reduced, and, their modes of use modified to reduce the negative effects.
- In addition, insects, diseases and particularly weeds are evolving resistance to pesticides at an accelerating rate, such that some pests are no long able to be controlled by pesticides and that this issue will only increase.
- It is clear therefore that pesticide and nitrogen fertiliser use must be reduced, and, that rotations are a 'back to the future' technology that will allow for productive, profitable, and resilient farms with reduced pesticide and N fertiliser use.
- Of the many benefits from using rotations a key one is the benefit to soil health. A healthy soil is vital at so many levels - from farm productivity, to farm resilience in the face of the climate crisis, to helping mitigate climate heating, and many further benefits to the wider environment and society.
- Rotations improve soil physical health mostly via improving soil biological health, the outcomes of which include, better soil structure, better drainage, increased water holding capacity, better rooting depth, and resistance to being degraded, e.g., erosion.
- Rotations improve soil chemical health, through the inclusion of leguminous nitrogen fixing crops which increase soil N levels, and transforming the lithospheric nutrients, e.g., phosphorus, into more plant available forms, improving fertility / nutrient holding capacity, and reducing the loss of nutrients to the wider environment.
- Rotations improve soil biological health principally through increasing the diversity of crop and animal residues being returned to the soil, which diversifies and increases soil biology and ecology, which in turn improves plant health & yield, suppresses disease causing organisms, and also help manage pests and weeds.
- And at a system level rotations assist in producing good yields of high quality plants, diversify the farm enterprise and therefore spread risk and make the farm more resilient and robust
- With these multiple benefits rotations will clearly be a key part of the new revolution in agriculture that is required if civilisation is to address the multiple massive global challenges we all face.

2. Introduction

Rotations have been an essential component of agriculture since at least Roman times (White, 1970) if not back to the origins of agriculture itself, not only in Europe but globally as well (King, 1911). The basics of rotations are very simple, but the full magnitude of their effects can be profound. Rotations are the antithesis of monoculture where the same crop is grown on the same piece of land year after year. With rotations a succession of crops is grown, a minimum of two, but, often four or more crops, or best more than seven, before a crop that has been grown previously, returns to the same piece of land. Ideally the crops are as diverse as possible in terms of their taxonomic relationships and physical attributes (e.g., root structure, weed competitiveness, nutrient requirements, etc.) and include a mixture of pasture, arable and vegetable crops. The benefits of rotations include:

On-farm benefits:

- Enhancing soil health:
  - Improved soil structure;
  - Increased organic matter / carbon levels;
  - Better 'fertility' through nitrogen fixation, increased cation exchange and microbial mobilisation of nutrients:
    - Leading to reduced need for nitrogen fertilisers and more efficient use of other fertilisers, especially phosphorus.
  - Increased water holding capacity helping counteract droughts;
  - Improved drainage helping to counteract high rainfall / flooding;
  - Increased resistance to erosion, both water and wind.
- Better weed, pest and disease (fungal and bacterial) management;
  - Leading to reduced need for pesticides and therefore reduced likelihood of evolved resistance.
- Increased crop growth and farm productivity in the absence or reduced input of pesticides and mineral nitrogen fertilisers;
- Reducing risk and greater stability of income and profit through an increased range of farm products;
- Mitigating weather and soil moisture based risk;
- Spreading the times of peak labour demand.

Off-farm benefits:

- Increased biodiversity, not just of planted crops, but also:
  - Above ground biodiversity: plants, vertebrates, invertebrates and microbes, at both farm and landscape scales;
  - Below ground biodiversity, particularly soil microbial biodiversity.
- Addressing the climate crisis:
  - Mitigation through:
    - Carbon sequestration;
    - Reduced nitrous oxide and methane production;
    - Reduced nitrogen fertiliser use (both upstream and downstream benefits).
  - Adaptation through increased soil resilience and therefore farm resilience.
- Reduced losses of nitrogen and phosphorus to the hydrosphere;
- Reduced losses of pesticides to the wider environment;
- Improved aesthetics of the farmed landscape.

Despite these many benefits, rotations have been used less and less since the middle of the 20th Century, due to the widespread and intensive uptake of mineral fertilisers, particularly nitrogen, and the agrichemical pesticides (xenobiocides), which along with irrigation, and mechanisation are used to replace the benefits and outcomes of rotations (e.g., pest control, nitrogen supply) and are therefore the foundation of the intensive / industrial systems of agriculture that dominate the developed world to this day (Pretty, 2008).

However, there are a multiplicity of problems associated with industrial agriculture, e.g., biodiversity and habitat loss, soil damage and loss, excess phosphorus and nitrogen in the environment, the climate crisis, xenobiocides and xenobiotic compounds (e.g., microplastics) in the environment, etc., (Steffen *et al.*, 2015). Not only has industrial agriculture created a very wide range of problems, it also faces major disruption to the inputs and technologies that have created it, such as: evolved resistance of insects, diseases and weeds to the xenobiocides (Steffen *et al.*, 2015); finite supplies of phosphorus (Jenkins & Jenkins, 2012; Science Communication Unit University of the West of England Bristol, 2013; Merfield, 2014); and nitrogen fertiliser which use large amounts of fossil fuels to manufacture (Sutton *et al.*, 2011). At the same time agriculture is having to adapt to external problems such as the climate crisis (Steffen *et al.*, 2015). There is therefore an increasingly urgent need for a new revolution in agriculture, to reduce its environmental impacts, while also adapting to the environmental challenges that it faces, e.g., climate change, soil loss, reduction of biodiversity, etc., and while still meeting demand for healthy food. In particular, while the pesticides and mineral nitrogen fertilisers reduced, even eliminated, the need for rotations, now that the pesticides are failing due to evolved resistance and societal rejection, and the environmental harm due to nitrogen fertilisers must be mitigated, rotations will again become an important part of the solution to address these, and the many more, negative impacts of industrial agriculture, while also assisting agriculture adapt to a more capricious climate.

Of the multitude benefits of rotations, the focus of this report is on the impacts of rotations on soil health. It does not aim to be a comprehensive review of the entire literature on rotations nor a meta study as that would require orders of magnitude greater resources than are available. Rather, it aims to give an overview of the potential diversity and type of impacts that rotations can have on soil health with the aim of informing those from outside of agriculture, and to inform policy and public debate.

3. Soil health

The term "soil health" is widely used, but, can mean quite different things to different people and it is also linked to the related, more utilitarian term, "soil quality". Soil quality can be most succinctly defined as 'fitness for purpose', but different purposes, e.g., as a foundation for a building vs. as a medium for crop growth, mean that the 'qualities' required from soil for the different purposes may be very different (Doran & Parkin, 1996). In comparison, soil heath has been variously defined as:

- "The capacity of the soil to support productivity and ecosystem services" (Kibblewhite *et al.*, 2008).
- "The capacity of soil to function as a vital living system, within ecosystem and land- use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health" (Doran & Zeiss, 2000).
- "Soil health refers to self-regulation, stability, resilience, and lack of stress symptoms in a soil as an ecosystem" (Brady & Weil, 2008 p. 874).
- "Soil health is the capacity of soil to function within ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran & Parkin, 1996).
- “Soil health is the capacity of soil to function as a living system, within ecosystem and land use boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and promote plant and animal health. Healthy soils maintain a diverse community of soil

organisms that help to control plant disease, insect and weed pests, form beneficial symbiotic associations with plant roots; recycle essential plant nutrients; improve soil structure with positive repercussions for soil water and nutrient holding capacity, and ultimately improve crop production" (FAO, 2008)

Soil health therefore contains both intrinsic values, e.g., "vital living system" (Doran & Zeiss, 2000) and "soil as an ecosystem" (Brady & Weil, 2008) as well as extrinsic values e.g., "support productivity" (Kibblewhite *et al.*, 2008), "sustain biological productivity, maintain environmental quality" (Doran & Parkin, 1996). Further, some benefits of soil health such as "support[ing] [crop] productivity" are mostly of benefit to the farmer or grower, while others are external benefits e.g., "maintain[ing] environmental quality" that benefit society and the wider environment. Rotations can therefore increase 'ecosystem services' (Science for Environment Policy, 2015; Costanza *et al.*, 2017), e.g., habitat provision, genetic resources, carbon sequestration, climate regulation, and cultural services. These have benefits for all of society and therefore it can be argued that society should support the increased used of rotations, for example, through subsidies.

At a practical level soil health can be divided into physical, chemical, biological and ecological measures, e.g., physical soil structure, optimal levels of chemical nutrients for plant growth, good levels of biological activity, and a large diversity of organisms (ecology). In more detail the characteristics of a healthy soil includes:

- Physical attributes:
  - Levels of soil organic matter (soil carbon) close to biophysical optimum;
  - Good soil structure;
  - Sufficient depth / lack of rooting impediments;
  - Good water holding capacity;
  - Good drainage;
  - Resistance to being degraded, e.g., eroded, compacted;
  - Only geological rates of erosion.
- Chemical:
  - Balanced supply and sufficient reserves of plant nutrients (nutrient exchange capacity) i.e., 'fertility';
  - Fixation of atmospheric dinitrogen into plant available reactive nitrogen;
  - Minimal losses of nutrients to the wider environment (especially nitrogen and phosphorus);
  - Minimising chemicals that harm plants (both eobiotic and xenobiotic).
- Biological and ecological:
  - Assists with minimising / managing plant and animal:
    - Pests, both invertebrate and vertebrate, e.g., insects, slugs, nematodes, rodents;
    - Diseases, e.g., fungi, bacteria;
    - Weeds.
  - Good levels and activity of plant-health promoting organisms, e.g., mycorrhizal fungi, nematodes, earthworms;
  - Maximising biodiversity across all kingdoms;
  - Well functioning ecosystem processes.
- System level:
  - Supports healthy, optimally yielding, plants / crops, and livestock;
  - Resilience and robustness (the ability to resist and/or recover a healthy state in response to destabilising influences).

4. Issues in crop rotation science

There are some important issues that need to be taken into account when undertaking and interpreting research into rotations.

4.1. The relationship between rotations and other farm practices

The use and diversification of rotation often goes hand in hand with changes to, and introduction of, other beneficial farm practices, e.g., crop species mixtures, reduced tillage (cultivation), and planting cover crops / green manures, all of which are well proven to increase soil health. Rotations are therefore often part of a matrix of tools that can improve soil health, often in a complimentary / synergistic way. For example, cover crops are not an obligatory constituent of rotations, but, having a diversified rotation can provide more opportunities for cover crops, both short and long-term, to be grown. Likewise, reducing tillage is not a requirement of rotations, but, where a farmer has a desire to change their farming practices to improve soil health, reducing the amount and intensity of tillage can be synergistic with increased rotations, for example, increased opportunities for undersowing / relay cropping, and the introduction of pasture. Therefore there are a range of farm management practices (tools) that farmers can use that are complimentary, even synergistic, with rotations to improve soil health.

However, when reviewing the evidence of the impact of rotations on soil health, care is required in attributing the outcomes to the rotation rather than other changes to farm practices. For example if an experiment compares two rotations, that are the same except one includes cover crops, then the experiment is really a study of the benefits of cover crops, rather, that the benefits of a rotation. Or alternatively an experiment has three rotations which are all the same except, one used no-till, the next minimum till, and the third, full inversion tillage (ploughing), again, this is not a rotational experiment but a tillage comparison experiment. A true rotational experiment, for example, could compare, a monoculture maize, with a maize-soya two year rotation with a maize-soya-wheat three year rotation. Or better, all three crops are grown in monocultures and all their possible two and three years sequences are compared. Comparing the exact same crops, e.g., pasture, wheat, oats, beans and barley, but, grown in different sequences, would also be a true comparison of different rotations. Therefore, in the research evidence review below, the aim has been to cite research that is undertaking a true comparison of different rotations, rather than studies that are comparing differing farm practices, such as the examples of cover crops and tillage given above, which are often described as a rotation experiment.

4.2. The science of researching rotations

There is a considerable number of crop rotation experiments, which study the many different impacts rotations can have, from soil health to economics. By its nature, research into rotations requires the use of long-term field experiments. Long-term field experiments produce some of the highest quality agronomic data to come out of agricultural science, particularly when the research is studying impacts on soil, as it can take many years, even many decades for soil to fully respond to changes in management practices, and only long-term field experiments using realistic farm practices can measure such slowly occurring changes. Therefore much of the research into rotations produces some of the most reliable and high quality results in agronomic science.

However, while much of the research into rotations is of high quality, it tends to be more focused on producer focused issues such as yield, profit, pest, disease and weed management. So, while long-term trials are ideal for studying soil health, fewer rotation experiments study soil health.

The issue of what constitutes a rotation is also exceptionally diverse; at the bare minimum a rotation can consist of alternating just two crops over two years, e.g., maize and soybeans, while at the other extreme a rotation can require more than a decade to complete and include a biologically/taxonomically diverse range of annual / biannual crops and a pasture phase containing many tens of plant species. Therefore making a general statement such as 'rotations increase soil health' is problematical as what is meant by 'rotation' can and does vary dramatically, and, it would not be expected that the benefits of a simple two crop rotation would be anywhere as near as large as a multi-year highly diverse rotation, as described above. Care must therefore be exercised when implying that 'rotations' can achieve a specified outcome as the detail of the rotations being compared is vitally important in relation to the outcomes.

With these issues in mind, the following section presents a range of evidence for the impact of rotations on soil health.

5. Research evidence on the impact of rotations on soil health

This section uses the outline of the soil health framework from section 3 to structure the experimental evidence for the impacts of rotations on soil health.

5.1. Soil physical health

Soil physical attributes, such as good structure, water holding capacity, and good rooting depth, are mostly the result of good soil biology - indeed, virtually all aspects of soil health are the result of circular processes, e.g., good structure enhances crop growth, which means increased returns of plant residues to the soil and more vigorous root systems, which in turn enhance soil structure. Soil health is therefore a clear example of a system that is either in a virtuous or vicious cycle.

At the core of good soil physical attributes, and pretty much any other measure of soil health is soil organic matter / soil carbon. Using two existing long term rotation trials of continuous corn, continuous soybean, corn-soybean, corn-soybean-wheat rotation, the most diverse rotation of corn-soybean-wheat rotation increased soil organic carbon content compared to continuous soybean, and there was an interaction of rotation and tillage with soil organic carbon 7% higher under no-till than chisel tillage (Zuber *et al.*, 2018). In a 21 year study of a more diverse rotation at three sites in southern Sweden, the effects of having a two year pasture (ley) phase (either pure grass or grass + legume) in an arable rotation, found that soil carbon was higher in the rotation with pastures at one of the sites but not the other two (Persson *et al.*, 2008). Jordan & Hutchinson, (1996) as part of the LIFE Project, studying less-intensive integrated production systems, also found that soil organic matter levels increased under the more diversified and integrated rotation designs. In a comparison of an ecological and standard farming system where in the ecological system the chemical inputs in the standard farming system were replaced by multifunctional crop rotation, ecological plant nutrition, and mechanical and physical weed control, the ecological system showed improved soil physical and chemical properties along with higher quality organic matter (Bartošová *et al.*, 1999). Based on two, long-term, no-till, cropping trials, a comparison of rotational diversity, residue management and cover cropping found that all three techniques aways improved soil structure, sometimes with synergistic effects between the three techniques (Perkons *et al.*, 2014).

Rotations, or more precisely more diversified rotations therefore have a nearly consistently positive effect on soil organic matter / soil carbon, and, increased soil organic matter is intrinsically linked to an overall improvement in all other aspects of soil health.

Walker *et al.*, (2011) studied the effects on soil structure and earthworms from a long-term organic trial of three, six year rotations, two of which were stocked, the first with three years of grass and white clover, followed by three years of cropping, the second had four years of grass and white clover with two years of cropping, and the final rotation was stockless with one year of grass and red clover and five years of mixed cropping. The longer the pasture phase, the more soil structure improved, with a peak at three years. Oats also improved soil structure while swedes with their associated tillage in in-crop cultivation worsened structure. In most other research looking directly at the effect of pasture on soil physical health, pasture almost always has a positive benefit, unless soil health is already high. It is considered that in pasture, the combined effects of no tillage occurring, having permanant (year round species) and the presence of grasses with their fibrous rooting systems all contribute to improve soil health. Conversely there is a wide range of research that shows that tillage and cultivation have negative impacts on soil structure in particular (as well as other impacts, e.g., reducing earthworm populations) so, the Walker *et al.*, (2011) study is consistent with other research showing the benefits of pasture and the issues with tillage. It is therefore recommended that having pasture as part of a rotation, i.e., mixed farming, is vital to maximise soil health.

Perkons *et al.*, (2014) studied the effect of rooting depth of the annual crops spring wheat, winter barley, and winter oilseed rape, that followed either two continuous years of chicory with deep tap roots, or oats and tall fescue which have fibrous roots. They found that the root-length densities of winter barley and winter rape below 115cm soil depth were greater after the deep rooting chicory pre-crop . The paper concluded that cultivation of tap rooted crops in a rotation could allow subsequent crops to establish more roots in deep soil layers, with potentially greater access to nutrients and water from the subsoil (Perkons *et al.*, 2014). This is an interesting example of an experiment studying one of the lesser considered aspects of soil health, in this case rooting depth, and it was particularly intriguing that the effect was only seen below 115 cm. Normal maximum tillage depth is around 30 cm (the 'plough layer') that typically coincides with the soils 'A' horizon in many temperate climate soils. That rooting was effected as deep as 115 cm highlights the importance of managing soil through biology, as soil at this depth is well out of the reach of tillage operations, except for the very largest sub-soilers.

Overall, therefore, there is clear evidence that rotations can have positive impacts on soil physical health and more diversified rotations tend to have greater improvements.

5.2. Soil chemical health

The term 'soil fertility' is one that can have multiple meanings. At one end of a spectrum it can be used to mean that mineral fertilisers have been applied so plant available soil nutrient levels are at their optimums, so plant yield will therefore be maximised, through to being used to indicate the ability of a soil to 'hold' large amounts of plant available nutrients, i.e., having a high cation exchange capacity, to the other end of the spectrum where soil fertility is used in an almost analogous meaning to soil health. It is important therefore to be clear what is meant by soil fertility in each situation.

5.2.1. Soil nitrogen

Of all the plant nutrients, the most important when it comes to rotations is nitrogen. This is because nitrogen is the only plant nutrient absorbed by plants via their roots (as opposed to carbon that is absorbed from the air), that can be increased in total amount in the soil, by growing leguminous crops, that can fix atmospheric nitrogen (or to be precise, it, is the bacteria symbionts in their roots that actually fix the nitrogen). Nitrogen is also the plant nutrient that is most often in shortest supply, and therefore its level in the soil determines yield. Prior to the advent of synthetic nitrogen fertilisers, rotating leguminous crops and/or pasture containing legumes / clovers was the only route to increase the total nitrogen in a farm system (animal manures can only move N (and other nutrients) around a farm, not increase the total amount). This is why rotations are so vital in organic agriculture as synthetic nitrogen is prohibited in organic agriculture.

In the first completed rotation of the Nafferton Factorial Systems Comparison trial, comparing an eight year organic and conventional mixed farming rotations, there was little difference in soil fertility between the two systems, with soil N being slightly higher under organic and available P lower (Cooper *et al.*, 2011). It was noted that as the two rotations are less dissimilar compared with other rotational experiments that one cycle of the rotation may be insufficient to show large differences. This is also considered a good example of the need to understand the details of what constitutes any given rotation as discussed in section 4.2.

Using two existing long term rotation trials of continuous corn, continuous soybean, corn-soybean, and a corn-soybean-wheat rotation, Zuber *et al.*, (2018) found the continuous soybean had the lowest total soil N compared to the other rotations, but there was no difference in microbial biomass N between the rotations. As soybean is a legume and therefore nitrogen fixing, this result does appear rather anomalous as it would be expected that the rotation with continual nitrogen fixing crop would have the highest nitrogen. However, Zuber *et al.*, concluded that crops with higher C:N ratio in their residues support higher C and N content in the top 20 cm of the soil (Zuber *et al.*, 2018), i.e., that it is not enough alone to fix lots of nitrogen, but, unless there is sufficient carbon in the soil to build organic matter to hold the nitrogen, then the extra nitrogen can easily be lost from the soil system.

Based on trials over three sites and three years in Canada it was found that of faba bean, narrowleaf lupin, and field pea, N-fixation ranged from 70 to 223, 78 to 147, and 46 to 173 kg N/ha, respectively, with faba bean having the highest average N fixation (Strydhorst *et al.*, 2008). This study highlights that there are considerable differences in N fixation among the legumes, due to both inherent / genetic differences and variable environmental factors, particularly the level of plant available soil nitrogen, where high levels of soil N inhibit fixation, and with the level of the inhibition also varying among plant species (Liu *et al.*, 2011). Other factors that influence the level of fixation is soil temperature, the presence of, or inoculation with, the correct symbiotic bacteria, soil moisture levels, the amount of photosynthesis and therefore carbon and energy to be given to the symbiotic bacterial, and the longevity of the legume phase, for example. It cannot therefore be assume that just having legumes in a rotation is a guarantee of a good nitrogen supply and a multitude of factors need to managed to achieve optimum N fixation.

A study on the amount of N required by winter wheat found an interaction between soil type and previous crop - winter wheat, winter barley, spring barley, winter oats, winter oil seed rape, potatoes, sugar beet and peas. There was a lower demand for N on heavier soils where there was less nutrient leaching than on lighter / sandier soils. While the average N requirement across all preceding crops was 206 kg N/ha there was significant variation with the maximum being 377 kg N/ha required on a shallow soil following winter wheat, to zero on a clay soil following oil seed rape, and peas on a silt soil (Goodlass & Sylvester-Bradley, 1996). This research shows the important interaction of soil type and rotations, and therefore that rotations needs to be matched to soil type, and other variables such as climate etc.

In the study by Bartošová *et al.*, (1999) discussed above, of an integrated and ecological rotation, where the chemical inputs in the integrated system were replaced in the ecological system by a multifunctional crop rotation, ecological plant nutrition, and mechanical and physical weed control, the ecological system had higher levels of biological N and nitrification.

5.2.2. Losses of N to the wider environment

A study of the effect of longer term use of cover crops to reduce overwinter nitrate leaching in arable rotations found that only about 20% of the N taken up by the over-winter cover crop was mineralised over the following year and therefore ongoing use of cover crops would result in a build up of soil N as organic matter that could be mineralised in future and therefore represent a risk of enhanced leaching (Harrison & Peel, 1996). It is therefore important that where soil organic matter is increasing, (which is positive) and therefore the amount of mineralisable N also increases, that this is taken into account when determining fertiliser recommendations, as this will mean that the quantity of N fertiliser can and should be reduced, with resulting environmental and financial savings.

As part of the LIFE Project studying less-intensive integrated production systems, a reduction in the amount of N and P lost to the environment was achieved by increasing soil cover index due to diversified rotations and more accurately matching nutrient supply to that removed at harvest (Jordan & Hutchinson, 1996).

Unlike soil physical health where rotations, especially more diversified rotations, generally result in increased health, increasing soil nitrogen requires the deliberate placement of nitrogen fixing crops, i.e., legumes, into the correct part of the rotation, i.e., where soil N has become depleted, thus forcing the legumes to increase the amount of N they fix.

5.2.3. Phosphorus

After nitrogen, phosphorus is often the next most yield limiting nutrient. Unlike nitrogen fixation, there is no biological process to increase the total amount of P in soil. This also applies to all the other 'lithospheric' nutrients, e.g., K, Ca, Mg, Zn, etc. However, while the total amount of P cannot be increased, it is possible to transform some of the plant unavailable forms of P into plant available forms. For example a cover crop of buckwheat can increase soil available P (Teboh & Franzen, 2011).

However, there appears to be very little research studying rotations for their ability to change soil P, or any other soil nutrient, availability. The one exception is the highly regarded, long-term, DOC (bio-**d**ynamic, **o**rganic and **c**onventional) trial run by Forschungsinstitut für Biologischen Landbau (FiBL, Research Institute of Organic Agriculture) in Switzerland where as part of the analysis of soil fertility, increased microbial phosphorus delivery for crops was found (Mäder *et al.*, 1999).

5.3. Biological and ecological soil health

At a fundamental level soil is a living entity: without life soil is just 'regolith' - broken up rock. Therefore by definition and practical experience a healthy soil is a biologically active or living soil. In a substantial review Stockdale & Watson (2012) found there are three key management actions that increase soil biological and ecological diversity and function:

- Increasing the variety and overall amount of organic matter adding to the soil (e.g., having a range of crop residue types and using green manures); and / or
- Reducing tillage, both the total amount and also intensity (e.g., surface working vs. ploughing); and / or
- Diversifying cropping systems (having a wider range of crops and/or pasture). (Stockdale & Watson, 2012; Merfield & Shaw, 2013)

Diversified rotations are therefore a key means of increasing soil health by increasing plant diversity. To increase the diversity of plants in a farm system there are two options:

- Increase the number of plant species in a field at the same time i.e., single species crops to multi-species crops.
- Increase the number of plant species grown in a field over time, i.e., to increase rotational diversity.

Diversified rotations are therefore an essential mechanism for increasing soil health by increasing the diversity of crops, both cash crops and cover crops, and therefore the diversity of organic matter added to the soil. It also follows the greater the rotational diversity the greater the benefit to soil health. Rotations can also facilitate the ability to change tillage practices thereby reducing both the amount and intensity of tillage undertaken, which is the third means of increasing soil biology identified by Stockdale & Watson (2012).

Where rotational experiments do measure soil attributes, soil biology and ecology are often key measures.

In a seven year trial in New Zealand comparing potato and onion production systems from monocultures, through, alternating potato-onion rotations, to, four year rotations, soil microbial activity was greatest in the most diversified potato rotation (Wright *et al.*, 2017). In contrast, using two existing long term rotation trials of continuous corn, continuous soybean, corn-soybean, corn-soybean-wheat rotation no affect was seen on microbial biomass C and N which are measures of the microbial biomass (Zuber *et al.*, 2018). Based on two long-term no-till cropping trials a comparison of rotational diversity, residue management and cover cropping found that all three techniques aways improved microbial activity, sometimes with synergistic effects between the three techniques (Perkons *et al.*, 2014).

As part of the Less Intensive Farming and Environment (LIFE) project, Hutcheon & Iles, (1996) studied the effect of rotation type and crop management systems on earthworms. There was no difference among the rotations, but, tillage did have an effect with inversion / plough based systems having lower earthworms than non-inversion tillage was used. The lower input integrated regime also had higher worm biomass than standard farm practice. In the study by Walker *et al*., (2011) the effect on worm populations was negatively impacted by the cereal and root crops but the pasture phase helped them recover. The highest populations were under the longest term pasture. Red clover in the stockless system was found to be particularly effective at boosting worm populations. Both these studies show the importance of understanding if an outcome, in this case increased worm populations, is caused by the rotation itself or, particular components within the rotation, in these examples, pasture and red clover.

As part of the DOC trial (see section 5.2.3) an analysis of soil fertility found that soil fertility was enhanced in the biological verses the conventional treatments, which included higher microbial biomass, enhanced mycorrhizal root colonisation, increased biodiversity of microorganisms and an increased efficiency of those microbes to metabolise organic carbon sources, plus better soil aggregate stability (Mäder *et al.*, 1999). In the study by Bartošová *et al*., (1999) (see section 5.1) of a conventional and ecological rotation they found that the ecological system had higher levels of soil respiration indicating enhanced soil biological activity.

Utilising a long term experiment with two rotations, a conventional six year rotation of barley, rye, oat and potato vs. a low input system, where one year of barley was replaced by clover, and, monocrop oats were grown in a mixture with peas, with a second factor of full or half rate fertilisation, Kahiluoto & Vestberg, (1999) found that mycorrhizal infectivity and spore densities were highest in the low-input system using compost for nutrient supply, though it was found that the incorporation of clover markedly inhibited mycorrhiza.

In Europe farmers are paid to plant 'biodiversity crops' to provide pollen, nectar and seeds for wildlife due to the diminishing of such resources because of the intensification of agriculture. Leake *et al*., (2011) found that the standard practice of growing these crops in the same location every year due to compliance and inspection requirements was resulting in dramatic underperformance of the crops and that rotating them boosted pollen, nectar and especially seed production dramatically. This showed that even with mixed species crops rotation has significant benefits and that rotations are not just beneficial for cash crops but also non-cash crops.

5.3.1. Pests & beneficials

Along with nitrogen management, the other dominant purpose of rotations is for pest disease and weed management. Indeed it was the advent of the agrichemical pesticides for pest, disease and weed control that made possible the simplification and even elimination of rotations. Pest, disease and weed management are therefore frequently a focus of rotation experiments, and also because they also directly impact yield, sometimes to the point of reducing yield to zero.

In part of the LIFE Project studying less-intensive integrated production systems (see section 5.3) Jordan & Hutchinson, (1996) found that by basing nitrogen supply on targeted yield and supply of N from the soil the less dense canopies resulted in lower pest and disease severity, lower weed competition, and thus reduced the need for agrichemicals.

Winstone *et al*., (1996) monitored the populations of polyphagous predators the first five years of a trial with four rotations: 1) conventional rotation and standard farm practice, 2) conventional rotation with low inputs, 3) integrated rotation and standard farm practice, and 4) integrated rotation and low inputs. Unexpectedly, there were no differences in the pitfall catches of adult Carabidae and Staphylinidae, and while fewer Linyphiidae were trapped in winter months most years, this was principally put down to the insecticides used in autumn sown crops. The effects of rotation, either standard farm practice or integrated farming system, over four years and four sites on Carabid population found that the largest variations were between the four sites and individual fields, rather than rotation type. Notably, seed potato crops were found to greatly reduce carabid activity for up to two years following potatoes (Holland *et al.*, 1996).

In north east Scotland field surveys found that leatherjackets (*Tipula oleracea*) were overwhelmingly found in winter cereal crops following oil seed rape, due to the adult flies being unable to escape from the oil seed rape canopy but still being able to mate and lay eggs resulting in large aggregated populations in the subsequent crops (Coll, 1996). The effect of previous crops on slug damage in subsequent crops is well recognised. Based on field surveys Gould (1961) found there was higher slug damage in winter wheat where the previous crop was dry harvested peas, leys, cereals and brassica seed crops, while slug damage was lower following fallow, potatoes and sugar beet. Similarly Glen *et al*., (1996) found winter wheat to be at higher risk of slug damage following oilseed rape, while oilseed rape was at higher risk where the straw from previous cereals crops is incorporated into the soil surface, compared with ploughing (inversion tillage). Both these examples illustrate the importance of crop sequence, in that the exact same crops grown in rotation, but, in different sequences, can have quite different outcomes.

The ability of rotations to control plant parasitic nematodes depends on the biology of the nematode species, including: fecundity, number of host species, presence / absence of a resistant stage (survival ability) and dispersive powers (Hancock, 1996). For example, potato cyst nematode (*Globodera* spp.) has a very limited host range, and can be controlled solely by rotations longer than seven years on mineral soil and ten years on organic soils, though this can be further reduced by combining rotations with other control techniques, e.g., partially resistant cultivars and nemacides. In comparison, control of beet cyst nematode (*Heterodera schachtii*) in the UK is almost totally dependent on rotations due to limited alternative control options, with a minimum return period of three years (Hancock, 1996).

Hancock's study is considered a good example of the importance of understanding the biology and ecology of specific pests, if rotations are going to be optimised to control them, i.e., rotations can be highly effective at controlling, in this case, plant parasitic nematodes, but, only if the rotation is specifically designed to achieve that. This further highlights the challenge of designing a rotation in that there are so many different outcomes desired of a rotation, some, even many of which, may conflict with each other, there cannot, therefore, be a 'perfect' rotation: all rotations are compromises.

5.3.2. Diseases

Rotations are still the most effective means of managing take-all of cereal (*Gaeumannomyces graminis* var. *tritici*) (Kwak & Weller, 2013). Indeed due to the difficulty of using agrichemicals against soil born diseases, due to the diseases being protected by the bulk and chemical denaturing abilities of soil, rotations are still among the most effective means of soil borne pest management (Curl, 1963).

In the research on potato and onion rotations by Wright *et al*., (2017) (see section 5.3), black scurf (*Rhizoctonia solani*) of potatoes was highest in the potato monoculture in a trial comparing potato and onion production systems from monocultures, through alternating potato-onion rotations, and four year rotations . A similar result was found by Read, (1996) whereby double cropping potatoes increased disease symptoms caused by *Rhizoctonia solani*. The soil borne potato diseases, *Rhizoctonia solani*, silver scurf (*Helminthosporium solani*) and common scab (*Streptomyces scabiei*) were reduced by 10% to 52% in at least one year at both sites in a trial that introduce rapeseed (*Brassica napus*) into a potato rotation (Bernard *et al.*, 2014).

5.3.3. Weeds

Writing in the 1938 Yearbook of Agriculture, Clyde E. Leighty stated

> "Rotation of crops…is the most effective means yet devised for keeping land free of weeds. No other method of weed control, mechanical, chemical, or biological, is so economical or so easily practiced as a well-arranged sequence of tillage and cropping." (Leighty, 1938).

At the dawn of the pesticide / herbicide era the value of rotations for weed management was almost considered self-evident.

Smith *et al.*, (2008) analysing national-scale arable farmland data sets in the UK, where herbicides are used, found community composition of standing weed species and weed functional types is strongly related to the current crop, i.e., that weed variation within a crop is much lower than variation in weeds between crops. Smith *et al*., (2008) then showed that current weed assemblies could be predicted based on the previous three years crops, with the key determinant factors being season of sowing, crop type and target weeds for herbicide application. Bohan *et al*., (2011) again using actual farmland data sets of seedbank data, also found that the previous three years crop sequence explained over 80% of weed seedbanks variation.

Non-inversion tillage frequently results in an increase in grass weeds, however in the study by Jordan & Donaldson (1996) this build-up was contained, by using an active rotational strategy swapping between cereals and break crops, targeting grass weeds in broad-leaved crops and vice versa, broad-leaf weeds in cereals crops using herbicides backed up with mechanical intervention. This not only achieved good weed control, it also resulted in a 50% reduction in herbicides compared with a standard herbicide program (Jordan & Donaldson, 1996). Similarly Jordan & Hutchinson, (1996) as part of the LIFE project, studying less-intensive integrated production systems (see section 5.1), found that targeting specific weeds when crop species permit the use of the most effective herbicides, and then tolerating the same weeds in crops where herbicide options are less effective, achieved better weed management with less herbicide use. In a study looking at crop sequence, cultivars, sowing date and nitrogen on weed biomass and species composition it was found that the greatest effect on weed biomass was the two preceding crops and the interaction between them, with greater biomass observed in rape than wheat in the second rotational year, with wheat-rape having more biomass than wheat-wheat (Froud-Williams *et al.*, 1996). Sowing date of the current crop also contributed to weed biomass, while wheat cultivar had no effect. Higher levels of nitrogen application in the previous crop resulted in increased weed biomass in the following crop immediately after establishment. Weed species composition was also influenced by both previous crop and sowing date (Froud-Williams *et al.*, 1996). In a study of three rotations over a period of 18 years, a two year corn-soybean rotation, a three year corn-soybean-wheat rotation, and a six year corn-soy-bean-wheat-hay rotation, there was a strong rotation by crop interaction effect on weed cover with the two year rotation having an average weed cover of 40%, the three year rotation 27%, and the six year 20% (Teasdale *et al.*, 2018).

A key aspect of using rotations for weed control is having sufficient diversity from a weed's 'perspective'. For example, in intensive vegetable market garden systems there are often many tens of different crops, often from different plant taxonomic Families, meaning that rotations can be for many years (e.g., >7 years), and, due to the genetic diversity of the crops, the rotations are highly effective means of pest and disease control. But, from a weed's 'perspective', most of the crops are short term, often spring or early summer sown annuals, and, therefore very similar, so large populations of spring germinating, quick growing weeds will build up, i.e., it is a poor rotation for weed management. To improve weed control, non-spring sown crops need to be introduced, such as autumn sown cereals, and/or a pasture phase. In arable production, a key weed management technique is to alternate between spring, and autumn sown, crops as the weed floras that germinate at sowing time are quite different, and also contrasting control measures can be used. So, again, as for pests and diseases, it is vital to understand the biology and ecology of the weeds that rotations are being used to manage, to ensure that the rotation achieves the desired outcomes.

5.4. System level effects

Of all the system level effects of rotations yield is the one, of most interest, to producers and scientists alike. Yield is considered a system level effect as it can be influenced by all the above soil health parameters, i.e., soil physical health, soil chemical health and soil biological / ecological health. However, with increasing stresses being placed on agricultural systems due to climate heating, increasing robustness and resilience through diversified rotations is another system level benefit also gaining attention

In a trial comparing potato and onion systems ranging from monocultures, through alternating potato-onion rotations, and a four year rotations (see section 5.3) potato yields were greater when potatoes were not the preceding crop, and the highest potato yield was in the four species rotation, while onion yield was lowest for the onion monoculture (Wright *et al.*, 2017). In the same trial, the greatest benefit of the four year rotation was the improvement in crop yields. Stobart (2011) studying oil seed rape found that in virgin ground rape yielded 3.9 t/ha, while continual rape only yielded 2.79 t/ha, rape every other year yielded 3.13 t/ha and with a two year break 3.36 t/ha. In a 21 year study at three sites in southern Sweden, the effects of having a two year pasture (ley) phase (either pure grass or grass + legume) in an arable rotation found that winter wheat yield was higher in the rotation with grass + legume pasture at one of the sites (Persson *et al.*, 2008).

In a comparison of three, four year, organic stockless rotations based on an initial red clover green manure, followed by: A) two years of winter wheat followed by spring oats, B) potatoes, winter wheat, and winter oats, and C) winter wheat, winter beans, winter wheat, found that the double cropping of wheat in rotation A had negative impact on second year yields, while in rotation B the wheat following potatoes had the same yield as when wheat directly followed clover (Bulson *et al.*, 1996). It was considered that the red cover was fixing more that sufficient nitrogen for the following two crops but the success of the third crop was dependent on the use and release of N from the previous crops, e.g., from the significant soil disturbance required in potato production and harvest compared to the high carbon straw locking up soil N. The benefit of the leguminous winter beans break crop was clear with the winter wheat following beans having much higher yield than wheat following wheat. Rotation B also had much lower weed biomass, due to potatoes being late spring planted, thus breaking autumn germinating weeds lifecycles, and also as potatoes can be aggressively mechanically weeded, plus the highly competitive nature of the winter oats (Bulson *et al.*, 1996).

Based on three year crop rotations, running for two cycles, with a focus on chickpea, with either three different crops, two chickpea crops, or continuous chickpeas, Li *et al*. (2019) found that the most diversified of the rotations were the most robust to both abiotic and biotic stresses, and improved the constancy in crop productivity across rotation cycles, resulting in a 14% increase in system robustness. Further in the first rotation cycle there was total crop failure in the continuous chickpea rotation.

6. Conclusions

This short review of the impacts of crop rotations on soil health has shown many examples where rotations are clearly beneficial, a few examples where differences are minor and very little evidence for negative impacts of rotations on soil health. With this evidence of the many clear benefits of rotations on soil health, it is counterintuitive that rotations have diminished so dramatically since the 1950s. It is suggested that while it was the widespread uptake of synthetic nitrogen fertilisers and the advent of the agrichemicals that allowed rotations to be supplanted, it was economics, that fundamentally caused the decline of crop rotations by allowing farmers and growers to grow only their most profitable crops. However, with the substantial increase over the last few decades in the scientific understanding of the negative effects of agrichemicals and nitrogen fertilisers, ever increasing agrichemical resistance, the broadening of the understanding of the purpose of agriculture, e.g., through the lens of ecosystem services, and its place in society, rotations will clearly be a key part of the new agricultural revolution required if civilisation is to address the multiple, massive, global challenges we all face.

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8. References

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