Partnership Summary Report

Management of Rotations, Soil Structure and Water
(Rotations Research Partnership)

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CONTENTS

1. EXECUTIVE SUMMARY

The AHDB project: Management of Rotations, Soil Structure and Water (also known by its short title: Rotations Research Partnership) was built around a consortium of researchers, agronomists, supply-chain members, and growers who had an interest in a better understanding of rotations, and how these rotations might be monitored and improved. To achieve this the consortium had a very diverse skill set, ranging from on-farm practitioners to specialists in bioinformatics, farm economics, modellers, and data scientists. Linking this together were a team of research agronomists who helped synthesise the research into on-farm practical advice.

The core of the whole project was the ‘Grower Platform’ which comprised about 25 growers or agricultural businesses who hosted experiments, provided survey data and, importantly, provided guidance and constructive criticism to the researchers. The on-farm experiments investigated effects of cover crops, organic amendments, and tillage practices on the yield of subsequent crops in the rotation. In total, 96 field experiments were established. Most of these experiments had potatoes as a test crop, but other crops included spring and winter cereals, sugar beet and root vegetable crops. In 32 experiments, use of a cover crops was shown to increase total potato yield by 3.0 t/ha – this increase being statistically significant. Similarly, in 46 comparisons, use of an organic amendment was associated with a 1.3 t/ha increase in total potato yield, but this increase was too small to be statistically significant. When compared with cereals or other root vegetables, potatoes were more responsive to both cover crops and organic amendments. Whilst use of cover crops was associated with increases in total potato yield, there should be a note of caution. A recent review has indicated that use of cover crops may be associated with increases in wireworm damage to potatoes – which may decrease marketable yield. Therefore, successful integration of cover crops into potato rotations will need careful consideration of cover crop species and management.

A three-year series of large scale, fully replicated experiments conducted by researchers at the James Hutton Institute showed the benefits of cover crops (particularly those with a large brassica component) on the yield and quality of spring barley. However, another series of replicated experiments completed by NIAB in Cambridge, showed that a previous oat cover crops had no effect on the yield and quality of potato crops but, there were indications that the cover crop was useful in drying the soil at depth in this may be of particular benefit in wet springs.

Survey data showed, in the absence of a cover crop, average surveyed potato yields were 42.3 t/ha compared with 54.8 t/ha when a cover crop was used. The survey data need to be treated with caution since the survey was self-selecting, limited in number, and not stratified. However, the survey data are consistent with data from the on-farm experiments and lend support to wider use of cover crops when agronomically sensible. Economic analysis completed by James Hutton Institute and NIAB showed benefits of integrating cover crops into the rotation but, again, this conclusion must be treated with caution.

A small number of tillage experiments showed that mis-matched wheelings and over inflated tractor tyres resulted in increased soil damage and, in turn, resulted in decreased crop yield. Closely linked with this on-farm work, a component of the rotation project was to develop the Terranimo® decision support module for UK growers. This model allows growers to select soil types, tractor, and harvester types (including asymmetric root-crop harvesters), tyres and tyre pressure and then estimate the likely effect of this loading on soil properties. This information can help to optimise on-farm management strategies that minimise the yield penalties that were seen in the tillage experiments.

A component of the project was to better understand the effects of organic matter inputs on rotational productivity. In part, this objective was addressed using the simple, on-farm comparisons described above. However, data from long-term experiments and from a modelling approach were also employed to help provide useful insights. The main long-term experiment compared, in factorial combination, historical applications of FYM (once every 3 years from 1965 to 2011) and a single application of FYM in October 2016. The experiment was in Suffolk and overseen by NIAB. This experiment showed that the potato crop responded positively to both the historic and recent application. However, subsequent crops in the rotation mainly responded to the long-term applications. These data suggest that the benefit from organic amendment accrues over a period and that single one-off applications may be of limited benefit. This was demonstrated in a series of experiments with municipal composts conducted at NIAB's farm in Cambridge. Initial recommendation from the organic matter model, developed by scientists at Rothamsted Research broadly support this approach. The model suggested that on taking on a new parcel of land, a grower should apply a large OM dressing and then, on a regular basis, smaller amounts. On leaving a parcel of land (for example at end of a rental agreement), organic inputs should be halved three years before the end and there should be no applications in the final two years. Whilst further work is required to refine the recommendations, this practice should maximise the value of amendments.

Experiments with the Grower Platform, together with the long-term experiments and models have emphasised the importance of soil organic matter. However, quantifying changes in soil organic matter concentration and composition is difficult and time consuming. Researchers at James Hutton have been developing Fourier Transform Infra-Red (FTIR) scanning of soils as a way of overcoming these barriers. Using soil samples from Platform experiments, estimates of soil organic matter using FTIR are correlated with those derived from more traditional soil analysis. Similarly, using soil samples from the Platform experiments, the FTIR method showed that it could detect changes in organic matter content resulting from the applied treatments. Using data from long-term experiments at Rothamsted, there was evidence of correlation between soil FTIR spectra and grain and straw yields, and this could be an area of research in the future.

New technology has allowed growers, agronomists, and researchers to have a better understanding of spatial variation in soil properties and in crop performance. A component of the Rotations Research Partnership project was to identify how this technology may be used to increase the economic and environmental sustainability of rotations. Researchers at Lancaster University provided high-resolution electrical resistance tomography (ERT) and electromagnetic induction (EMI) scans. Analysis of these scans showed that they may be used to infer information about depth of water abstraction and this may aid water management. Furthermore, detailed analysis also showed that variation in scanned EMI properties was highly predictive of variation in potato crop emergence. At present the underlying mechanism for this linkage is not known, but more research may allow improved management of crops.

Quantifying and understanding the effect of management changes on soil structure is a key component in relating rotational practices to crop performance and profitability. Traditional methods of measure soil structure are often labour intensive and subjective. Researchers at James Hutton employed flatbed scanning technology to obtain high quality data in a cost-effective way. Using soil cores taken from the fields of collaborating Grower Platform members, the scanning and image analysis technology was able to measure changes in soil structure due to imposed treatments. Whilst some more work is required to use this technique on high resolution imagery, the methodology has enormous potential for helping to monitor changes in soil structure.

Defining root structure and function is important in understanding the link between soil conditions and crop performance. Traditional methods of quantifying roots in soil are labour intensive and expensive. In this Project, two alternative methods were used to measure roots. The first (performed at NIAB) used DNA technology, the other (performed at James Hutton Institute) used imaging technology to measure root growth and penetration in soil cores. Whilst the DNA method has been shown to work in cereals, a preliminary assay of cores taken from a potato field in 2017 showed poor correlation between the DNA method and the traditional soil washing and counting method. This may have been due to poor specificity of the primers. Due to time and budgetary constraint this method was not pursued further. The imaging method showed cultivar differences in root growth of parsnip and carrots in relation to bulk density and soil water content. Preliminary analysis suggested that for young seedling, soil moisture content was more important than dry bulk density in determining growth rates.

As part of the project, Grimme equipped two potato harvesters with GPS enabled load sensors to enable yield mapping. Data from these harvesters as well as from earth observing satellites were analysed by Rothamsted Research to explore the benefits of zoning potato fields into contrasting management zones. In total, yield monitor data were obtained from 72 fields of which 53 had data of sufficient quality. From this a total of 49 fields were zoned. Satellite derived NDVI data were obtained for 42 of these fields. Despite the relative sparsity of yield mapping and satellite data, it was found that variation in potato yields exhibit spatial coherence and thus are amenable to a zoning approach. Of the 49 fields successfully zoned, 36 had either 3 or 4 zones. The zoning approach needs to be refined by using other spatially resolved data (e.g. from maps of grain yield or soil properties). A virtual grower survey indicated that many growers were receptive to a zoned field management approach, since it was felt that it may result in increased yield and profit. The survey also indicated that these benefits would likely accrue with better use of nutrients, water, and seed. However, a key blocker to progress were concerns about data privacy and the lack of useful on-farm data.

2. INTRODUCTION

The project comprised four interlinked work packages (WPs) designed to achieve the project's objectives. Each WP was delivered by combinations of different research from National Institute of Agricultural Botany (NIAB), The James Hutton Institute (JHI), Rothamsted Research (RR) and Lancaster University (LU). WP1 entailed the gathering and analysis of survey data from collaborating growers; the reinstatement of a long-term, rotational experiment at Broom's Barn, Suffolk and conducting some replicated experiments investigating composts and cover crops. The main objective of WP2 was to investigate the use of spatial information (e.g., maps of cereal and potato yields or of soil properties) to define higher and lower yield zones within fields which may then be used to improve crop management practices. In addition, this WP investigates novel scanning technologies to better understand the dynamics of soil organic matter. Much of the experimental work with cover crops and soil amendments were conducted in WP3 and a further output from this WP was decision support tools to aid management of both soil structure and organic matter content. WP4 will investigate novel method to quantify root distribution and the effects of soil conditions and crop management on root function and crop productivity.

Whilst each work package has been reported separately, it is important to remember that they are not stand alone and are closely interlinked. The key findings and conclusions of the respective work packages are reported below.

3. WP1 THE GROWER PLATFORM

3.1. Long-term experiments at Broom's Barn Suffolk

An objective of this Work Package was to re-instate a long-term experiment at Broom's Barn, Suffolk, and use it to investigate the relative benefits of long-term applications of cattle farmyard manure (FYM) with a single application of FYM made in autumn 2016. The effects were measured over one complete potato rotation. This work was completed by NIAB and the key findings are summarised below:

- Relative to control plots that received no FYM, potato fresh weight yields were increased by similar amount by both 'historic' and 'fresh' FYM.
- Analysis showed that much of the increase in fresh weight (FW) yield was explicable by FYM decreasing tuber dry matter concentration rather than increasing tuber dry matter yield.
- The effect of FYM on cereal yield, in the rotation was smaller and, in some instances, negative.
- Overall, when compared with unmanured plots, historic FYM increase rotational productivity by 12 % but the autumn 2016 application was associate with a numerical decrease in rotational productivity of 1 %.

3.2. Replicated experiments with amendments and cover crops at NIAB

From 2017 to 2020 a series of fully replicated and randomised experiments at NIAB investigated the effects of autumn sown oat cover crops or spring applied municipal composts on the performance of a subsequent potato crop. In some instances, the residual effect of the compost application was measured in the cereal crops that followed potatoes.

- In 2017, application of municipal compost was associated with an increase in tuber FW yields, but this was mainly due to a decrease in tuber DM concentration. Residual effects of the compost on cereal yield were small and inconsistent.
- Experiments in 2018 and 2019 evaluated the effects of composts in factorial combination with soil compaction and irrigation. In 2018, compost was of benefit only in the uncompacted soil whilst in 2019 the opposite occurred.
- Experiments in 2018, 2019 and 2020 evaluated the effect of an oat cover crop on a subsequent potato crop. Effect of the cover crop on potato crops were generally small and inconsistent. Due to a mulching effect, surface soil moistures were often larger under a cover crop than in the control. However, there was some evidence that cover crop could usefully dry the soil at cultivation depth when left to grow into April.
- A series of experiments at Balruddery, managed by JHI, showed significant benefits of cover crops on the yields of subsequent spring barley. This was particularly noticeable as the proportion of brassicas in the cover crop mix increased.
- The impact of cover crop species on the yield and quality of subsequent crops in the rotation merits further research.

3.3. Survey of practices within the Grower Platform

From its inception, it was recognised that a five-year project was too short to study effects of cropping and amendment on rotational performance. One way to mitigate this was to use data from long-term experiments or by using modelling approaches. An alternative method is to survey farmers on their rotational practices and outcomes and from analyses of these data make inferences about optimal practices. This work was undertaken jointly by NIAB and by the James Hutton Institute. Longitudinal data on management, crop and yield data were collected from farms across the UK and analysed to identify key features. It forms a sound base for benchmarking common practice and has fed into economic modelling and linked to soil health to identify the potential impact and efficacy of various practices. Key findings of the analysis of rotational features include:

- Cover crops are associated with higher yields in potatoes.
- The application of organic amendments is associated with a reduction in agrochemical application in barley, oil seed rape and potatoes and lower nitrogen application in potatoes with no corresponding loss in yield.
- Livestock in a rotation are associated with fewer agrochemical applications in barley and root vegetables with no corresponding loss of yield in barley and in increase in yield from root vegetables.
- Whilst some of these data are consistent with experimental data, the survey data set is, however, self-selecting, and partial. It is of a limited size, and the analysis presented is exploratory. These findings suggest important areas to consider for confirmatory experiments but should not be taken as in any way proven.

3.4. Economic evaluation of rotations

The economic evaluation of rotations was performed by the James Hutton Institute, primarily based on data from the Grower Platform survey.

- These results need to be considered carefully as are based on rotation data collected around the UK; with the limitations of the survey as outlined in section 3.3.

- Potato gross margins are significantly higher after cover crops, even if management costs during the cover crop interval are subtracted; this is mainly due to higher yields.
- There are no significant effects on the gross margins for barley, oilseed rape, potatoes, and wheat of applying organic amendments during the previous or current interval; indeed, while the unitary costs of nutrients are lower if a larger share comes from organic amendments, and the number of other farm operations decreases, total costs of fertilisation are higher.
- Gross margins per hectare are significantly higher in smaller fields for barley, oilseed rape, potatoes, and wheat, and for barley and potatoes this is also due to significantly lower costs.

3.4.1. Economic evaluation of integration of cover crop into rotations

Studies undertaken as part of WP3 showed that, on average, use of a cover crop was associated with an increase of potato yield of 3.0 t/ha. Grower Platform members were asked a detailed set of questions by NIAB to staff to determine the costs of growing and managing a cover crop so that this could be compared with the increase in crop value resulting from an increase in total FW yield.

- Assuming an average benefit of c. 3 t/ha from using a cover crop (see report for WP3), a potato value of £150/t and a total cost of establishing, managing, and destroying a cover crop of £225/ha, then use of cover crops could be justified solely from an economic standpoint.
- However, this analysis ignores potential problems that may be associated with integration of cover crop into potato rotation (e.g., problems with slugs and wireworms, or providing hosts for pathogenic, free-living nematodes).
- Likewise, it also ignores potential benefit that may accrue including reduced fuel consumption for cultivations and benefit elsewhere in the rotation.
- More detailed and sophisticated studies will be needed to better understand the likely economic impact of widespread use of cover crops in the rotation.

4. WP2 Using New Technologies to Enhance Rotations

4.1. Zoning of yield potential

Yield monitor data are now collected as standard on many farms. In addition to this, processed satellite data, which are available at increasingly fine resolution, can be used to see how crop response varies within a field throughout the growing season. These sources of data offer a means to understand and predict the variation in crop response within fields. The aim of this work, undertaken by Rothamsted Research, was to investigate how farmers could make best use of the information captured by yield monitor data and satellite data and apply this knowledge within the context of precision management in potato crops. There were three main outcomes from this part of the work package:

- The quantitative methodology developed within the project is sufficient to deal with the ever-increasing availability and sparsity of data.
- Potato yields exhibit somewhat coherent variation which can result in the formation of meaningful zones. The work has demonstrated how this can be useful for benchmarking and for informing management practice. However, such zones are hard to predict given

the current levels of available data. Further work in this area using i) yield monitor data from the rest of the rotation ii) higher resolution (both temporally and spatially) of satellite imagery and iii) other sources of data such as soil maps is necessary to improve the robustness of identified zones. In addition, a change in data management practice would be required to overcome issues associated with data sharing, for example GPS location, and farm performance, and with data ownership, for example collection of data from fields on rented land. These data privacy issues can become large barriers to the development of robust methods but also in the wider implementation of such methods through e.g., decision support tools.

- Expert knowledge remains a valuable resource to be incorporated, whether this is the downstream practical input on how management can be adapted based on zonal information or whether it is a direct input into how the zones are derived based on extensive knowledge of field features.

4.2. Using geophysical technique to better understand soil and crop variability

Use of non-invasive scanning of soil properties using electrical resistance tomography (ERT) and electromagnetic induction (EMI) scans has the potential to provide cost-effective information on spatial variation of important soil properties. Over the course of the experimental program, Lancaster University provided scans of fields which were then analysed in relation to crop water use and variation in crop development.

- Geophysical methods have demonstrated their usefulness in providing cost-effective ways of providing metrics of variation in soil texture which, in-turn, can be used to design more effective experiments.
- A better understanding of the causes of variation in potato crop emergence will be key in understanding the wider issue of spatial variation in potato crop performance and yield.
- This study has provided useful insight into the effects of agronomic treatments (irrigation, organic amendments, and compaction) on water abstraction by potato crops.
- Apart from providing further insights into the link between soil conditions and crop performance, these techniques have wide applicability in phenotyping potato varieties to efficiently gather information on water capture.

4.3. Using plough draft to map soil variability

The objective of this study was to use a draft-recording plough to map spatial variation in soil strength and relate this to the variations in yield observed in the zoning project. The plough was developed at Rothamsted Research and was to be used by NIAB. Unfortunately, at the start of the project, the plough was found to be faulty and beyond economic repair. Alternative sources of similar spatially resolved information were sought but without success.

4.4. Fourier Transform Infrared (FTIR) scanning of soil to quantify organic matter content

Ongoing work at the James Hutton Institute has shown that Fourier Transform Infrared (FTIR) scans of soil can give valuable insight into the soil organic matter (SOM) and mineral composition of soils. As such, development of FTIR techniques may be invaluable in studying the effects of soil amendments with organic matter or receiving residues of cover crops. Results from this study include:

- Interpretation of FTIR spectra of amended soil can provide valuable information on the changes in the amount and chemical composition of the SOM.
- Results show accurate prediction of soil organic carbon percentage are possible on a field scale using FTIR.
- FTIR is a novel method for characterising soil which can rapidly assess variation in soil across a field, providing insight not otherwise available.
- FTIR soil characterisation would give more accurate zoning of soil across a field and could be recommended prior to field trials being set up.
- The potential for correlating crop yields directly to soil spectra has been shown and more in this area would be useful.

4.5. Use of flat-bed scanners to understand rooting in soils

This study builds upon ongoing work at JHI where flat-bed scanners have been used to image soil structure. The objective of this work was to use imaging technology (high resolution, red-green-blue scanners and lower resolution, hyper-spectral cameras) to examine soil structure at scales important for root growth and function. Key findings from this project include:

- Flatbed scanner imaging, followed by image analysis of the soil structure was sensitive enough to differentiate between structural changes under different tillage / management systems.
- Multispectral imaging with *Ximea* cameras followed by image analysis was faster than the flatbed scanner process due to smaller datasets. This process was also able to demonstrate differences between treatments in terms of soil spectra and in terms of soil, structure.
- Edge correction was possible for the RGB due to the lower resolution, but further development is required to apply this to the higher resolution RGB images.
- The tool offers a protocol for tracking structural changes over time at a scale relevant to root-soil interactions.
- Further analyses are required to assess whether the spectral patterns obtained from the multispectral camera correlates with soil properties.
- Both methods gave an alternative way of tracking structural changes in soils, and as previously experienced with soil structural measures (See WP3 Rotational Resilience report), differences in soil more frequently when comparing across trials or sites, however there were also differences within sites across treatments.

4.6. Trafficking in soils

NIAB and used field-based observation of soil properties and crop yield to gather information on trafficking and tyres pressures on crop performance.

- Simple comparisons were set up in Grower Platform Members' fields to map variation in soil penetration resistance across potato bed as a result of trafficking by either wheeled or tracked machinery.

- Trafficking caused large variations soil compaction across potato beds, and this was associated with yield variation.
- In part, soil damage may be mitigated by reducing tyres pressures.
- Data from this work was used to develop/validate the Terranimo® model (see 5.3 below).

5. WP3 ROTATIONS & RESILIENCE

5.1. Split field comparisons and limited replication experiments

This work was primarily completed by NIAB and used simple on-farm, grower-led trials to examine the effects of organic amendment or cover crops on the yield of subsequent crops. In most cases the subsequent crop was potato, but in several experiments, it was root vegetable crops (these latter comparisons were provided by Vegetable Consultancy Services). Highlights include:

- Between 2017 and 2020, a total of 52 comparisons (32 on potato) tested the effect of an autumn sown cover crop on the yield of the subsequent crop. In the same period, 54 comparisons (46 on potato) tested the effect of winter/spring applications of organic materials on the subsequent crop.
- These comparisons showed that, on average, use of a cover crop increased total potato yield by 3.0 t/ha when compared with the control and this difference was statistically significant. On average, organic amendments (all types) increased potato yields by 1.3 t/ha but this effect was not significant.
- The effects of amendments or cover crops on key soil properties (dry bulk density and water stable aggregates) were generally small and inconsistent and could not explain the observed yield difference.
- The majority of this work concentrated on total potato yield. Depending on the cover crop species used, it is possible that widespread use of a cover crop may increase incidence of economically important pests (e.g., wireworm), and thus reduce marketable yield. Further investigation would be required in this area to aid growers with species selection.

5.2. Development of a soil organic matter model

Rothamsted Research built upon existing models of soil organic matter (SOM) dynamics and effects of SOM on nutrient response curves and yield. Key findings from this piece of work were:

- The yield-enhancing power of organic matter is somewhat variable and probably does not persist in soil as long as the organic matter from which it derives. The decline in yield enhancement was found to be most rapid in a sandy soil, but less so in a silty clay loam soil.
- In contrast to earlier work, it appeared beneficial to apply amendments at a constant rate for much of the timeframe of interest, but to begin with a large application to raise the fertility as much as possible, as soon as possible.
- Amendments should be approximately halved three years before the end of the period of interest and reduced to zero for the final two years of any period of interest.
- Model parameters could be inferred from simple grower trials (i.e. similar to those described in rather than from large-scale, long-term experiments. However, these simple grower trial could still take 10 years to provide unambiguous results.

5.3. Development of the Terranimo® model

Terranimo® is a computer-based tool developed at Aarhus University, Denmark that uses information on soil type and moisture content to predict the risk of compaction following trafficking by different configuration of farm machinery. This project developed the basic Terranimo® model for use on UK soils and with machinery often used in the UK (for example asymmetric potato harvesters). The work was completed by the James Hutton Institute and Dundee University. Key outputs:

- The Terranimo model and website was adapted to allow utilisation by UK farmers and is now available at https://terranimo.uk.
- Selection of soil type is available for farms based in Scotland via the National Soil Map of Scotland dataset, and in England and Wales via the Land Information System (LANDIS) soil database.
- Assessment of the soil compaction risks including from repeated wheelings.

6. WP4 Linking Soils, Water and Roots to Productivity

6.1. Development of a DNA based assay for quantifying root distribution in potato and other root crops

NIAB planned to use the quantification of potato DNA in soil as a proxy for root length density, with the technique having been already demonstrated for cereals.

- Initial work showed that the correlation between DNA and observed root length poor. Due to limited time in the project, this work ceased, and resources reallocated into other areas.

6.2. Models of root penetration resistance

The James Hutton Institute developed an existing technique to examine the effects of soil physical condition on root elongation in soil cores. Key findings of this research include:

- For carrot and parsnips, variation in root responses to soil physical properties including dry bulk density (DBD) and water availability have been demonstrated at the species and cultivar level.
- In intact field soils root elongation was associated most strongly with the gravimetric water content of the soils, suggesting these small seedlings are more vulnerable to changes in water than to the variation in DBD.
- Features obtained from the image analysis of the soil cores using the red-green-blue method were linked with the root elongation rates of the cultivars, including interactions between cultivars and the parameters, suggesting cultivars are highly sensitive to changes in soil structure.