Agronōmics – an arena for synergy between the science and practice of crop production

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Abstract

Progress towards sustainable intensification depends on effective exchange of knowledge and data between industry and academia. This requires engagement of both farmers and researchers, recognition that innovations can occur in the field as well as in the lab, and that researchers have as much to learn from farming and farmers as vice versa. A number of initiatives in the UK are recognising the value of farm networks for effective knowledge exchange and for asking questions of relevance on-farm; however the value for science is less well recognised. Uptake of digital record keeping and precision farming technologies is now becoming ubiquitous, giving new opportunities for farmers to share data amongst themselves and with researchers to provide new insights, but crucially also allowing farmers to make interventions in-field and to measure their impacts on-farm, for example by yield mapping. New statistical approaches are required to draw robust conclusions from this sort of data, but the authors believe its use could be transformative of agronomic science, so much so that we have created a new term to describe the approach; namely, ‘agronōmics’. The major benefits of experimenting in fields with farmers are; i) working at a relevant scale with the ability to test treatments not possible at the plot scale; ii) the potential to assess treatment interactions with soil differences (experimenting with soils is challenging with conventional plots); iii) the potential for greater precision to evaluate treatments with confidence intervals of less than 0.5 t/ha; iv) engagement of farmers, hence embedding knowledge exchange within research. However, it is crucial for effective knowledge exchange that farmers and researchers share the same concepts and metrics. ADAS has thus established the Yield Enhancement Network to allow both arable innovators and researchers to compare actual farm yields with theoretical ‘potential’ yields (estimated using conventional crop science concepts) and hence to develop the common conceptual framework necessary to underpin yield-targeted innovations.

1. Connecting science with practice for sustainable intensification

Biology extends physics and chemistry into the heightened complexities of life, and agricultural science extends biology because it invokes human intelligence to manipulate life. However, we submit that science has yet to recognise and achieve significant intimacy with the fascinating emergent properties that determine field and farm-scale production processes. As a consequence, there remains significant potential, both for systems-thinking and agricultural progress in developing new approaches and conceptual frameworks for application at the broad (field to region) scales of most agricultural outcomes and decisions. A new holistic approach to agriculture should augment and complement conventional reductionist research of plants in pots or plots, where fine scale effects of genes, proteins, cells, tissues and organs are studied; we call this new arena 'agronōmics'[1]. Timescales for implementation of agronōmics are short because the challenge facing agriculture of producing more whilst impacting less is very real and immediate (Foley *et al*., 2011), yet current progress is slow, especially in crop productivity (Grassini *et al*., 2013). To be successful in meeting the challenges it is crucial that researchers, farmers and food supply chains engage effectively (Klerkx *et al*., 2010). It is increasingly recognized that knowledge generation and exchange is not a one way process from the researcher's lab to the farmer's field, yet the UK has largely dismantled its infrastructure for agronomic research, exchange and education (Royal Society, 2009). Funding and operation of relevant knowledge generation are currently separated (Wielinga 2014); the two communities habitually work at different scales, and in different places, their concepts for analysis of crop performance differ, and any extrapolation between small (science) and large (industry) scales has to entail large untestable 'leaps of faith'. We contend that what is needed is a shared interest in the challenges and constraints faced in farmers' fields.

Participatory research has long been practised in developing agriculture but it has seldom occurred in developed agriculture, particularly in the UK (Edwards-Jones, 2001) and it has yet to make a tangible impact in science. It is our contention that a detailed consideration of the problem's and limitations faced in the field and at larger scales (as in the supply chain) is needed by the research community in order that scientific understanding can be enhanced and appropriate solutions developed. In addition to translating scientific innovations from the lab, science is incomplete and ungrounded whilst it is disconnected from the innovations and observations made by practitioners in the field or in the supply chain. Researchers need to understand, develop, test and assimilate these innovations and the underlying problems that they address.

2. Knowledge Exchange networks

Whilst there have always been social networks of growers around agronomy groups, clubs, societies and farming associations, a number of recent initiatives have sought to augment these with new networks, often exploiting new IT capabilities. Many new networks concern one-way extension of scientific programmes. However, the European Innovation Partnership (EIP) programme under the EU Horizon 2020 programme challenges traditional ideas about Agricultural Knowledge and Innovation Systems (AKIS) and pursues an 'interactive innovation model' seeking to link farmers, advisors, researchers, businesses and other actors in 'Operational Groups' (Wielinga, 2014).

Also, acknowledging the primacy of industry practitioners, the Agriculture and Horticulture Development Board (AHDB) Cereals and Oilseeds sector has established over 24 Monitor Farms across the UK. Each Monitor Farm is 'owned and operated' by groups of around 20-30 local farmers and advisors set their own agenda around issues of local concern from which they find relevant solutions (http://cereals.ahdb.org.uk/get-involved/monitor-farms.aspx). The emphasis here is on farmer to farmer learning rather than top-down dissemination of 'best practice'.

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[1] The line over the second 'o' signifies that it is pronounced long, as in genomics, and means the science of field-scale agriculture, as distinct from agronŏmics, sometimes used to mean the existing branch of economics that deals with agriculture, pronounced with the second 'o' short.

2.1 Field labs

It is becoming acknowledged that 'best practice' is not a rigidly defined recipe, rather it continually evolves through recent innovations and experience. Furthermore, best practice is quantitative, involving adjustment of chemical quantities or dates of sowing or of chemical applications; optimal crop management in each field depends on the specific combination of soil, weather, genetics and a myriad of environmental interactions, such that 'best practice' for one farm system and in one location cannot be expected to hold for another similar one 100s of miles away, and often not for one next-door! This points to the importance of local generation and adoption of optimal practices for individual farm circumstances. MacMillan & Benton (2014) recognize that farmers are practical experimentalists who continually innovate, test and adapt agronomic practices, cultivations and technologies, but until now this has been largely unrecognized and uncollated by formal science; refereed scientific papers with farmer authorship are extremely rare.

However, a recent UK farmer-focused innovation programme set up by Duchy Originals Future Farming Programme with funds from the Prince of Wales Charitable Foundation is adapting participatory approaches used in developing countries to help UK farmers assess their own ideas in 'Field Labs' (MacMillan & Benton, 2014). Small groups of farmers tackle identified problems in workshops with a facilitator and relevant researcher to advise on experimental designs and existing knowledge. Around 450 farmers have participated in the field labs so far on 20 different subjects. Given their recent introduction, there is as yet little evidence to say that Field Labs will hasten progress or precision in crop management, or hasten progress in crop science, but if farmers are measuring (therefore studying) the most telling metrics then at least the introduction of a scientist, who can suggest advise and analyse the data, offers the prospect of more impact, both on practice and science. We therefore hope that participation in Field Labs will spread more widely, and we are encouraged that a network for 'Innovative Farmers' has been formed (www.innovativefarmers.org) and that individual groups are eligible to receive financial support under the EIP scheme administered in the UK with CAP Pillar 2 funds.

2.2 Yield Enhancement Network

In response to cereal yield stagnation (Knight *et al*., 2012) and in recognition of the need to engage and energise farmers, suppliers and scientists in joint understanding of yield and its limitation, ADAS set up the Yield Enhancement Network (YEN; www.yen.adas.co.uk) in 2012. The YEN's aim is to identify arable innovators and support them in testing yield enhancing ideas (Sylvester-Bradley & Kindred, 2014). Thus far the YEN has been entirely industry funded, it engages with many farms including several AHDB Monitor Farms, and rather like the ICI '10 Tonne Club' in the 1970-80s (Weir *et al*., 1984) it engages with research organisations such as ADAS, NIAB and Rothamsted Research. It runs a yield competition, and uses the yardstick of biophysical yield potential (based on light energy and water availability) to allow fair engagement of farms with lower yield-potential as well as those able to achieve high absolute yields. The competition element provides a focus for the YEN and ensures capture of trustworthy yield values, along with associated data on crop development and management; crucially the YEN includes analysis of crop samples to explain the variation in yields. In its first three years the winning yields were 13.6 t ha^{-1} in 2013, 14.5 t ha^{-1} in 2014 and 16.5 t ha^{-1} in 2015. The latter yield broke the previous official world record (Sylvester-Bradley *et al*., 2016). The YEN has achieved broad engagement of the arable industry, farmers and the farming media through workshops and 'Ideas Labs', and it is now working to become a vital platform for scientific engagement; i) providing ideas and hypotheses on routes to yield enhancement for researchers to test; ii) generating a growing dataset of yields with associated soils, meteorological, physiological and agronomic data, and; iii) providing a network of farmers who are keen to interact with scientists and conduct or host experiments on farm. A key element of the YEN is the establishment of a common conceptual framework and quantitative metrics to analyse yield, in order to ensure effective industry-science dialogue. Interestingly, whilst most current research investment is seeking yield enhancement through genetic advances, analysis of YEN data indicates that the technologies required to overcome yield shortfalls are just as much logistical, mechanical and chemical, as they are genetic.

3. Precision farming technologies

3.1 Farm data capture

Most large arable farms now use farm management software to record cropping information and an increasing proportion of arable farms utilize precision farming technologies to monitor and treat their crops (Defra, 2012). Yield monitors are ubiquitous now on modern combine harvesters, giving farmers instantaneous measures of yield during harvest and yield estimates by field. Whilst there are many issues around the calibration and accuracy of yield monitors (Ross *et al*., 2008) it is clear that these provide the best (and often only) measure of yield on a field by field basis. Connecting the yield monitor to GPS allows yield mapping, thus recording and reporting spatial variation in yield within fields. In addition to these new yield measurements, many crops are now assessed in-season via measurement of spectral reflectance, either by on-tractor sensors (e.g. N-Sensor, OptRx and Isaria systems), unmanned aerial vehicles (UAVs or drones), manned airplane flights (e.g. Spectrum Aviation, 2Excel) or by satellite imagery (e.g. SOYL and AgSpace in UK, FarmStar Expert in France). Soil variation is also commonly assessed by soil electrical conductivity (Corwin & Plant, 2005).

Technologies on modern application equipment such as seed drills, fertiliser spreaders and sprayers allow application rates to be varied on-the-move. When combined with global positioning systems (GPS) and crop sensing technologies, variable rate applications can be set up, informed by the variability seen in yield maps, crop sensing, satellite imagery and soil sensing.

Earth Observation by satellite is now widely used at national and regional scales to judge crop condition and expected yields. With the launch of the Sentinel satellites by the European Space Agency, satellite data are increasingly available at a scale and frequency to monitor and compare crops at the field scale. Wide opportunities exist for the exploitation of this free data both commercially and by researchers.

Thus there is a rapidly increasing wealth of spatially defined data available at scales relevant to farm decision-making, and thereby a new arena for research is being created. We call the new science being generated at this scale ‘agronōmics’.

3.2 Using farm data

Despite the wide commercial uptake of precision technologies, questions remain over appropriate management responses to spatial data; benefits of variable rate applications are often difficult to prove and appear relatively small (Kindred *et al*., 2016). It is of concern that many farmers have collected large volumes of data without extracting good value from them; once the obvious lessons have been learned (e.g. the extent and positions of consistent yield variation within a farm) there can be an element of ‘so what?’ The science of agronōmics is still too immature even to offer routine means of data processing and analysis at this scale, let alone guidance on how best to derive understanding and to optimise industry practices.

However, there is a lot of current interest in ‘big data’ from both industry and academia. Initial plans, for example of the new Agri-Tech Innovation Centre ‘AgriMetrics’ are to both amalgamate multiple sets of farm records and integrate these with spatially referenced measures such as of meteorology, soil, and satellite imagery. Commercially, the big interest is in using such datasets to develop algorithms for decision support. However, in order to realise the benefits from such datasets, new statistical techniques and analytics are needed; even the seemingly simple notions of just collating and then viewing data from different precision technologies and different systems over multiple years should not be under-estimated; our experience is that collating such data across farms presents significant challenges and, whilst automation will eventually be possible, data preparation and analysis are currently time-consuming. Cloud based systems clearly now offer the best theatre for integration of spatial datasets, with potentially far easier data transfer (e.g. via telematics), processing, storage, viewing, amalgamation, interrogation and computation, especially for analysis across large numbers of farms. However, cloud based systems are as yet far from ubiquitous, and their functions still require development.

Given the vast expansion in farm-generated data, their often-novel constitution (e.g. multi-spectral reflectance, magnetic inductance, lidar), and their direct availability to practitioners rather than to crop scientists, approaches to spatial data analysis and interpretation have commonly been simple, superficial and empirical. On the other hand, the sciences of crops and soils have built comprehensive and mature conceptual frameworks for measurement, analysis and explanation of performance over recent decades. The immediate and vital challenge for agronōmics is thus to effectively integrate the various data sources currently available (e.g. soil, weather, crop sensing, satellite sensing, historic yield maps and imagery) into meaningful metrics that are of value both in practice and in science. Based on the farmer-researcher networking initiated in the YEN, we believe there is now an urgent need to translate the data appropriately and devise ‘Crop Intelligence Systems’ that sense and report crop growth and development in relation to available resources (light energy, water and temperature). This would provide a platform for comparing crop performance between fields, farms, regions and years, and a framework for drawing inferences on the impacts of management decisions in relation to impacts of soil, climate and environment. It would also provide the rational basis from which to drive algorithms to support strategic and tactical decision making in crop management.

3.3 On-Farm testing

It is our contention that the most valuable attribute of precision farming technologies is the capability they provide to farmers of assessing the effects of management decisions. On-farm testing has long been carried out by interested farmers in tramline or split field comparisons, often with support from the agricultural supply industry in the form of free products to test. The advent of GPS, yield monitors, yield maps and variable rate application equipment has made setting up, measuring and recording these treatment comparisons easier. Farmers can and do set-up comparisons on farms to address a range of questions, including choice and optimisation of varieties, cultivations, fertilisers, pesticides, biostimulants, organic additions and cover crops. In the past these sorts of ‘demonstration’ trials have generally been ignored by scientists; they are considered inexact, unscientific and inconclusive, due to the lack of quality control, randomization, replication and statistical analysis. Furthermore, as any cursory examination of farm yield maps will show, considerable care is needed in drawing conclusions from farm trials; spatial variation is such that no two areas in a field will yield identical average measures. As Fisher identified when devising conventional methodology for field experimentation (e.g. Fisher & Wishart, 1930) proof is not just required of a difference between two treatment areas, but that the difference is due to the treatment and not just inherent spatial variation. Some studies have however recognized the potentially greater measurement replication available from mapping harvesters and have developed approaches for using farm strip trials with more scientific credibility, often for use in developing and evaluating variable rate applications (e.g. Hicks *et al*., 1997; Plant, 2007; Griffin *et al*., 2008; Whelan *et al*., 2012; Lawes and Bramley, 2012).

We believe that it is feasible that the greater replication of individual measures from yield mapping and crop sensing, combined with the right geospatial models and statistical tests, could provide credible high precision comparisons. If a farmer can see a difference in the crop 'to a line' coinciding to a known management difference, this provides the farmer with overwhelming evidence that the intervention has had an effect. Within standard conventional science and agricultural statistics however there is no current framework for accepting such evidence as 'proof' of a causal effect.

4. Spatial experimentation, a useful addition to conventional plot experiments

Conventional crop experimentation relies on small plot trials laid out in replicated, randomized blocks analysed by 'analysis of variance' as set out by Fisher in the 1920s (Street, 1990). This approach effectively separates the spatial variation and measurement errors in order to conclude on the significance of treatment effects and has served agriculture well for the past 80 years. However, these experiments only compare treatment effects over relatively small areas; the same relationships might not apply over larger management zones, whole fields, whole farms or regionally. Also, the limited replication within the experiments may limit their precision. The precision of conventional trials with 3 or 4 replicates harvested by small plot combine harvester typically can't significantly detect differences of less than 0.5 t/ha, yet many individual agronomic decisions made by farmers cost in the region of £10 to £30/ha, equivalent to less than 0.3 t/ha.

In addition, choice of uniform land and randomisation of treatment positions in conventional experiments is specifically used to minimise effects of soil variation, thus disabling the ability to test soil differences or any effects that soil differences might have on treatment effects. The conventional approach to assessing soil differences is simply to compare multiple experiments from fields with different soil types. However, soil differences between fields are confounded with many other differences, including farmer, variety, management, previous cropping and weather. In contrast, most fields vary significantly in soil properties, and these offer opportunity to examine soil effects and variations in response to farm interventions with minimal confounded effects (i.e. where crop management etc. are identical); indeed soil attributes can be used as explanatory factors in an analysis of experiments involving systematic treatment allocation across known soil variation. This approach is best exemplified by the chessboard experiments conducted by ADAS to evaluate variation in nitrogen fertilizer requirements across fields, with systematic N response treatments (0,100, 200 & 300 kg N/ha) set up by the farmer at multiple grid points across a field (Figure 1; Kindred *et al*., 2014, 2016).

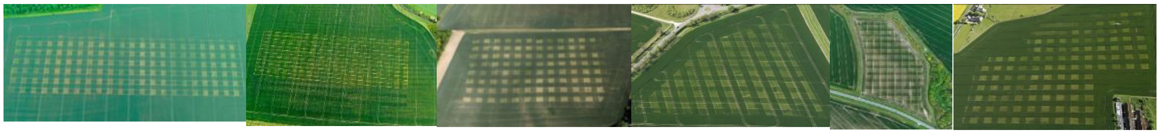

Figure 1. Aerial photographs of chessboard N response trials 2010-2012 (Kindred et al., 2016)

These experiments have transformed our interpretation and understanding of variation in N responses and the role of soil variation (Kindred *et al*., 2016). Also, because these trials were set-up by farmers using commercial application equipment they have also demonstrated the power and relevance of working with farmers at a field scale. Whilst these experiments were highly replicated with ~10m plots harvested by plot combine, they demonstrate the potential for learning about soil variation at larger scales, and potentially using commercial ‘yield mapping’ combine harvesters to measure the ultimate outcomes.

5. Developing agronōmic systems

Recognising the potential of spatial experimentation and farm-run trials to support a shared arena for investigation between scientists and farmers, to provide greater precision in treatment differences, and to allow evaluation of soil interactions, ADAS is developing agronōmics systems. These exploit many of the emerging technologies for on-farm automation and precision farming so as to enable quantitative crop phenotyping at the scales of field and farm, and to provide new understanding of spatially variable factors, particularly soil, through scaling-up field experimentation.

As seen at present, the essential components of effective ‘agronōmics’ systems will be (i) motivated and coordinated networks of farmers with regional and landscape dimensions, (ii) more precise on-farm and experimental machinery, (iii) new spatially-referenced statistical techniques for on-farm testing, (iv) facilitating software, and (v) accepted explanatory concepts, such as the analysis of crop yield in terms of ‘resource capture’. ADAS has initiated work to support the development of ‘agronōmics’ (funded by Innovate_UK), collaborating with British Geological Survey, AgSpace, BASF, Trials Equipment Ltd., and VSNi. We are developing the farmer networks, harvesting protocols and machinery, software, and spatial statistics that should enable farmers and researchers to establish and harvest tramline-scale treatments, transfer and store yield data in a standard format, clean the data to remove outliers, add information on combine run, direction and position, correct data for time lags, locate tramlines, treatments and wheelings and allow calculation of means and variances by combine run and by tramline. We have also devised ‘Spatial Discontinuity Analysis (SDA)’ (i) to test for differences in yields on either side of a treatment boundary, and (ii) to assess how treatment responses vary within-field e.g. due to soil variation (Rudolph *et al*., 2016).

Example yield maps of tramline trials are shown in Figure 2 where comparisons were made of fertiliser nitrogen (N) rates of 60 kg/ha more and less than the standard field N rate. Whilst spatial variation within fields is generally larger than the effects of imposed treatments, we have been able to assess treatment effects at tramline scale with detection limits of between 0.05 and 0.8 t/ha, dependent on the quality of the yield data and the inherent spatial variation. Whilst there are still improvements to make in quality of data from yield monitors, and in statistical approaches, it seems that comparable precision can be made in tramline-scale comparisons as is currently achieved in conventional small plot trials.

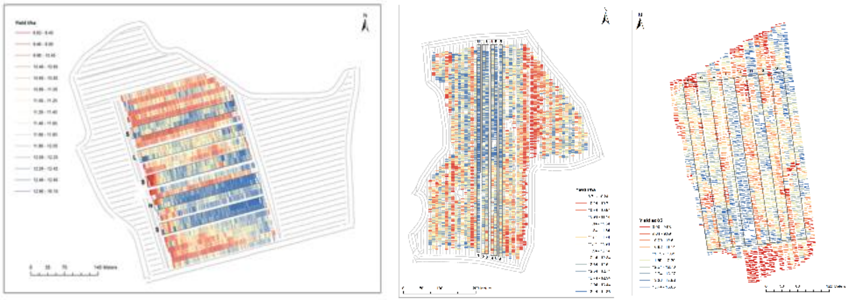

Figure 2. Example yield maps showing effects of different N treatments applied to tramlines, red = low yield, blue = high yield. Yield (t/ha) ranges: 9-12.5 t/ha.

ADAS is also investigating the use of plot combine harvesters fitted with continuous weighing hoppers and GPS to derive finer-scale yield maps than are possible with current commercial harvesters and that should enable higher precision treatment comparisons than can be achieved through commercial farm operations.

6. Farm Research Networks

Wielinga (2014) holds that effective interactions between farmers, advisors, researchers, consumers, policy makers and other stakeholders should increasingly be seen as the most important means of achieving joint learning and innovating for sustainable intensification. This could supersede the old model of innovations supposedly flowing from the researcher to farmers as end users. The European Innovation Partnership scheme under Horizon 2020 explicitly seeks to support such networks of farmers, advisors, industry and researchers in order to develop farm innovations.

There are a number of farm networks in the UK that now act (or could be held to act) as ‘farm research networks’, where farmers are working with researchers to gain new knowledge. The Field Labs organized by Innovative Farmers and the YEN are two examples of this already mentioned above. In addition:

- The AHDB LearN project is working with 18 farms across the England using simple tramline comparisons by farmers on 3 fields per farm over 4 years to assess variability in N requirements between fields, farms, regions and years, and to determine better ways of judging how much N to use farm by farm.
- As part of the Cost-Effective Phosphorus Project funded by AHDB Cereals & Oilseeds Frontier Agriculture Ltd. is developing a network of farms using tramline trials to test how the value of phosphate placement interacts with soils of different P status.
- Working with Sainsbury’s, the co-operative Camgrain, millers and around 30 growers in the Sainsbury’s Wheat Development Group, ADAS has conducted research to seek better understanding of variation in grain protein and its effect on breadmaking, and identify routes to predict and improve protein content. Insights have been gained from the pooling of farm data across fields and years with known yields and protein contents, analysed by multi-variate analysis. This generated hypotheses on fertilizer use that were later tested using tramline comparisons, providing grain and flour samples for quality measures and baking tests giving useful conclusions on farmer decisions that affect the quality of the end product, as well as farm profitability and environmental efficiency.
- In support of marketing hybrid barley varieties, Syngenta has organised a series of 20 reference fields per year, where their hybrids’ performance is compared in split fields with conventional varieties.
- The AHDB Monitor Farms offer the potential to act as a Farm Research Network, though is not currently set up to fully engage research & development with knowledge exchange.

Thus there is an increasing experience amongst farmers of engagement in research activities. The vision for Agrōnomics is to develop the facilities, techniques and infrastructure (virtual, web-enabled networking) whereby increasing numbers of interested farmers with yield mapping capability can elect to take part in structured tramline comparisons to address their most compelling questions. For the existing research community such networks should offer significant new opportunities for progress in the sciences of both soils and crops.

7. Opportunities in evolving agronōmics

The idea that investment in science naturally delivers innovations of use to industry is patently too simplistic. Any analysis of agricultural progress (e.g. Sylvester-Bradley, 1991) reveals that it is the farmers, or those close to farms, who make the most numerous and telling innovations. Science creates understanding, so provides the arena in which innovation can take place, but it is industry practitioners who know the detail and can tailor innovations to fit the farming jigsaw. Thus, whether on farm or in lab, effective innovators usually 'know farming'. Unfortunately, in many developed regions of the world over recent decades, we have largely lost the intimacy between farming and science that existed hitherto.

Furthermore, it is the nature of innovation that initial ideas or discoveries are often rough, and need honing; this process takes time and needs investment. Ideas often come to nothing, failures exceed the successes and successes tend to be haphazard so, for rapid progress, lots of ideas are needed. However, there are now fewer farms and farms have far fewer staff and make less profit than during the first green revolution 50 years ago. Whilst innovators are often passionate people, willing to put in much effort to prove their idea, they and their businesses must be able to cope with failures. Also, farm innovations commonly involve several technologies including engineering, chemistry, genetics and logistics so effective innovations commonly depend on integration and collaboration between disciplines, facilitated by effective integrators. Benefits of farming innovations are often difficult to exploit commercially, as most involve making changes to systems rather than using new 'widgets'; the benefits may be big but are often diffuse, being spread across many products and businesses, and without protectable IP for the innovator.

We believe that the new technologies available within this innovation arena now create a major opportunity for the research community. They should now recognize and act in the gap between conventional applied science and field-scale crop production. However, their success will depend on working with different communities, different technologies and different methodologies than hitherto. For example, traditional crop research employs experimental designs that minimise effects of uncontrolled environmental variables so that measured responses to controllable inputs can be tested, but the small area of these plots trials commonly restricts the relevance of their results to one soil, and it limits precision. We maintain that, in addition to the scientific challenges at lab scale, research scientists could recognise a big opportunity in investigating the multiple unknowns involved in extrapolation between small and large scales; not least amongst these are the interactions between agronomic innovations – new germplasm, chemistry or machinery – and soil variation. New research programmes are needed to understand such interactions, using the new methods of investigation now in prospect.

In this new arena it will be well to note that standards of proof are commonly much lower for farmers and industry than they are for scientists; farmers don't need to be 95% sure that a decision that costs £10/ha will deliver a yield benefit of >0.5 t/ha, they just need to be confident that the extra investment will pay for itself with yield benefits of >0.1 t/ha most of the time. Finding no significant differences between product comparisons in conventional trials isn't necessarily proof that a treatment is uneconomic, just that the effect can't be proven beyond the detection limits of the trial. However, farmers and industry need to appreciate the common extents of experimental and spatial variability in order to avoid drawing flawed conclusions from comparisons of simple averages. There are thus opportunities for scientists to be more respectful of farm experiences, and to be more helpful in devising ways of integrating farm datasets such that results are assimilated and conclusions are drawn with appropriate levels of confidence.

With the extensive support for networking amongst farmers, we conclude that adoption of an agronōmic approach offers powerful opportunities for both farmers and researchers to work jointly on questions that matter to both, at a scale that is relevant to commercial cropping, and that enables new understanding of soil (and other spatial) interactions. The use of remote sensing and 'big data' together with precision farming technologies and web-enabled networking confers exciting opportunities for not just translating research, but also conducting it. By providing tools for scientists and farmers to collaborate and network in testing hypotheses in fields across farms we believe that the agronōmics approach has potential to transform agronomy worldwide.

Few lines remain to consider the interplay between agronōmics and education, but it is important to recognise the vital potential role of students and teachers in affecting agronōmic progress, and to consider how agronōmic knowledge may best evolve through the generations. A difficulty arises in comparison with the more conventional fine-scale sciences in that soil and weather dominate agronomic phenomena, so agronōmic processes will be best understood over large scales of space and time. Clearly the agronōmics arena promises to be data-rich yet, for the foreseeable future, much agronōmic intelligence will be subject to much uncertainty. Given that experience will be a vital precedent to effective agronōmic reasoning, students of agronōmics may well be best distributed widely, in virtual classrooms across the farming landscape so that, with virtual support and coordinated activities, they can acquire their farming experience whilst playing an essential role in the aggregation, assimilation and interpretation of the large farm-derived datasets that will be so crucial to developing agronōmic laws for the future.

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