Agronōmics: eliciting food security from big data, big ideas and small farms

Roger Sylvester-Bradley[1], Daniel Kindred[1] & Pete Berry[2]

[1] ADAS Boxworth, Cambridge CB23 4NN, UK;
[2] ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire YO178BP, UK.

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Abstract. *Most farmers globally could make their farms more productive; few are limited by ambient availabilities of light energy and water. Similarly the sustainability of farming practices offers large scope for innovation and improvement. However, conventional 'top-down' Agricultural Knowledge and Innovation Systems (AKISs) are commonly failing to maintain significant progress in either productivity or sustainability because multifarious and complex agronomic interactions thwart accurate predictions of site-specific best practices. A revolution in knowledge generation and exchange is therefore needed to realize the potentials of individual farms and fields. This farmer-centric revolution will best arise from coordinated and widely shared farmer-centric monitoring, benchmarking and experimentation. These all require more coordination, care and quality control than can generally be provided by farmers so they must be driven by investments in farm facilitators and their training, as well as development of easy-to-use, supportive digital platforms.*

Initiatives for farmer-centric knowledge generation and exchange have occurred across the world but past models have not generally been targeted at eliciting site-specific progress, and they have been weak in fostering comprehensive feedback between farmer and researcher. Models enabling engagement by the largest number of farms and the most thorough feedback are expected to engender fastest agronomic progress. Whilst digital tools such as are currently used in 'precision farming' are seen as essential to this fast feedback, it is suggested that most emphasis should be placed on creating the social infrastructures that will maintain communication channels throughout the new 'bottom-up' AKIS.

Keywords: *Agronōmics; participatory research; transdisciplinarity; productivity; sustainability.*

Introduction

Security of human nutrition and bioenergy supply is crucial to happy and sustained human progress. It is highly desirable that any improvements in primary production are achieved with decreased impacts on the farmed environment. The essential drive towards farm productivity and sustainability to meet these aims has been termed 'green development'. Note that primary producers may soon also need to become global 'carbon sequestrators' (i.e. through bioenergy carbon capture and storage; Azar *et al*., 2006). Thus, irrespective of farmers' aspirations for increased income, pressures are increasing for their productivity to be enhanced whilst also decreasing their environmental impacts, particularly through reducing their use of inefficient, and therefore polluting, inputs of fertilizers and pesticides.

Agricultural innovation, research and dissemination have traditionally been undertaken by the science community and funded by governments, especially in countries where a large proportion of the electorate is engaged in farming. Bio-scientists form big ideas – genomics, metabolomics, and the like – and agri-technologists amass digital tools and robots, for which they both claim big potential impacts on farm productivity and sustainability. However, translation of such innovations into practice has many pitfalls and, with the urgency of global needs, progress in farm productivity and sustainability are both too slow, whether in developed or developing regions, and it has been concluded in Europe that the 'top-down' agricultural knowledge and innovation system (AKIS) is "no longer sufficient" (EU, 2017).

Managed primary production is undertaken on about ~5% of the earth's surface by 2-3 billion farmers operating on more than 570 million individual farms (IFAD & UNEP, 2013; Lowder *et al*., 2016). Most farms are smallholdings and even the world's largest 'industrial farm' is still small in global terms, occupying only one thousandth of cultivated land (Orange, 2011). Thus agriculture and agricultural improvement require engagement amongst large numbers of farmers, very few of whom have the capacity to undertake their own research.

This paper highlights needs for a revolution in knowledge generation and exchange within global agriculture, and outlines essential components of a new AKIS that could bring the disparate communities of science, technology and farming together more effectively, it suggests that a new 'science of farming' should be recognized, called 'agronōmics' (Kindred *et al*., 2016). It asserts that the design of farming systems must take precedence over their analysis, hence agronōmics must favor transdisciplinarity (Mauser *et al*., 2013; Ingram *et al*., 2018). The potential power of farm-derived 'big data' is acknowledged, with agricultural students becoming instrumental in effecting good connections between farming and science (Zhang *et al*., 2016). Digital technologies should be directed to provide the vital tools to enable fast change. Finally, a new global institution is required to develop and support new farmer-centric AKISs worldwide.

The Challenge

Existing AKISs are generally based upon scientific principles; however, the principles of biology are rarely sufficient alone; extensive experimentation is necessary region by region to determine optimum regional farming strategies and economic levels of inputs. The protocols for conduct and analysis of these experiments were established almost a century ago (Fisher, 1924), with replication and random allocation of treatments being key; bespoke machinery has since been developed to facilitate plot management and treatment application, and computer packages facilitate statistical analyses. Trials are placed within the most uniform field zones and soil variation is minimized by trial areas seldom exceeding 0.5 ha. Nevertheless, many issues compromise this conventional small-plot research strategy:

- Individual experiments have large errors; the average of Least Significant Difference for grain yield comparisons in the UK is ~0.5 t ha^{-1}, 5% of the mean yield, yet costs of the decision options being tested are commonly <0.2 t ha^{-1}.
- Results are compromised by large and uncertain intra-field variation; for example the position within a field of a small trial testing optimum nitrogen (N) applications was typically found to

affect N optima by >150 kg ha^{-1}, and optimal yields by >2 t ha^{-1} (Kindred *et al.*, 2017).

- Most treatments show large interactions with site factors; for example Fig. 1 shows large site effects on variety performance.
- Because of their variable performance many experiments are required to reach robust conclusions about best practice for a region, and it is seldom that most of the variation in these experiments can be explained, so extrapolations to specific fields are very uncertain.
- Comparisons between sites do not only concern soil differences; site comparisons commonly entail confounding of differences in weather, farming and cultivation systems, rotational positions, and standards of husbandry, so it is rare to be able to draw conclusions about soil effects, or about interactions between tested factors and soil characteristics.
- Similarly, although large yield variation is commonly observed between sites, this cannot be analyzed or explained through small plot comparisons.
- Finally, records are seldom kept by farmers of their modifications to best practice, effects of these are not tested, and any feedback to researchers is haphazard.

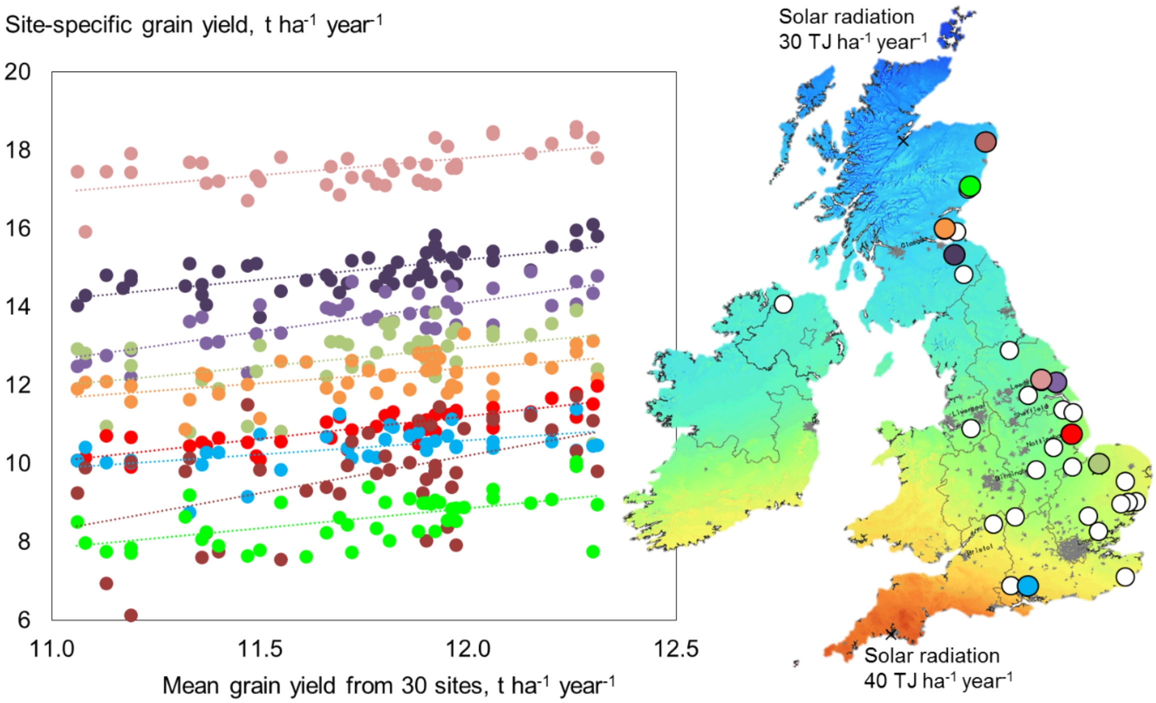

Fig 1. Grain yields in 2015 at nine out of 30 sites distributed from the south to the north of the UK for ~50 commercial wheat varieties as they relate to mean grain yield in all 30 experiments in 2015 (sites are color-coded according to a position on the map). Coefficients of determination (R^2) varied from 0.2 to 0.7, and slopes varied from 0.6 to 1.9.

The only inputs that relate directly to a crop's growth are the light energy and water that it captures (Fig. 2a). Conversion of these to biomass remains relatively stable across a range of crops and throughout a crop's life (Monteith, 1977), so the biophysical potential yield of a crop can be estimated from the availability of light energy or water at that site, whichever is the more limiting (Sylvester-Bradley & Wiseman, 2005). Even though many developed countries such as the UK have reached a relatively mature state of agricultural development, and even though yields of key crops have stagnated for 20 years (Koning & van Ittersum, 2009) estimates of biophysical potential for most crops far exceed the average, or even the highest, levels currently achieved on farms. Yield gaps in developing regions are even larger (van Ittersum *et al.*, 2013). Thus there appears to be plenty of scope to increase crop production without use of more land if site-specific yield constraints can be identified.

Farmers continually strive to attain higher yields, but often without understanding the relationships of yield with capture of light and water. The most efficient diagnosis of yield gaps should be by assessing whether the main cause is a deficiency in light or water capture, and thus whether attention should be paid to enhancing (by enlarging or prolonging) the green canopy or the root system. However, farmers tend to associate outputs with boughten inputs, fertilizer and pesticides and, depending on the state of agricultural development in a region, input applications may be optimized or may be still optimizing. In countries such as the UK where boughten inputs are used in large quantities, much testing is undertaken to determine optimum amounts. Unfortunately, as explained above, recommendation systems and decision tools developed to account for variation in input optima are very imprecise (Kindred *et al*., 2016); thus farmers are tempted to over-use these inputs in order to avoid any yield shortfalls. In seeking greater sustainability of crop production a range of technologies may be used to reduce the demand for boughten inputs such as plant breeding, chemical formulation, or application method and timing. In seeking such 'green development', the ultimate aim must be, to reduce the requirements for boughten inputs, say by increasing levels of nutrient recycling in the farming system or by introgressing genetic sources of immunity to disease (Fig. 2b). However, much progress remains to be made.

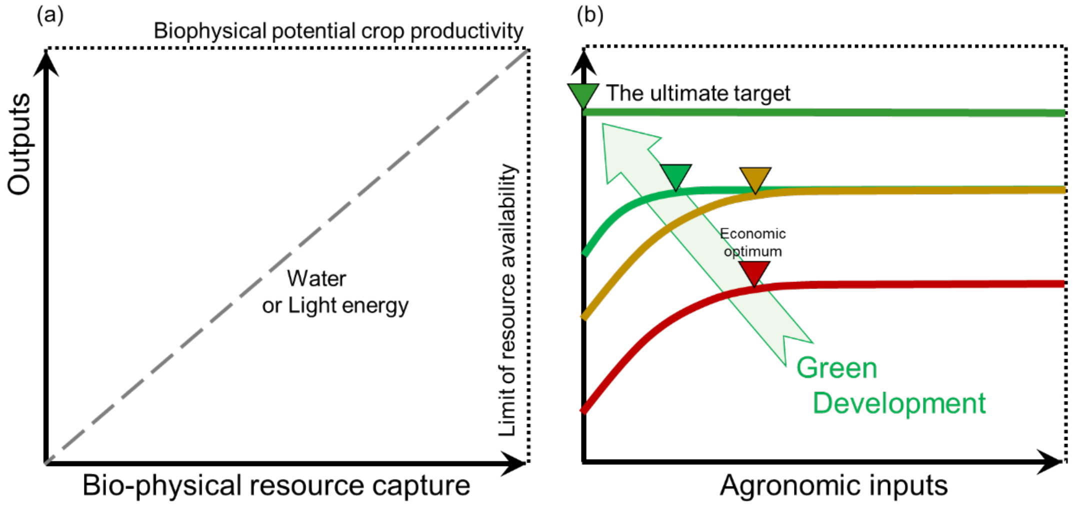

Fig 2. (a) Capture of bio-physical resources (water or light energy) determines crop output; the biophysical potential of each crop is determined by availability of these resources. (b) Relationship of crop outputs to boughten agronomic inputs, fertilizers and pesticides. Development from red to orange or green production involves using a combination of technologies to either increase output or decrease inputs, or both. The ultimate target for Green Development must be to design farming systems which produce close to the biophysical potential of the land, but without any need for agronomic inputs, say through 100% nutrient recycling and crop immunity to weeds, pests and diseases.

For many reasons the degree of optimization of farming systems and practices differs across global regions, only one cause of which is the effectiveness of knowledge generation and exchange. In Africa farm productivity is often constrained by unavailability or unaffordability of conventional inputs such as fertilizers, whereas in Asia (India and China) fertilizers are so cheap and easily available that they are commonly over-used. In Europe and the Americas optimization at a regional scale has been achieved for many years, and further progress in farm productivity or sustainability has become frustratingly slow (e.g. Koning & van Ittersum, 2009).

Opportunities & Solutions

The challenges of large site-specific variation in crop performance and crops' responses to inputs demands resolution through better collation, integration and interpretation of site-specific evidence. Such evidence is becoming available in large volumes through digital 'precision farming' technologies, so a major opportunity now arises in planning appropriate measurements and in marshaling and interpreting the resultant data to address key site-specific uncertainties. However, the complexity of crop agronomy, for example in the UK (taking into account the numbers of soils, regional climates, species, varieties, nutrients, fertilizers, pesticides, growth regulators, and market requirements), is such that the number of farming options (UK estimate

$\sim 10^{30}$) exceeds the number of arable fields (UK estimate $\sim 10^{6}$) by many orders of magnitude. Even if all fields could be recorded and if this evidence were tailored to address farmers' key questions, passive collation and interpretation of 'big data' would be grossly inadequate for the task. Hence active site-specific experimentation will be required to provide essential targeted evidence. Farmer experiments are not a new idea (e.g. Atta-Krah, 1992) but in terms of the conventional researcher-to-farmer AKIS adopted in most regions world-wide, the introduction of farmer experimentation into normal farming practices represents a revolution (Fig. 3), and it will be important to deduce the features that determine how it can have the most positive impacts.

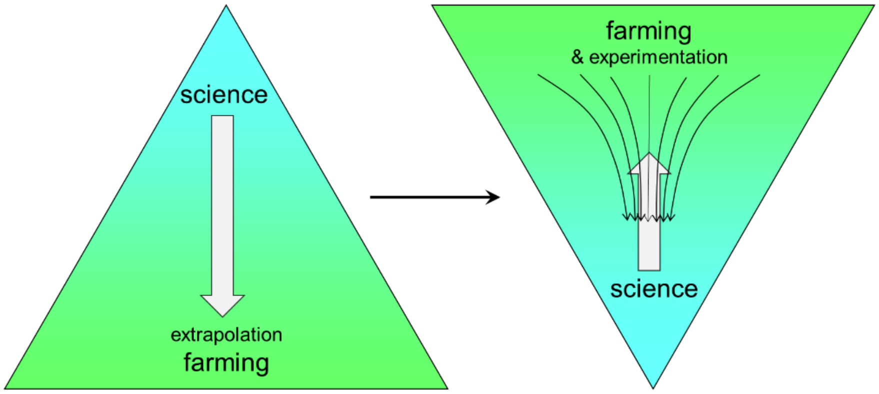

Fig 3. An AKIS revolution, from top-down to bottom up. Widespread on-farm experimentation using precision farming technologies enables feed-back on the success of extrapolation using science-based decision rules.

Many initiatives world-wide promote and support 'on-farm experimentation' both in developed (e.g. Cook *et al.*, 2013; Macmillan & Benton, 2014; ENRD, 2015; EU, 2015) and developing (e.g. Micheni *et al.*, 2015; Zhang *et al.*, 2016) agricultural regions. These initiatives vary in their design and particularly in the extent to which they aim to provide feedback to the researcher; often they merely aspire to validate generalized best practice, rather than to add a layer of site-specific understanding that introduces finesse into the adoption of products or practices. However, the most ambitious approaches can include sufficiently close crop monitoring, statistical analysis and reporting to provide for improvements in site-specific crop management (Martin & Sherington, 1997; Sylvester-Bradley *et al.*, 2017).

Experience shows that a key issue in determining the success of farmer-centric networking and experimentation is whether researchers and farmers employ the same explanatory concepts (Cook *et al.*, 2013). For example, in the UK it has been found that despite the longstanding appreciation by the research community of crop yields in terms of resource capture (e.g. Monteith, 1977; Penning de Vries & van Laar, 1982) and ready availability of this understanding through publications for growers (Sylvester-Bradley *et al.*, 2008), growers' reasoning about crop yields did not generally invoke the concept of resource capture. Hence a Yield Enhancement Network (YEN) was initiated in the UK in 2012 to establish a common explanatory framework for cereal yields and thus to encourage reasoned thinking on feasible means of enhancing these yields (Sylvester-Bradley & Kindred, 2014). In the five seasons since 2012, the yields of approximately 400 wheat crops observed by YEN entrants have ranged widely between 5.2 and 16.5 t ha^{-1} (mean 11.1 t ha^{-1}; Fig. 4) and crop monitoring and reporting have focused on metrics that support yield analysis in terms of resource capture. Although the site variation in grain yield was similar in all seasons, the complex nature of cereal yield determination in the UK environment has allowed few simple conclusions about site-specific yield determination. Now, after five seasons, a program of experimentation has been initiated to test some of the farmers' best ideas, and to analyze any effects using resource-related metrics.

As with adoption of explanatory concepts and prioritization of metrics, work on the methodology of farmer experimentation has needed to resolve approaches that are acceptable to both farmer and researcher (Martin & Sherington, 1997; Sylvester-Bradley *et al.*, 2017). Of course the research community employs statistical analyses to gauge the confidence that can be placed in any comparison of treatments, whilst the farming community generally cannot; with their machinery dictating large plot sizes relative to field size, UK farmers can seldom achieve the necessary degree of treatment replication and randomization required to support conventional analysis of variance. Nevertheless, it has proved possible to develop and adopt less conventional statistics (e.g. spatial discontinuity analysis; SDA; Rudolph *et al*., 2016) that estimate certainty levels based on the highly replicated and spatially defined nature of data underlying yield maps (and other sensor maps) (Sylvester-Bradley *et al*., 2017).

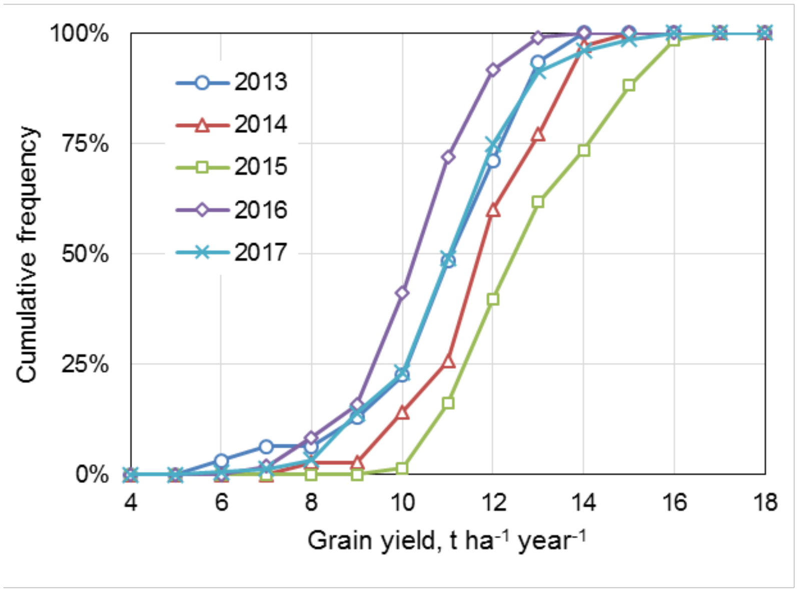

Fig 4. Distributions of grain yields by harvest year in the YEN yield competitions from 2013 to 2017, showing minimum of 5.2 and a maximum of 16.5 t ha^{-1} year^{-1}. Means and standard deviations of the grain yields in successive seasons were 10.9±1.8, 11.7±1.5, 12.8±1.7, 10.3±1.3 and 11.0±1.7 t ha^{-1} year^{-1}.

With present standards of trial design and harvesting, levels of certainty in treatment comparisons made by UK farmers tend to be worse than with conventional small plots (Kindred *et al*., 2018). However, a few farmer-run trials, particularly those conducted with controlled traffic systems, have achieved much higher levels of precision and it is possible to envisage developing guidance and harvesting technologies in future that will facilitate regular achievement of such high precision. In particular it will be most helpful when harvester manufacturers come to realize that the opportunities offered by routine precise experimentation by farmers are considerable; not only should it prove possible to detect small treatment effects and then to accumulate these in new husbandry designs, but important effects of variation in soil characteristics across a field should also become detectable. Recent experience using SDA shows that precision increases with the length of the strips being compared so, as precision improves, differences should become detectable over shorter and shorter treatment boundaries, such that variation in crop responses along the boundary could in future be explained by soil differences along that boundary. This opens the prospect of directly validating ‘variable rate’ protocols i.e. testing means of overcoming soil-related variation in crop performance, and thereby much enhancing crop productivity. From an academic standpoint, precise along-the-line comparisons offer a new means of quantifying and understanding soil functions, thus creating a new arena of science.

Whilst much may be learned by analyzing responses along transects of individual fields, the potential power of digital sensing, recording and analyzing spatially referenced crop and soil data will be hugely enhanced by sharing of those data between fields and farms. Thus new AKIS models which enable easy engagement by the largest number of farms and provide the most thorough feedback between farmer and researcher are expected to engender fastest agronomic progress. It is possible to envisage that the attraction of data sharing could be enhanced if the act of uploading data was rewarded by providing immediate comparisons with a farmer’s closest peers.

It follows from the promise of elucidating complex site-specific interactions with big data, including big experimentation, that there will be a need for optimized site-specific husbandry designs. Hitherto agricultural sciences have seldom formalized a design process for farming systems, but it seems likely that this will be needed and that it should involve teamwork between different specialists; hence agronōmics must favor transdisciplinarity (Mauser *et al.*, 2013; Ingram *et al.*, 2018).

Farmers in many developed and some developing regions are well served by advisors; these are either independent or associated with the supply of farm inputs. The role of the advisor is to know the detail of best practice and to effect extrapolations of this to individual farm and field circumstances. In general, farmers choose an advisor that they trust, and the advisor takes responsibility for determining specific aspects of the farmer's husbandry even though both know that most decisions are subject to considerable uncertainty. However, the prospect of farmers being able to test routinely the value of husbandry decisions offers to change the relationship between farmer and advisor. Given that farmers' experimentation will require some specialist support, and that the advisor is commonly the most frequent visitor to the farm, it seems sensible that the advisor should train to fulfill the role of experiment facilitator. But furthermore the outlooks of both advisor, supplier and farmer seem likely to change, because some of the advisor's advice and some of the supplier's products will be open to test. The relationship should thus move towards becoming a joint partnership, resolved to provide the evidence base from which to design the optimum site-specific husbandry for that farm and that farmer.

Conclusions – a new paradigm

It appears that most variation in crop productivity is site-specific and poorly understood. However, precision farming technologies have been shown able to facilitate precise experimentation not only to test the decisions that a farmer makes but also to reveal the way that these decisions interact with soil characteristics in localized zones. This raises the prospect of a new paradigm of bottom-up research to augment the conventional top-down approach to agricultural knowledge generation and exchange; essential features of the new paradigm, as determined in the UK, are illustrated in Fig. 5.

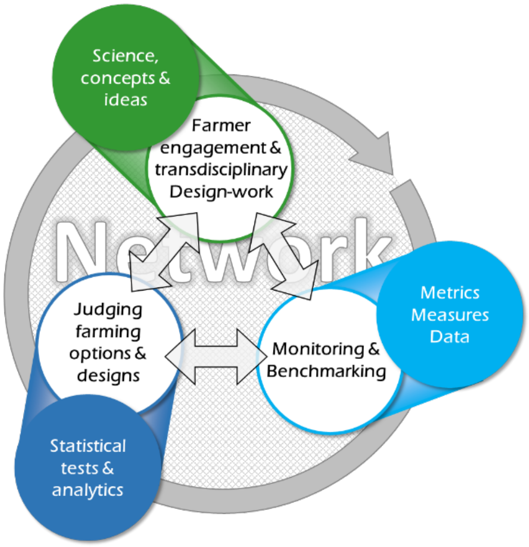

Fig 5. Three essential pillars of any open farmer-centric network for the generation and exchange of knowledge on a particular farming challenge e.g. yield enhancement of a crop species, control of a pernicious weed or minimization of nutrient emissions. Each pillar uses externally derived concepts to guide each of its internal interactive activities.

The extent of change offered by this new approach seems sufficient to merit creation of a new global institution responsible for developing and supporting such new farmer-centric AKISs worldwide. Whilst farms globally are multifarious in their size, their products and their farming systems, all farms are concerned with a series of common farming processes: cultivating, sowing, fertilizing, protecting, harvesting, storing and marketing. Also the principles underlying production responses are understood in the same way. Agronomy thus has a common language world-wide, and would seem important to explore the breadth of global environments across which it will prove valuable to amass and interpret agronomic data and experimental findings. Many further questions arise from the new paradigm, which only time and experience will resolve: for instance, what determines the best AKIS model for a particular region, how should each AKIS be funded, who should be in control, what key specialisms are needed, and how should education and training be incorporated?

Initiation in the UK in recent years of small scale farmer networks (e.g. YENs) and farmer idea-testing groups (FIGs) has revealed the essential value of engaging large numbers of farms and hence the importance of developing easy-to-use and attractive digital platforms that automate much of manual work of collating farmers data. These UK initiatives have also underlined the important role of farmer facilitators. Interestingly, farmer experimentation in China has been facilitated by graduate students who are stationed for considerable periods within farming communities (Zhang *et al*., 2016). Strong mutual benefits of this approach are apparent for the farmer, the student and the researcher. It seems possible that an analogous scheme could be introduced in other regions.

Thus the overall conclusions from this paper are that farmers can themselves be increasingly important in developing the science as well as the technology of farming and cropping, because of (a) their creativity in designing practices and systems at the actual scale of production, (b) their site-specific knowledge, and (c) their increasing capacity for digital recording.

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