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Article

What Do We Need to Know to Enhance the Environmental Sustainability of Agricultural Production? A Prioritisation of Knowledge Needs for the UK Food System

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Abstract: Increasing concerns about global environmental change and food security have focused attention on the need for environmentally sustainable agriculture. This is agriculture that makes efficient use of natural resources and does not degrade the environmental systems that underpin it, or deplete natural capital stocks. We convened a group of 29 'practitioners' and 17 environmental scientists with direct involvement or expertise in the environmental sustainability of agriculture. The practitioners included representatives from UK industry, non-government organizations and government agencies. We collaboratively developed a long list of 264 knowledge needs to help enhance the environmental sustainability of agriculture within the UK or for the UK market. We refined and selected the most important knowledge needs through a three-stage process of voting, discussion and scoring. Scientists and practitioners identified similar priorities. We present the 26 highest priority knowledge needs. Many of them demand integration of knowledge from different disciplines to inform policy and practice. The top five are about sustainability of livestock feed, trade-offs between ecosystem services at farm or landscape scale, phosphorus recycling and metrics to measure sustainability. The outcomes will be used to guide on-going knowledge exchange work, future science policy and funding.

Keywords: agriculture; environment; knowledge gaps; sustainability; farming; retail; food

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1. Introduction

The sustainability of food production has become a strong focus of attention in recent years, in policy, within the food industry [1] and in research [2]. This is partly in response to emerging risks to food production from global environmental change, particularly climate change [3], risks to food security from increasing global population and changing dietary habits [4] and the rising prominence of the sustainability agenda amongst consumers and in corporate governance [5].

One aspect of this 'sustainability' is environmental sustainability. Environmentally sustainable food production can be defined as food production that makes efficient use of natural resources and does not degrade the environmental systems that underpin it, or deplete natural capital stocks. In a recent working paper [6], the United Nations Sustainable Development Solutions Network proposed four post-2015 environmental development goals for agriculture. These can be summarised as: (1) slow the expansion of agriculture into sensitive natural ecosystems; (2) increase the efficiency of resource use, (3) stop unsustainable withdrawal of water and degradation of soil and (4) protect biodiversity and other ecosystem services in farmland. These proposed goals sit alongside (and will have to be reconciled with) proposed food security, economic and social development goals. The latter include the suggested requirement to increase global food supply through a combination of increased productivity and less waste of food products both pre- and post-harvest, whilst minimising the use of food crops for bio-energy.

As part of the focus on sustainable food production, many organizations within and linked to the food and farming industry, are actively supporting or developing more environmentally sustainable agriculture. Government, industry and third sector organizations use a number of levers to influence farming practices to this end. They include regulation to impose minimum environmental standards; advice, guidance or voluntary approaches to encourage the uptake of good practice; investment in research and development [7] and economic incentives and disincentives through agri-environment or farm assurance schemes, including business-to-business schemes such as GlobalGAP, and consumer-facing certification schemes such as organic, Rainforest Alliance and LEAF Marque [8]. These organizations commonly express interest in ensuring that they have access to and use the best available science, to increase their likelihood of improving environmental sustainability.

Scientific knowledge about the environmental sustainability of agriculture is derived from a wide range of disciplines including: agronomy, livestock science, ecology, hydrology, climate science, plant and animal pathology, entomology and economics. Some aspects of environmental sustainability in agriculture have been well researched, such as management methods to supply floral resources for pollinators on farmland [9]. In these cases, there is typically a need for knowledge exchange, as the knowledge is rarely synthesized and users of research in the food and farming sector do not have full access to the scientific literature, or the time to synthesize it and develop an integrated understanding. Other aspects of agricultural sustainability, such as means to reduce greenhouse gas emissions from crop and livestock production systems, are of relatively recent interest [10] and even less well integrated with the full range of environmental concerns for example, [11]. The type of integrated, multidisciplinary research required to develop novel production systems that are better for the environment overall is rarely conducted. Little has been done since the projects on integrated farming were conducted in the 1990s [12].

With increased appreciation of the importance of sustainable food production, new funding streams are being developed in the UK and elsewhere to bridge these key research and development gaps. It is now important to identify the most pressing knowledge needs, from both scientist and practitioner perspectives. Three of the authors (LVD, RPF and WJS) have been involved in several previous exercises to identify questions of importance to policymakers and practitioners [13]. These have generated substantial interest and been used to shape science policy. For example, in the UK Government's Marine Science Strategy [14], the research questions were acknowledged as being based on an exercise to identify 100 ecological questions of high policy relevance [15]. In addition an exercise to identify the top questions in agriculture [1] was subsequently used as the basis for a workshop that informed the initial priorities of the UK Global Food Security Research Programme. Both examples demonstrate the importance of bringing a diverse interest group together to identify knowledge needs, and the demand for studies of this kind.

Improving the environmental sustainability of agriculture will inevitably involve changes in farming practices, aided by the development and adoption of new products and technologies [16]. There are a number of interacting drivers of farming practice [17], with farmers' attitudes and beliefs expected to be key determinants of the management actions ultimately undertaken [18,19]. In the UK, farmers receive advice from a complex array of sources that include government, industry and non-governmental organizations [20]. A growing body of evidence highlights farmers' confidence in different sources of advice. Other farmers and family members have long been considered as valued sources of advice [21], and research has shown that this advice is more highly valued than information from commercial, Government or other organisations, which might be viewed as having vested interests [18,22]. Farmers also value trusted relationships with professional advisers, including agronomists, feed advisers, land agents and vets, who focus on improving farm business performance and resource efficiency to deliver economic as well as environmental outcomes [21]. If the research community is to engage the farming community in developing environmentally sustainable agricultural systems, it must be a collaborative process, carried out in partnerships between researchers and farmer-led organizations, or organizations trusted and respected by the farming industry.

The exercise described here uses such a collaborative approach to identify and rank knowledge needs which, if addressed, would facilitate change and enhance the environmental sustainability of agriculture in some way. It goes beyond identifying research questions, as it includes cases where the scientific knowledge already exists but needs to be communicated or adapted for use. Often the challenge comes in translating a large body of existing scientific information to address an applied problem. In common with a recent exercise on conservation of wild insect pollinators [23], the organisers made a particular effort to include the full range of interest groups directly linked to the production aspects of farming, including large private sector commercial interests such as supermarkets, agrochemical companies and food manufacturers that play a significant role in the agri-food supply chain, along with policymakers and non-Governmental organisations.

Scope

This exercise is about enhancing the environmental sustainability of agricultural production within the UK or for the UK market. It includes agricultural areas around the world that provide food for UK markets, as well as all UK farming. It does not include issues surrounding consumption and demand for food, or human health and nutrition.

2. Methods

Our process of defining priority knowledge needs for enhancing sustainable agriculture involved collaborative development of an initial long list, followed by three stages of voting or scoring. Online surveys were designed and conducted using the online survey tool Qualtrics [24].

2.1. Who Was Involved?

Forty-six people participated in one or more stages of the prioritisation process. They comprised 17 research scientists, 20 from businesses or trade associations involved in agriculture, food production or retail, five from government departments or agencies and four from charitable organizations with a strong focus on sustainable agriculture. Of these 46, eight participated in only the early stages of prioritisation, by suggesting knowledge needs or taking part in the initial round of voting. The remaining 38 (those included here as authors) participated in all stages.

The research scientists were either from UK higher education institutions, Government-funded or independent research institutes, including the British Trust for Ornithology and the UK Centre for Ecology and Hydrology. They were all either leading academics, selected by the Natural Environment Research Council (NERC) Knowledge Exchange Programme on Sustainable Food Production, or Knowledge Exchange Fellows working on aspects of sustainable agriculture, funded by NERC. Leading scientists from the following research areas pertinent to sustainable farming were selected, based on relevant research grants awarded and publications in the scientific literature: soil science, crop ecology, weed ecology, biogeochemistry, farmland biodiversity and ecosystem services, plant disease, livestock disease and farm management. Of the 14 research scientists who took part in the full process, three had expertise in soils, three in biodiversity, three in crop ecology or health and two in whole farming systems, while one had expertise in livestock health (specifically diseases of dairy cattle). The remaining two researchers were Knowledge Exchange Fellows working with large food sector businesses.

We use the term ‘practitioners’ for all the non-academics, or end-users of research in the process. This encompasses people engaged in promoting or practising sustainable agriculture at a wide range of levels, from corporate sustainability strategies and large-scale international procurement decisions to management of individual farms. The selected participants were all directly linked with the production aspects of farming. We did not seek organisations whose main focus was food processing, waste management, packaging, distribution, consumer choice or health and nutrition. We invited representatives from the seven largest UK supermarkets by market share [25], three of the four largest agrochemical companies globally, seven food or feed manufacturers playing leadership roles in corporate sustainability in the UK, either through involvement with the NERC’s Knowledge Exchange Programme on Sustainable Food Production or the Cambridge Programme for Sustainability Leadership, seven major trade associations representing UK food retail or farming, nine charitable organizations well-known for campaigning on issues related to UK farming or farm wildlife, and nine UK or devolved national government departments or agencies responsible for agricultural, land management and environmental policy. Of the 41 practitioner organizations invited, twenty-nine participated. Twenty-four of the 38 people involved in every stage of the process (those listed as authors) were classed as practitioners.

2.2. The Process of Defining Priority Knowledge Needs

The initial long list of potential knowledge needs was developed by all participants submitting up to 10 possible knowledge or evidence needs for consideration by the group. Participants were invited to select issues that they considered important for making agriculture more sustainable. The objective was for suggestions to be as specific as possible, but for the list as a whole to consider all aspects of the natural environment—air, soil, water, biodiversity, climate, weather and natural hazards, disease, pollution and human health. Participants consulted their colleagues and told them that the outcomes from the process would be used to shape future science investment. Thirteen example knowledge needs were provided. These were either gathered from previous or concurrent exercises that identified knowledge needs or research priorities, such as the Feeding the Future project [26] and recent workshops on soil carbon [27] or nitrogen [28], or they had been identified in individual meetings with businesses as part of the NERC Knowledge Exchange Programme on Sustainable Food Production. The examples were carried through into the subsequent stage of the process alongside new suggestions generated by the current exercise.

All the submitted knowledge needs were compiled into a list by the first author (LVD) and categorized by subject area. Nine categories were selected to provide groups of knowledge needs as similar in size as possible. Each knowledge need appeared in only one category. Where possible, the categories were chosen and named to reflect priority research areas for sustainable agriculture recently identified for new funding by the Department of Environment Food and Rural Affairs (Defra) and two UK Research Councils (NERC and the Biotechnology and Biological Sciences Research Council, BBSRC). This matching was a deliberate effort to enhance the linkage between the identified knowledge needs and future research investment, but no matching category was created if there were insufficient suggested knowledge needs to make a group of at least 15.

In the first voting stage, all members of the group anonymously voted on the long list of knowledge needs, using an online survey. Participants were asked to select between three and five items from each of the nine categories that represented the most important current knowledge needs for sustainable agriculture either within the UK, or serving UK food markets. For groups of similar knowledge needs, participants were asked to select one that most matched their concern, and told there would be a chance either to amalgamate similar needs at the workshop or to identify the most useful need. Participants had the opportunity to make comments or suggest alternative wording for each knowledge need.

The final prioritisation of knowledge needs took place at a one-day workshop held in Cambridge on 8 January 2013. In the second stage, each item on the long list was discussed during a 90-minute session dedicated to each section of the list (see Table 1). Three sessions ran in parallel, so each person was involved in discussions for three of the nine categories, and was able to choose which they attended. The only rule was that each group had to have between three and seven research scientists. This was imposed to ensure that the groups always had a mix of scientists and practitioners.

Table 1. Structure of the initial long list of knowledge needs for environmentally sustainable agriculture.

Category	**Label**	**Description**	**Number of proposed knowledge needs**
Crops	C	Crop plants, including crop selection, rotation, plant breeding, yields and agroforestry, but not including pests and diseases. Future impacts of climate change on crop suitability or cropping patterns were included here.	**36**
Livestock	Li	Management of livestock, including livestock health and interactions between environmental sustainability and animal welfare.	**31**
Nutrients	N	Includes the use of non-mineral fertilizers, nutrient-related emissions to air and water.	**16**
Soil	S	Managing and understanding soil health and fertility, including soil carbon.	**38**
Pest control	P	Sustainable strategies to deal with crop pests (including plant diseases) and weeds, but not livestock disease.	**23**
Farm-scale management of biodiversity and ecosystem services	F	Management of biodiversity, habitats & ecosystem services at farm scale (except soil carbon and water quality issues associated with nutrients, which are in soils and nutrients respectively).	**37**
Landscape-scale planning for sustainable agriculture	La	Balancing ecosystem services and food production at landscape scale (beyond the individual farm). Includes governance and decision-making at this scale.	**20**
Markets and Drivers	Ma	Understanding the wider drivers for decision-making on farms, including influences of global commodity markets, global environmental change (expect impacts of climate change on cropping patterns) and developing markets for ecosystem services or biofuels. Issues related to farm economics and farmer behaviour were included here, including questions about implementing precision agriculture and other new technologies.	**45**
Monitoring	Mo	Understanding the status of the farmed environment through monitoring or application of existing datasets.	**18**
TOTAL NUMBER OF PROPOSED KNOWLEDGE NEEDS			**264**

During the discussion sessions, all participants could see the anonymous comments or alternative wording others had suggested during the first voting stage along with the number of votes for each knowledge need. Similar knowledge needs were placed together, shaded in colour and then placed in the rank according to the one in the group that received the most votes during Stage 1. However, the original wording of each need was always retained, to maintain transparency in the process and avoid misinterpretation of individual knowledge needs.

Participants were told to identify knowledge needs that, if met, would allow their organizations to take action, change practice or enhance agricultural sustainability. They were guided by session chairs to discuss, for each knowledge need, what could be done if this was known, and to prioritise needs that would catalyse or facilitate change and could be delivered in a reasonable timeframe of less than five years.

In general, knowledge needs with more votes were given more discussion time, but there was ample opportunity to speak up for needs that had no votes, or few votes. Some knowledge needs were re-worded or amalgamated with others at this stage, by consensus. It was also possible to add additional needs at this stage. Knowledge needs were first eliminated to create a short list, then voting by show of hands during each session was used to produce a shorter list of knowledge needs under each section. We aimed to emerge from each session with four, six or eight knowledge needs, depending on the number of knowledge needs in the initial list for each category. The thresholds were set so that approximately 20% of the initially suggested knowledge needs from each category could proceed to the next stage. The selected knowledge needs in each category were also ranked, by counting votes or by consensus.

In a final plenary session, 53 knowledge needs drawn from all categories of the long list were presented to all participants, each showing the category it came from and the ranking it achieved. The list was ordered so that high-ranking knowledge needs from all categories appeared first, the low-ranking knowledge needs were at the end and the categories were dispersed evenly through the list. Each knowledge need was briefly discussed by the whole group (largely for the benefit of those who had not been in the relevant sessions). Then all participants privately scored each knowledge need between 0 and 10, with 10 being of highest importance, using hand-held electronic voting devices. The workshop facilitators (WJS and LVD) did not vote or score the knowledge needs at any stage. An initial ranking of all knowledge needs was presented to participants at the end of the one-day workshop.

As the final scores are ordinal data, we used medians to rank them. This also reduced the influence of unusually high or low scores from single individuals. The list of priority knowledge needs was initially drawn up as the top 20 knowledge needs according to scoring by practitioners. Taking a cut at the top 20, allowing for ties, included 23 knowledge needs scored by practitioners with a median of 7 or higher. To give scientists an equal hearing, we added to the priority list any knowledge needs scored with a median of 7 or higher by scientists, even if scored lower by practitioners.

During the workshop, all participants were asked to record how many people they had consulted to suggest knowledge needs or to help them with the initial voting stage. At least 293 people were consulted in identifying and voting on the knowledge needs prior to the workshop, in addition to the 46 involved in the process, giving 339 consultees in total.

We used a Friedman test to identify whether any of the knowledge needs were scored significantly differently from others. We used a Multiple Factor Analysis, using the R Package FactomineR [29], to look for differences in scoring patterns between scorers, for all 53 knowledge needs scored in the final session. We also used a Spearman rank correlation test to assess the correlation between practitioner and scientist median scores for each knowledge need. All statistical analyses were carried out using R version 2.15.0 [30].

3. Results and Discussion

Our initial long list comprised 253 knowledge needs. Three were discarded because they were too general or out of scope, and 14 were added after the initial voting stage, due to late submissions. In total 264 knowledge needs fed into the meeting where the final stages of voting and scoring took place.

The knowledge needs were categorized into groups as shown in Table 1.

Five of these categories could be matched to already emerging research priorities at Defra, NERC and BBSRC. These were: nutrients, pest control, landscape-scale planning for sustainable agriculture, farm-scale management of biodiversity and ecosystem services, and markets and drivers. One area identified for research investment by the two research councils as part of a new Sustainable Agriculture Research and Innovation initiative—water—did not emerge as a category of knowledge needs in its own right from this group. However, nine suggested knowledge needs were specific to water, and these were placed in ‘crops’, ‘nutrients’ or ‘farm-scale management of biodiversity and ecosystem services’.

Similarly, twelve questions about adoption of practices by farmers, on-farm economics, use of evidence/decision support and precision agriculture were placed in ‘markets and drivers’, because there were not quite enough of them to warrant their own section, which might have been called ‘farmer adoption’. This made ‘markets and drivers’ the largest section.

We identified 26 priority knowledge needs that met the scoring criteria identified above. These are shown in Table 2. The full list of 53 knowledge needs scored in the final workshop session is given, with scores, in Table S1 (supplementary file).

Table 2. The 26 highest scoring knowledge needs, ranked according to median score (0 = not a priority, 10 = high priority) from practitioners (n = 24). The median scores according to scientists (n = 14) are also given and the overall median from scores across both groups. This list includes the knowledge needs scored with a median of 7.0 or more by either practitioners or scientists. Cutting off at 7.0 gives the top 23 practitioner knowledge needs and the top 14 as scored by scientists. When practitioner medians were equal, knowledge needs are ordered according to overall median, then scientist median score. The sections of the list to which each knowledge need belongs are described in Table 1: C = Crops, Li = Livestock, N = Nutrients, S = Soil, P = Pest control, F = Farm-scale management of biodiversity and ecosystem services, La = Landscape-scale planning for sustainable agriculture, Ma = Markets and Drivers, Mo = Monitoring.

Rank	Number	Knowledge need	List section	Median practitioner score	Median scientist score	Overall median (interquartile range)
1	1	How can we develop a sustainable animal feed strategy?	Li	8.5	7	8 (3.75)
2	2	What are the trade-offs between delivering different ecosystem services (including biodiversity and crop production)?	F	8	8.5	8 (1.75)

Table 2. *Cont.*

Rank	Number	Knowledge need	List section	Median practitioner score	Median scientist score	Overall median (interquar-tile range)
3	3	How can phosphorus be recycled effectively for farming systems?	N	8	7.5	8 (3)
4	4	How can we develop 'multi-functional' land management options to maximise both agricultural productivity and environmental benefits?	La	8	7.5	8 (2)
5	5	What is the smallest set of metrics to evaluate the sustainability (economic, social and environmental) of agricultural systems and interventions at farm and landscape scales?	Mo	8	6	8 (3)
6	6	Can integrated control strategies protect crop yield and quality as the number of available plant protection products falls?	P	8	7	7 (2)
7	7	What metrics define "soil health" and how can we measure this?	S	8	5	7 (3)
8=	8	What is the relationship between soil biodiversity and agricultural production?	S	7.5	7	7 (2)
8=	9	What measures might be adopted to deliver more effective means of marketising ecosystem services (such as auctions) and rewarding land managers for their delivery?	Ma	7.5	7	7 (3.5)
10	10	Assuming a substantial increase in the demand for livestock products, what systems of production, and in which locations, have the least adverse effects?	Li	7.5	6	7 (3)
11	11	Why is there an increasing gap between observed yields and maximum attainable yields in arable systems, and how can this be closed?	C	7	8	7 (2)
12	12	How will climate change affect the suitability, yields and management of crops on which the UK is currently or could become reliant?	C	7	7.5	7 (4)
13=	13	How much further can we increase potential yield and quality of the crops on which the UK is reliant, via whatever technology?	C	7	7	7 (3)
13=	14	How do we best make crop production more water efficient?	C	7	7	7 (2)
15	15	How can we optimise nitrogen inputs for different agricultural systems whilst minimising nitrous oxide emissions?	N	7	6.5	7 (3)

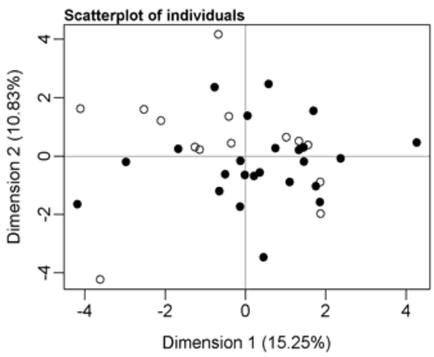
Table 2. *Cont.*

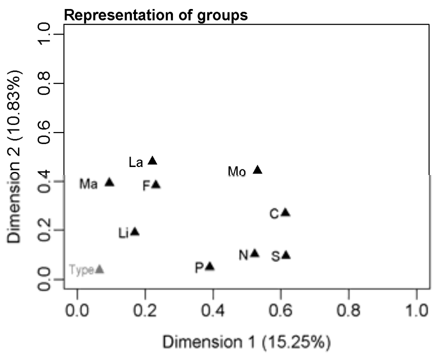
Rank	Number	Knowledge need	List section	Median practitioner score	Median scientist score	Overall median (interquar-tile range)
16	16	What are the relative benefits of changing different management practices (e.g. tillage, cropping system and crop choice) for soil health?	S	7	6	7 (3)
17	17	Which technological advances are most likely to deliver sustainable intensification in the next 10 years?	Ma	7	4.5	7 (3.75)
18	18	How can we economically and efficiently provide sources of livestock feed protein?	Li	7	5	6.5 (3.75)
19	19	Better use of data sets such as yield mapping to enable precision farming methods that target resources (such as nutrients, pesticides or water) to where they are needed	Mo	7	5	6.5 (4)
20	20	What factors control the resistance and resilience of soils to environmental change?	S	7	6	6 (1)
21	21	How could agri-environment scheme options be targeted and adopted at the farm scale to meet shortfalls in ecosystem services underpinning production?	F	7	5.5	6 (3)
22	22	How are we going to reduce losses due to soil-borne pests and diseases in the long-term (for example nematodes in potatoes)?	P	7	5	6 (2.75)
23	23	What would increase the feed conversion efficiency/ratio of ruminants and monogastrics?	Li	7	4	6 (3)
24	24	What are the appropriate scales for managing different ecosystem services?	La	6	7.5	7 (3)
25	25	How can we create a business case for food processors, retailers (as the major buyers) and consumers to financially reward growers for adopting better sustainable methods in conventional agriculture?	Ma	6	7.5	7 (4)
26	26	How can we build more resilient and sustainable agriculture in the face of increasing variability, in terms of market commodity prices and changing climate?	Ma	6	7	7 (3)

A Friedman test found that there were significant differences between the scores given by scientists and practitioners for the 53 different knowledge needs scored at the end of the workshop (Friedman test statistic M = 238.01, $p = 2.2 \times 10^{-16}$). We do not present the results of post-hoc tests to identify where these significant differences lie, because the high number of pair-wise tests required with 53 knowledge needs makes it difficult to assign significance to any differences.

Figure 1 shows the results of our multiple factor analysis. This would reveal differences between individuals in scoring patterns, according to whether they were a scientist or a practitioner, and according to the nine knowledge need categories, which were analysed separately as groups of variables in the analysis. Scorers are plotted according to the first two dimensions generated by the analysis (top panel). This showed no strong difference in scoring pattern between scientists (open circles) and practitioners (closed circles). The percentages of variation explained by each of the first two axes are shown in Figure 1, with a cumulative total of 26.08% explained by these two dimensions. The third dimension, not shown, explained a further 10.62% of the variation. Analyses of variance showed no significant differences between scores of scientists and practitioners on the first, second or third axes (p = 0.123, 0.252 and 0.505 for dimensions 1, 2 and 3 respectively).

Figure 1. Results of Multiple Factor Analysis. Upper panel: Individual scorers plotted in multivariate space according to the first two dimensions. The percentage of variance explained by each dimension is given in brackets. Closed circles (•) = practitioners, open circles (o) = scientists. Lower panel: Groups of knowledge needs corresponding to relevant categories of the list (described in Table 1), each represented as a single point: C = Crops, Li = Livestock, N = Nutrients, S = Soil, P = Pest control, F = Farm-scale management of biodiversity and ecosystem services, La = Landscape-scale planning for sustainable agriculture, Ma = Markets and Drivers, Mo = Monitoring. The grey triangle shows the representation of scorer type (practitioner or scientist).



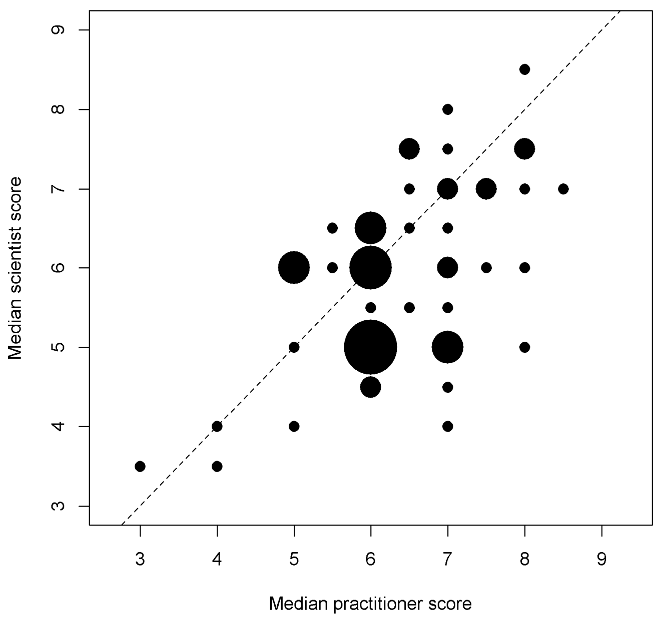


The importance of each category of knowledge need to the classification is plotted in the bottom panel of Figure 1. Monitoring is important to both dimension 1 and dimension 2. Crops, soil, and nutrients are also important in the first dimension, while farm-scale management, landscape-scale planning, markets and drivers were also important in the second dimension. This means there was some evidence that people in the group could be divided primarily according to how they weighted (1) the importance of monitoring, (2) agronomic considerations in agriculture, such as soil condition, plant nutrition and which crops to grow, and (3) issues of biodiversity, ecosystem services and wider drivers of sustainability. It should be noted, however, that most of the variation in scores (74%) is not represented in the first two dimensions, so numerous other factors clearly also influenced the scorers' priorities.

Interestingly, the type of scorer (scientist or practitioner) was relatively unimportant in the first two dimensions. We also ran the multiple factor analysis with the scorers re-categorised as 'business', 'government or NGO' and 'scientist', to see if the practitioner groups separated out. Results were very similar, again with no clear differences between groups.

Figure 2 shows how the practitioner and scientist median scores for all 53 scored knowledge needs were positively correlated (Spearman rank correlation test: $r_s = 0.488$, $p = 0.00021$).

Figure 2. Median scores for each of the 53 knowledge needs given by practitioners (n = 24) and scientists (n = 14); 0 = not a priority, 10 = high priority. Spearman rank correlation coefficient $r_s = 0.488$, $p < 0.001$. Points are sized according to the number of knowledge needs with each combination of scores. The largest circles represent five knowledge needs, the smallest just one. The dashed line shows the identity line where y = x.



3.1. What do the Priorities Tell Us?

Our analysis demonstrates that the practitioners and scientists in this exercise generally agreed on what knowledge is needed, despite coming from a wide variety of backgrounds and knowledge bases.

Many of the knowledge needs (particularly numbers 2, 4, 5, 6, 8, 9, 10, 17, 21, 24 and 26) demand integration of strands of knowledge from different disciplines to inform policy and practice. As argued above, much existing evidence on the environmental sustainability of agriculture focuses on individual environmental outcomes or aspects of land management. The challenge now is to integrate this evidence in a coherent way to inform farm and landscape management. Our exercise demonstrates that this challenge is coming from practitioners in business and government who are trying to implement sustainable agriculture in the real world. There is a need for integrated sets of metrics, understanding of how different aspects of agricultural systems and different environmental services interact, and adequately substantiated modelling tools that allow the results of management decisions to be visualized easily.

The sustainability of livestock systems in a global market is prominent in the priority list. Four knowledge needs relate to it (number 1, 10, 18 and 23 in Table 2), including the highest priority of all. Three of them are concerned with how livestock are fed and where their feed comes from (1, 18 and 23), whilst the other (10) is concerned with where in the world livestock production systems have the least environmental impact. Livestock management is a particularly prominent issue for agricultural sustainability when viewed on a global scale. Global demand for livestock products is increasing, and expected to continue increasing for at least the next three decades [31]. Both demand and production increases in livestock products are expected to derive largely from the developing world, where eating habits and wealth are changing rapidly. The implications of using imported feed products in the UK are also related to land-use change and habitat loss elsewhere in the world.

Seven out of the top 14 priorities had a specific crop- or animal-feed focus (numbers 1, 6, 8, 11, 12, 13 and 14). In general the animal component of livestock systems was not highly ranked, featuring in only knowledge needs 10 and 23. Livestock feed, rather than the animal component, was also the focus of knowledge need 18. The relatively low prioritisation of knowledge needs related to the animal component of livestock systems is perhaps surprising, seeing that the value of the output of the UK livestock sector is about 40% greater than the value of the UK crop sector [32]. In addition, the most recent environmental accounts for UK agriculture [33] are dominated by the negative effects of methane and ammonia emissions, which are largely associated with livestock. There is however, a bias towards crop production systems in the community of publicly-funded research scientists working on environmental aspects of agriculture. Biodiversity and ecosystem services are more thoroughly studied in arable systems [34]. Of the 14 research scientists who took part in the full process, three had specific expertise in crop systems and one in livestock farming, although several had broad interests across farming systems. At least five of the practitioners were primarily interested in the sustainability of livestock, rather than arable or all farming.

Practitioners tended to consider metrics to measure sustainability as more important than did scientists. Two knowledge needs rated with relatively high priority by practitioners (numbers 5 and 7 in Table 2) are concerned with sets of metrics to measure sustainability and soil health respectively. Both were scored lower by scientists. The need for metrics to monitor ecosystem services is widely acknowledged [35,36], and development of globally standardized sustainability metrics for agriculture is currently being discussed [37–39]. Metrics are needed for national-scale reporting, monitoring the success of policy interventions, environmental sustainability programmes in the food and drinks industry and for self-assessment of performance by farmers. Clearly there is specific support for this work from those involved in moving towards more sustainable agriculture within the UK food system. There was good understanding amongst the group that the number of metrics is likely to be reasonably high, given the complexity of agroecosystems. For example, the recent Linking Environment And Farming (LEAF) report, focused on sustainable farming includes 24 objectives [40]. This is why knowledge need 5 refers specifically to identifying the minimum number of metrics needed.

Phosphorus is a greater concern than nitrogen in this set of priorities. Knowledge needs 3 and 15 are the only two from the nutrients category that made it to the priority list. The priority need related to phosphorus is not ‘Where are the supplies going to come from?’ or ‘How much do we have left globally’, or even ‘How can we reduce dependence on phosphorus?’, all of which have been raised in several fora recently [1,41–43]. This group prioritised the knowledge need for practical approaches to recycle phosphorus more effectively in farming systems. One specific example of this—recovering phosphorus from manures—was also raised as a researchable issue by the Feeding for the Future project [26] in the context of new models of integrated mixed farming.

Three of the four priority knowledge needs relating to soil (knowledge needs 7, 16 and 20), are about monitoring and maintaining its natural integrity and fertility, often referred to in policy as ‘soil health’ [44] and its resilience to environmental change.

Soil is the only feature of agro-ecosystems for which this group wanted to know more about the role biodiversity plays in delivering ecosystem services (knowledge need 8). In a previous exercise focused on the conservation of wild insect pollinators [23], understanding the relationship between biodiversity and delivery of the pollination service was the highest priority knowledge need. This was felt to reflect a desire within the group to reconcile new ecosystem service objectives with more traditional objectives to conserve the diversity of species and habitats for their own sake. In the broader context of environmentally sustainable agriculture, protection of farmland biodiversity is often stated as an aim [6], but it seems that the role this biodiversity plays in delivering farm productivity through services other than those related to soil fertility, such as pest control, pollination and water quality, is less of a concern.

There are three knowledge needs at the end of the list which would not have appeared in the top 20 according to scoring by practitioners, but which were scored with medians of seven or higher by scientists. One is about the appropriate scale of management of environmental services (knowledge need 24). Whilst both groups saw a strong need for knowledge about the implications of managing for several different services at once (knowledge needs 2 and 4), scientists saw scale as a stronger component of this than practitioners. Scale is much discussed in the academic and policy communities and known to be very important for understanding and managing trade-offs between ecosystem services [36,45,46]. For example, scale was identified as an important consideration for policy development by a recent stakeholder-led exercise to balance food production and environmental objectives [47].

The opportunities for re-integrating arable and livestock farming at the farm-scale was an issue represented in three separate proposed knowledge needs in the initial long list, but none made it through even to the final scoring session of our workshop. This may reflect the increasingly global nature of food production systems and the economic advantages of specialisation in farm businesses, processing and logistics. The priority questions on livestock feed (1, 18 and 23) are perhaps indicative of the interdependencies between specialist arable and livestock farms on a larger scale than individual farms.

Of the 26 priority knowledge needs in Table 2, six can be matched to one (or in some cases two) of the 100 questions of importance to the future of global agriculture identified by Pretty *et al*. [1]. These are knowledge need numbers 5, 10, 12, 14, 17 and 26. The overlap is small, with less than 25% of our knowledge needs matching the 100 questions. The global agriculture exercise identified questions that, "if addressed, would have a significant impact on global agricultural practices worldwide". Here we prioritised knowledge needs that, if addressed, would enable a move towards more sustainable agriculture for the UK food system. There was a stronger focus on the large-scale commercial production enterprises that dominate the UK food system in the current exercise, as opposed to the low income small-scale agricultural enterprises that dominate global agriculture in terms of numbers of people. The priorities here also reflect the European policy context of the UK food system, with several of our knowledge needs relating specifically to EU policies such as agri-environment schemes (number 21), regulation of plant protection products (number 6) and prominence of the ecosystem services agenda in the European Union (numbers 2, 4, 9, 21 and 24) [45].

3.2. Next Steps

In the next stage of this process, the same group of scientists and practitioners will consider how the priority knowledge needs they have identified can be addressed. We will follow similar methods, working collaboratively with iterated discussions to specify, in detail, what is already known in each area, where the relevant knowledge lies and what steps can be taken within or outside the group to meet the knowledge need cost-effectively. Our aim will be to ensure that knowledge and data from all sectors are taken into account.

The list of knowledge needs includes a range of different types of question and levels of information. Some are scientific questions that require large research programmes. These may need to be unpacked into smaller, more manageable scientific questions.

Aspects of many of the knowledge needs have already been tackled, or are in the process of being answered by existing projects in the UK or internationally. Trade-offs between ecosystem services, for example (knowledge need number 2), are the subject of active on-going research [36]. Here, the need is to review and synthesize existing and emerging knowledge, and make it accessible to an array of users. Other priority knowledge needs may require new standardised data collection, or stakeholder-driven policy development.

Clearly, the priorities that emerge from a process like this depend to an extent on the participants involved. As in previous similar exercises, we made every effort to be as inclusive as possible, and to involve representatives from all sectors, so we suggest that these results reflect a broad range of interests relevant to the implementation of environmentally sustainable agriculture for UK food systems.

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Conflict of Interest

The following authors represented the interests of their organizations in this process. We do not interpret this as a conflict of interest because the process was designed to take account of a wide range of interests, including those of commercial and campaigning organizations.

Angela Booth (AB Agri), Jan Bouwman (Syngenta), Chris Brown (Asda), Ian Crute (AHDB), Frances Dixon (Welsh Government), Caroline Drummond (LEAF), Andrea Graham (National Farmers Union), James Hallett (British Growers Association), Beth Hart (Sainsbury's), John Holland (Game and Wildlife Conservation Trust), Vanessa King (Unilever), Tom MacMillan (Soil Association), Daniel McGonigle (Defra), Carmel McQuaid (Marks and Spencer), Tim Nevard (Conservation Grade), Steve Norman (DowAgro), Catherine Pazderka (British Retail Consortium), Inder Poonaji (Nestle), Duncan Sinclair (Waitrose), Juliet A. Vickery (RSPB) and William Wolmer (Blackmoor Estate).

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