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ORIGINAL RESEARCH

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What agricultural practices are most likely to deliver "sustainable intensification" in the UK?

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Abstract

Sustainable intensification is a process by which agricultural productivity is enhanced whilst also creating environmental and social benefits. We aimed to identify practices likely to deliver sustainable intensification, currently available for UK farms but not yet widely adopted. We compiled a list of 18 farm management practices with the greatest potential to deliver sustainable intensification in the UK, following a well-developed stepwise methodology for identifying priority solutions, using a group decision-making technique with key agricultural experts. The list of priority management practices can provide the focal point of efforts to achieve sustainable intensification of agriculture, as the UK develops post-Brexit agricultural policy, and pursues the second Sustainable Development Goal, which aims to end hunger and promote sustainable agriculture. The practices largely reflect a technological, production-focused view of sustainable intensification, including for example, precision farming and animal health diagnostics, with less emphasis on the social and environmental aspects of sustainability. However, they do reflect an integrated approach to farming, covering many different aspects, from business organization and planning, to soil and crop management, to landscape and nature conservation. For a subset of 10 of the priority practices, we gathered data on the level of existing uptake in English and Welsh farms through a stratified survey in seven focal regions. We find substantial existing uptake of most of the priority practices, indicating that UK farming is an innovative sector. The data identify two specific practices for which uptake is relatively low, but which some UK farmers find appealing and would consider adopting. These practices are: prediction of pest and disease outbreaks, especially for livestock farms; staff training on environmental issues, especially on arable farms.

1 | INTRODUCTION

Sustainable Intensification (SI) is generally considered a process by which agricultural productivity is enhanced without negatively impacting the environment, preferably also creating social and environmental benefits (Gunton, Firbank, Inman, & Winter, 2016; Struik & Kuyper, 2017; Weltin et al., 2018). Developed initially in an African context in the 1990s (Clay, Reardon, & Kangasniemi, 1998; Pretty, 1997; Reardon et al., 1997), the term "sustainable intensification" (SI) has become increasingly popular in scientific and policy discourses. Two reviews by Bernard and Lux (2017) and

Mahon, Crute, Simmons, and Islam (2017) have assessed the prominence of different SI discourses over time. Both reviews highlight the prominence of a productivist lens, in other words, SI aims to increase agricultural production in order to feed a rapidly growing global population. This productivist lens, often described in combination with a desire to increase food security, is noticeable in scientific reports and journal articles, as well as in policy documents released in the last decade (Elliott & Firbank, 2013; Foresight 2011; Franks, 2014; Garnett et al., 2013; Lal, 2016; The Royal Society 2009; Tilman, Balzer, Hill, & Befort, 2011). Major policy initiatives, such as Defra's Sustainable Intensification Research Platform (www.siplatform.org.uk), and a wider Sustainable Intensification Research Network (https://sirn.org.uk) funded by the Biotechnology and Biological Sciences Research Council, have recently explored the potential for SI in the UK and elsewhere.

Over the last two decades, debate has focused on whether SI is an oxymoronic term, or rather whether it represents a useful paradigm shift in global agriculture (Mahon et al., 2017; Rockstrom et al., 2017). Indeed, the critical debate over the usefulness of the term has become so intense that some have questioned whether it is helpful at all in a scientific context (Gunton et al., 2016; Petersen & Snapp, 2015). Much of the research agrees that SI represents a goal rather than a defined aim; something to work towards rather than a set target to be achieved (Godfray, 2015; Gunton et al., 2016; Pretty & Bharucha, 2014; Struik & Kuyper, 2017). Furthermore, the scientific and policy communities generally accept that the aim of SI is to increase production without degrading the natural environment, although many articles suggest that political and social implications need to be more readily discussed (Gunton et al., 2016; Struik & Kuyper, 2017). Struik and Kuyper (2017) argue that SI is better conceived as two separate processes—sustainable intensification of the low input agriculture of the global south, and sustainable de-intensification of the industrialised agriculture of the north. Gunton et al. (2016) suggest the following all-encompassing definition of SI: "changes to a farming system that will maintain or enhance specified kinds of agricultural provisioning while enhancing or maintaining the delivery of a specified range of other ecosystem services measured over a specified area and specified time frame".

Since SI is generally considered to be a goal, rather than a defined aim, methods for achieving it are relatively undefined (Mahon et al., 2017; Petersen & Snapp, 2015; Wezel, Soboksa, McClelland, Delespesse, & Boissau, 2015). In a review of indicators used to measure SI, Mahon et al. (2017) found that many are very loosely defined, which has led to an under-appreciation of social implications, and a lack of specificity over the rationale, scale, and farm type for which SI is proposed. Many research articles on SI have focused on debating the usefulness of the term, and on refining definitions, at the expense of developing a set of SI practices that could lead to practical gains. We do not suggest that there is a set of practices through which SI can solely be achieved, but rather that progress towards realising practical benefits can be made while a concept is evolving (Owens, 2003; Weltin et al., 2018). For example, Weltin et al. (2018) propose an action-oriented conceptual framework to support identification of region-specific SI practices, based on participatory processes.

This paper focuses on the question of how SI may be delivered at farm scale in a UK context. The aim of this exercise was to identify specific practices with potential to deliver SI on UK farms. We aimed to identify practices that are considered feasible, commercially viable, with clear environmental or social benefits combined with improved productivity or profitability, but which are not currently widely practised. In the current national policy context of the re-configuration of UK agricultural policy following exit from the European Union, "sustainable production" that combines improved productivity with environmental enhancement is likely to be a policy goal (Defra 2018). This constitutes SI as we define it, so it is useful to identify a list of practices that could deliver progress towards SI relatively easily. The practices can also be used as part of the UK's effort to achieve the second Sustainable Development Goal, "Zero Hunger". This goal includes a target to "ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems …… and that progressively improve land and soil quality" by 2030 (UN General Assembly 2015).

Some of these identified priority practices have been the focus of research on study farms associated with Defra's Sustainable Intensification Research Platform, and potentially could be promoted or incentivised by government, through new agricultural policy. We hope that our research will stimulate further studies into what SI actually means in terms of farm practice and how it can be delivered.

2 | METHODS

2.1 | Prioritisation

The prioritisation of SI practices was carried out following well-developed methods for collaborative solution scanning and prioritisation (Dicks et al., 2013; Sutherland, Fleishman, Mascia, Pretty, & Rudd, 2011; Sutherland et al., 2014). We describe three stages as follows:

Stage 1: An initial long list of specific practices was drawn up collectively by 45 members of the Sustainable Intensification Research Platform (Defra SIP: www.siplatform.org.uk/). Defra SIP is a multi-partner research programme exploring the opportunities and risks of SI from a range of perspectives and landscape scales across England and Wales, funded by the UK Government's Department for Environment Food and Rural Affairs (Defra) and the Welsh Government. The group of participants, listed in the Appendix, included 21 academic researchers, five research farm managers, nine business representatives, eight Non-Governmental Organisation (NGO) representatives, and two Government representatives (Defra and the Welsh Government). All participants are actively working on aspects of agricultural sustainability. The researchers represented a range of relevant disciplines, including sociology, human geography, economics, engineering, environmental sciences and life sciences (including, for example, ecology, plant genetics, agronomy, animal breeding and nutrition).

Each participant suggested practices that could deliver SI, which was defined as follows: "A change in farm management that improves both farm-scale productivity and the farmed environment. Practices could be neutral for one and beneficial for the other. For example, they might increase yields with no negative environmental or social impact, or reduce pollution with no impact on productivity. Any change in farm management that causes a reduction in productivity, social or environmental status at farm scale is not included." This definition implicitly allows for trade-offs at field scale, within a farm. Such a trade-off happens, for example, if land taken out of production (field-scale loss of yield) generates ecosystem service benefits such as enhanced pollination, which increase yields on the remaining productive land, as demonstrated by Pywell et al. (2015).

The resulting long list was organised under the nine elements of Integrated Farm Management (IFM; as defined by LEAF www.leafuk.org/leaf/farmers/LEAFs_IFM/Whatisifm.eb): Organisation and Planning; Soil Management and Fertility; Crop Health and Protection; Pollution Control and By-Product Management; Animal Husbandry; Energy Efficiency; Water Management; Landscape and Nature Conservation; Community Engagement.

This initial list was then circulated through the networks of the authors listed, using a snowballing process, until three people had returned it without adding any new items. All consultees were invited to add or amend practices on the list. The final list contained 110 practices, among which all nine elements of Integrated Farm Management were represented by between four (Community Engagement) and 23 (Crop Health and Protection) practices.

Stage 2: Forty-one of the initial participants (Table A1) selected their top 10 practices from the long list of 110, using the online survey software Qualtrics. Each was asked to select 10 practices with the maximum potential to deliver SI, being currently feasible to implement on UK farms (i.e. not potential opportunities for the future) but not yet widely adopted, in their opinion or experience. Participants were given complete flexibility over how their top 10 were spread across the IFM elements.

These votes were counted, and the list ranked according to number of votes for each practice. No practices were removed at this stage. Participants were also given a further opportunity to suggest additional practices.

Stage 3: 36 of the initial participants (Table A1) met in a workshop in Cambridge on 21 November 2014. The full list of practices was provided to all participants, printed in rank order according to the number of votes (highest first). New practices added during Stage 2 were also presented for consideration.

Participants were divided into three parallel working groups of 12, each with similar representation of the different sectors (research, Government, NGO, business, farm management). Each group worked independently to identify the 10 options from the long list with the maximum potential to deliver farm-scale SI, with the help of an experienced facilitator who was also a participant, and a rapporteur who was not. The following characteristics of each practice were used by the group to guide discussions and make their judgement:

1. Benefits to productivity (ratio of outputs to inputs); can also be benefits to yield or profitability.
2. Benefits to the environment or socio-economic status of the farm business.
3. Feasibility to implement on commercial farms.
4. Potential for roll-out (i.e. currently available in the UK, but not widely adopted).

Original wording was retained, but alternative wordings or clarifications could be suggested for later discussion by the whole group. During discussions, facilitators suggested that the selected set of priority options should ideally be spread across the nine IFM categories, and continually reminded delegates that none of the priorities should lead to declines in productivity or environment/social benefits.

The votes from stage 2 were used as a guide to help elimination. The process proceeded by first eliminating all those in the list that received 0 or 1 votes in stage 2, then categorising all remaining practices into "yes", "no" or "maybe", according to whether the group felt they should be in the top 10. All 110 items on the list, plus 14 that had been added at stage 2, were given space for discussion as needed. Finally, each group voted by show of hands on the practices labelled "yes". Each participant was allowed 10 votes, and the 10 practices with the most votes comprised the top 10.

In a closing session of the workshop, the three parallel groups came together to discuss any alternative wording suggestions and agree a final list that included any practice selected in the top 10 by any of the groups.

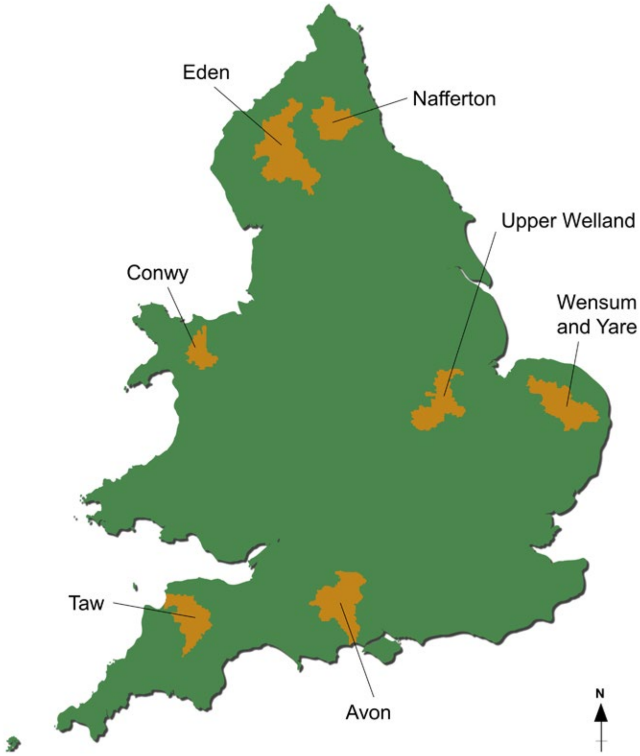

FIGURE 1 Study areas for farm survey

2.2 | Survey of uptake

To test attitudes of farmers towards the priority practices, we included questions in a wider baseline survey conducted in 2015 as part of Defra's Sustainable Intensification Research Platform (Morris, Jarrett, Lobley, Wheeler, 2017). Seven study areas were chosen on the basis of existing research investment in the area, availability of data, potential for building a network of collaborating farmers and stakeholders and link to agricultural research farms (Winter et al., 2014). These areas are not expected to be representative of farming in England and Wales, but they reflect many of the key agricultural land use types and locations (Figure 1).

Using the June Agricultural Survey Register (2013—data provided by Defra and The Welsh Government), farmers grouped by "robust farm type" were selected. Six farm types were chosen (Cereals, Dairy, Lowland Grazing, Less Favoured Areas, Grazing, Mixed, General Cropping), focusing on the farms that covered the vast majority of agricultural land in England and Wales. Together, these farm types represented 96% of all farmland in England, in June 2015 (Defra, 2017). The sample of farms in each survey area was stratified to reflect the main farm types in each area. Any robust farm types accounting for less than 10% of the case study area population were excluded. Farms were selected to give good geographical coverage of each area. In addition, to be included in the sample each holding had to meet the criteria of being a "commercial holding" as well as farming a minimum of 20 ha. Registered holders were sent an opt-out letter giving five working days to opt out of being telephoned to be invited to take part in an interview. 220 farmers (approximately 14% of the original sample) chose to opt out and a further 611 (38%) were uncontactable (including those who never answered the phone or where contact details were incorrect), leaving an effective sample of 782.

As part of the survey, farmers were provided with a list of 10 of the priority practices identified in the workshop, and asked to select from the following options—(a) already practising it, (b) would consider increasing/introducing practice of it, (c) would not consider doing it, (d) not applicable to my farm. A subset of the longer list of 18 SI practices was used for the survey, based on previous experience of conducting farmer interviews, which suggests lists of more than 10 items do not work well in a questionnaire. A sample of 10 of the practices was selected to represent the full range of available IFM elements and a balance across suitable farm types.

As the practices are not equally applicable across different farm types (Table 1), we analysed the data separately for arable farms, and livestock farms, according to the farm type, with farms classed as "mixed" being considered in both groups. We used Pearson chi-squared tests to evaluate whether practices were used, not used or would be considered more than would be expected by chance. Practices with the greatest potential for SI would be those that a larger than expected number of farmers say they would consider, but which a smaller than expected number of farmers are already practising. Analyses were conducted in R version 3.2.2 (R Core Team 2015), using the "vcd" and "vcdExtra" packages (Friendly, 2016; Meyer, Zeileis, & Hornik, 2006).

3 | RESULTS

The 18 priority SI interventions selected by the group are listed in Table 1. This list includes any practice selected in the top 10 by one or more of the workshop groups. Figure 2 shows how the priority practices are distributed among the nine elements of Integrated Farm Management. All except one element—community engagement—are represented by at least one practice, but the focus of these practices is on animal husbandry, crop health and soil.

3.1 | Survey results

From 782 farmers contacted, 244 farmers were interviewed face-to-face for the survey, a response rate of 31.2%.

Table 2 shows the distribution of the 244 farm respondents by robust farm type. Defra's data protection rules prevent us from breaking these numbers into separate study

TABLE 1 Priority practices for Sustainable Intensification (SI). Codes in the final column indicate those 10 practices from the longer list of 18 for which we have survey data. These codes are used in Tables 3 and 4, and Figures 1 and 2

SI practice	Applicability	Integrated Farm Management element	Included in survey data
1. Grow crop varieties with increased tolerance to stresses such as drought, pests or disease	All	Water/Crop health	CropVar
2. Reduce tillage to minimum or no till	Arable only	Soil	Till
3. Incorporate cover crops, green manures and other sources of organic matter to improve soil structure	Arable only	Soil	Soil OM
4. Improve animal nutrition to optimise productivity (and quality) and reduce the environmental footprint of livestock systems	Livestock only	Animal husbandry	Animal Nutrition
5. Reseed pasture for improved sward nutrient value and/or diversity	Livestock only	Animal husbandry	Reseed Pasture
6. Predict disease and pest outbreaks using weather and satellite data, and use this information to optimise inputs	All	Husbandry/Crop health	Predict Pests
7. Adopt precision farming: using the latest technology (e.g. GPS) to target delivery of inputs (water, seeds, pesticides, fertilisers, livestock manures)	All	Water/Crop health/Soil/Pollution control	Precision Farming
8. Monitor and control on-farm energy use	All	Energy efficiency	Energy Use
9. Improve the use of agriculturally marginal land for natural habitats to provide benefits such as soil improvement, pollution control or pollination, and allow wildlife to thrive	All	Landscape & nature	Natural Habitats
10. Provide training for farm staff on how to improve sustainability/environmental performance	All	Organisation & planning	Staff training
11. Use soil and plant analysis with technology to use fertiliser more efficiently	All	Pollution control	
12. Plant legumes—includes peas and beans, for forage and other products	All	Soil	
13. Use animal health diagnostics to enhance livestock productivity and animal welfare	Livestock	Animal husbandry	
14. Keep more productive/prolific livestock—genetics, breeding technologies (Essential Breeding Values, Artificial Insemination, Embryo Transfer)	Livestock	Animal husbandry	
15. Controlled traffic farming to minimise soil compaction and energy use	All	Soil	
16. Reduce the risks associated with pesticide use by adopting IPM techniques	All	Crop health/Husbandry	
17. Optimise grazing management to reduce bought-in feeds and increase nitrogen use efficiency	Livestock	Husbandry/Pollution control	
18. Benchmarking of environmental, in addition to financial, performance	All	Organisation & planning	

areas, as some farms could potentially be identifiable, with fewer than five farms of that type in an area. This is because each study area has a preponderance of particular farm types. For example, Eden and Henfaes and Conwy have mostly livestock farms, while the Morley and Wensum area has mostly arable. This results in a strong statistical association between study area and farm type ($\chi^2 = 277.32$, $p = 9.999 \times 10^{-5}$, using Monte Carlo simulation). Analysis of farm types in the sample compared to data in the Defra June Survey of Agriculture and Horticulture indicates that, with very few exceptions, the respondents are broadly representative of their study area in terms of farm type (Morris, Jarrett, et al. 2017).

Responses to the question on uptake of practices are shown in Tables 3 and 4. The practices differ in their applicability to different farm types (as shown in the "Applicability" column in Table 1), so we summarise the data separately for

TABLE 2 Number of surveyed farms classified in each farm type according to the June Agricultural Survey Register (2013)

Farm type	Classification for practices uptake data	Number of farms
Less Favoured Area grazing	Livestock	71
Lowland grazing	Livestock	59
Dairy	Livestock	18
Mixed	Livestock and arable	17
General cropping	Arable	16
Cereals	Arable	62
Other	Excluded	1
Total		244

livestock (Table 3) and arable (Table 4) farms. Mixed farms are included in both groups, while the single farm categorised as "other" is excluded from further analysis.

Farm type classification is based on the predominant enterprise types within a farm business (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/365564/fbs-uk-farmclassification-2014-21oct14.pdf). It does not mean for example, that all Cereals farms exclude livestock. While practices may be classified as "Arable only" and "Livestock only" (Table 1), the potential applicability of these practices to individual farms of a particular type will differ, depending upon the enterprise scale and importance relative to each overall farm business. For example, 42.1% of farmers whose holdings were classified as livestock (Table 3) said they were using, or would consider using minimum or no-tillage (intervention: Till). Conversely, 55.8% of farmers whose holdings were classed as arable (Table 4) said they were re-seeding pasture, or would consider doing so. These are much higher percentages than the proportion of those farms that was classified as "mixed" in the livestock and arable groups (17/165 = 10.3%; 17/95 = 17.8% respectively). These results indicate the range of enterprise types within real farm businesses. Hence, we consider the full set of 10 interventions for both livestock and arable farms in the remaining analysis.

TABLE 3 Uptake of 10 priority Sustainable Intensification practices on 165 livestock or mixed farms in England and Wales. Number of farmers is shown, with proportions of all farmers for each practice in brackets

Practice	Using (%)	Would consider (%)	Would not consider (%)	Not applicable (%)	Total
CropVar	46 (27.9)	27 (16.4)	13 (7.9)	79 (47.9)	165
Till	41 (25.0)	28 (17.1)	19 (11.6)	76 (46.3)	164
SoilOM	65 (39.6)	21 (12.8)	18 (11.0)	60 (36.6)	164
AnimalNutrition	120 (72.7)	24 (14.5)	14 (8.5)	7 (4.2)	165
ReseedPasture	115 (69.7)	25 (15.2)	18 (10.9)	7 (4.2)	165
PredictPests	23 (14.1)	46 (28.2)	46 (28.2)	48 (29.4)	163
PrecisionFarming	32 (19.4)	51 (30.9)	38 (23.0)	44 (26.7)	165
EnergyUse	62 (37.6)	42 (25.5)	29 (17.6)	32 (19.4)	165
NaturalHabitats	125 (75.8)	21 (12.7)	12 (7.3)	7 (4.2)	165
StaffTraining	23 (14.1)	21 (12.9)	18 (11.0)	101 (62.0)	163

TABLE 4 Uptake of 10 priority Sustainable Intensification practices on 95 arable or mixed farms in England and Wales. Number of farmers is shown, with proportions of all farmers for each practice in brackets

Practice	Using (%)	Would consider (%)	Would not consider (%)	Not applicable (%)	Total
CropVar	70 (74.5)	19 (20.2)	3 (3.2)	2 (2.1)	94
Till	76 (80.9)	7 (7.5)	5 (5.3)	6 (6.4)	94
SoilOM	57 (60.0)	27 (28.4)	8 (8.4)	3 (3.2)	95
AnimalNutrition	36 (37.9)	10 (10.5)	8 (8.4)	41 (43.2)	95
ReseedPasture	45 (47.4)	8 (8.4)	19 (20.0)	23 (24.2)	95
PredictPests	52 (54.7)	23 (24.2)	16 (16.8)	4 (4.2)	95
PrecisionFarming	48 (50.5)	30 (31.6)	8 (8.4)	9 (9.5)	95
EnergyUse	55 (57.9)	19 (20.0)	12 (12.6)	9 (9.5)	95
NaturalHabitats	82 (86.3)	6 (6.3)	3 (3.2)	4 (4.2)	95
StaffTraining	27 (28.7)	23 (24.5)	9 (9.6)	35 (37.2)	94

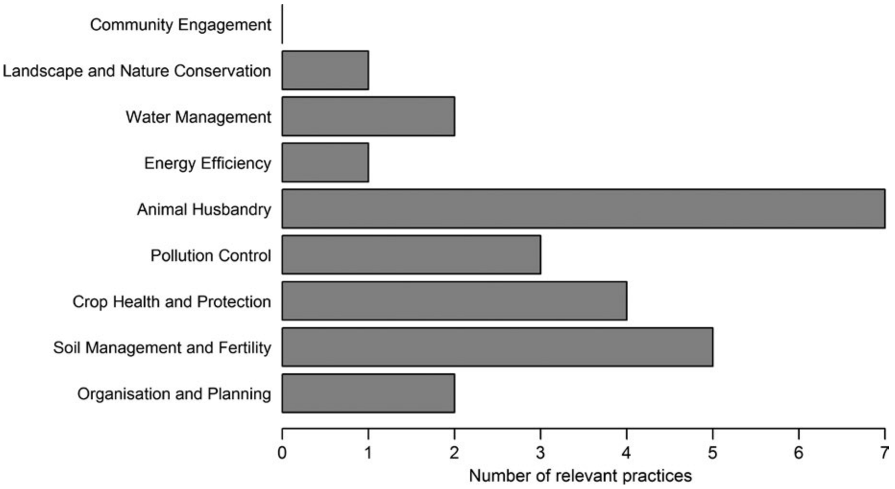

FIGURE 2 Distribution of priority SI practices among the nine elements of Integrated Farm Management. Some practices apply to more than one element, as shown in Table1

Pearson chi-squared tests on the data presented in Tables 3 and 4, excluding the "not applicable" answers, showed that among farmers who thought the practice was applicable on their farm, almost all practices were used significantly more, less, or both more and less, than would be expected by chance, at a significance level of $\alpha = 0.05$ (Table 5). These patterns are presented graphically in Figure 3, which illustrates how the proportions of each answer differed from expected values for each practice, if the farmers answered the question randomly.

Figure 3 shows a general pattern of more uptake than expected by chance across the practices. For arable farms, nine of the 10 practices were practiced substantially more than expected, as shown by the large, positive residual bars. The most widely used practices were "Grow crop varieties with increased tolerance…" and "Reduce tillage to minimum or no till" among arable farmers; "Improve animal nutrition" and "Reseed pasture" among livestock farmers, and "Improve the use of agriculturally marginal land for natural habitats" across all the farm types in the survey.

Only two practices were reported as "already in use" less than expected by chance—"Predict disease and pest outbreaks" and "Adopt precision farming"—both on livestock farms, and this was only significantly different from random for the former.

4 | DISCUSSION

In this paper, we present a set of priority practices at farm scale that could be targeted to promote sustainable intensification (SI) in UK farms. They were selected by a mixed group of 45 stakeholders, following a rigorous prioritisation process, based on standard methods to reduce bias and give each individual an equivalent voice.

Looking across the whole set of 18 practices, they cover most elements of Integrated Farm Management (Figure 2), but with a greater focus on crops, animals, soil and inputs, than on other elements. Only one element—community engagement—did not emerge at all in the priority practices. There were practices in the original long list related to this element, including "Hold public engagement activities", "Provide educational opportunities to schools and colleges" and "Maintain public rights of way", but these were not prioritised as practices with high potential for SI. The focus on productivity-related elements, with less focus on social and environmental elements, reflects the productivist lens through which SI is usually understood.

Technological solutions feature highly across the priority interventions, whereas only one of the 18 relates to natural habitats, wildlife or ecosystem services, although there were many such practices in the original long list. For example, "Wildflower strips", "Grass margins or beetle banks for pest control", and "Reduce cutting of hedgerows" were all ultimately

TABLE 5 Results of Pearson's Chi Squared tests on each practice and farm type. Answers were significantly different from random for all but two of the practices—PrecisionFarming and StaffTraining on Livestock farms. These insignificant test results are shown in italics

	Livestock/mixed farms		Arable/mixed farms	
Practice	χ^2	*p*-value	χ^2	*p*-value
CropVar	19.14	0.000	79.85	0.000
Till	8.34	0.015	111.43	0.000
SoilOM	39.94	0.000	39.80	0.000
AnimalNutrition	130.08	0.000	27.11	0.000
ReseedPasture	111.13	0.000	30.08	0.000
PredictPests	9.20	0.010	24.02	0.000
PrecisionFarming	*4.68*	*0.096*	28.00	0.000
EnergyUse	12.47	0.002	37.14	0.000
NaturalHabitats	149.78	0.000	132.15	0.000
StaffTraining	*0.61*	*0.736*	9.08	0.011

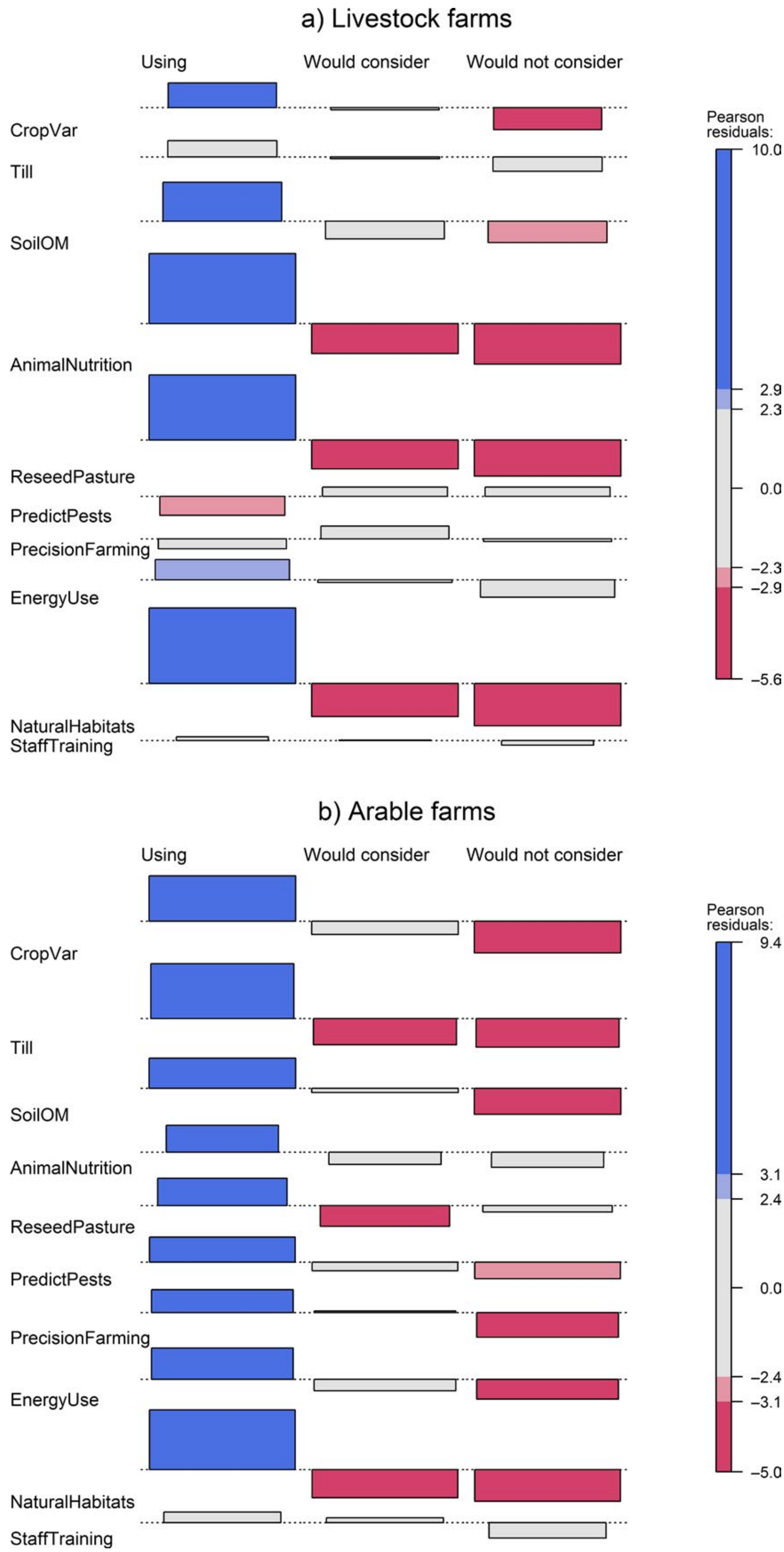

FIGURE 3 Visualization of contingency tables for each practice, showing the survey responses for (a) dairy, lowland grazing, Less Favoured Area grazing or mixed farms and (b) general cropping, cereals or mixed farms. Each plot indicates deviations from the expected values, if there was no preference for any answer. Shading indicates residuals based on Pearson's chi-squared tests conducted for each practice separately (see Table 5 for test results). Each rectangle has (signed) height proportional to the residual and width proportional to the square root of the expected counts, so that the area of the box is proportional to the difference in observed and expected frequencies. The dotted baseline for each practice represents zero residual, where the number of respondents matched the expected value. Practice labels are aligned with their lowest residual value

rejected by the groups. The dominance of technology may partly reflect the composition of the stakeholder group, and the prominence of the "Agri-tech" agenda being promoted by the UK government at the time of the workshop. However, technology has been seen as crucial to SI at least since the Royal Society report in 2009 (The Royal Society 2009). The report notes, for example, that SI: "… requires technologies and approaches that are underpinned by good science. Some of these technologies build on existing knowledge, while others are completely radical approaches, drawing on genomics and high-throughput analysis.", setting the scene for much of the discussion and research investment around SI that has followed.

Our 18 priority practices correspond well to Weltin et al.'s (2018) "agronomic development" and "resource use efficiency" fields of action for SI, those relevant at farm, rather than regional/landscape scale. Almost all the SI approaches defined by Weltin et al. in these areas are represented in our set of practices, with the exception of biotechnology and genetic engineering. Since Weltin et al.'s framework was based on a systematic literature review of 349 papers, over 20 years of research, this fit to their framework adds considerable strength to our set of priority practices.

It is likely that a different group of stakeholders would select a slightly different set of priority practices, but we made a concerted effort to represent a wide range of different viewpoints and expertise, and for many of the practices there was strong agreement. This is illustrated by the fact that only 18 priority practices emerged when three separate groups selected their top 10 in the workshop, indicating substantial overlap between the groups.

4.1 | On the uptake of 10 selected SI interventions

The most surprising point about the data on uptake of the 10 selected practices is how widely practiced they seem to be in the study areas, given that they were selected as practices thought to be "currently available in the UK, but not widely adopted" (Criterion (iv) used during the process). Seven of the 10 practices were already being used by more than half the surveyed arable farmers (Table 4), and seven of the 10 practices were already being used by one quarter or more of the livestock farmers (Table 3). The most widely used practice was actively managing natural habitats on marginal land for wildlife or ecosystem service benefits (used by 76% of livestock farmers, 86% of arable farmers in England and Wales). Minimum or no till agriculture was used by 81% of arable farmers (Table 4), while 73% of livestock farmers said they were improving animal nutrition to optimise productivity and reduce the environmental footprint of livestock systems (Table 3).

The recent history of these practices clearly has a role in explaining their level of uptake. Practices with higher uptake rates such as reduced tillage have been advocated for decades (e.g., a range of industry reports since 2002 advocating reduced tillage are cited in Townsend, Ramsden, & Wilson, 2016), whereas precision farming and predicting pest and disease outbreaks rely on big data and could be considered more recently available to farm businesses.

There is support from elsewhere for high uptake of at least some of these practices. In a recent survey of 271 farmers from seven European countries, including 20 UK farms (Kernecker, Knierim, & Wurbs, 2017), 77% of farmers said they experimented on their farms. Cover cropping, including green manure, trying new crop varieties and rotations and testing new cultivation techniques, including tillage and soil management methods, were frequently mentioned among experiments being conducted. These authors classed 130 (48%) of the 271 farmers surveyed across seven European countries as "adopters" of Smart Farming Technologies (explicitly including precision agriculture), based on their attitudes and preferences, although the proportion of adopters varied by country. This is not dissimilar from the uptake rate for precision farming reported for arable farms here (51%, Table 4). These findings support the survey results here, in indicating that European and UK farmers are innovative and keen to adopt new practices to improve sustainability and productivity.

Estimates from the Defra-funded Farm Business Survey in England (specifically the Fertiliser Usage module capturing data on 1329 farm businesses in 2015/16 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/612286/fbs-fertiliseruse-statsnotice-04may17.pdf]) also provide some support for the uptake rates in our survey, although tend to be lower. They show that 21% of farmers carried out some form of precision agriculture, with 23% using soil nutrient software packages to determine fertiliser application rates. This compares with 19% and 51% of livestock and arable farmers, respectively, in our survey using precision farming. In relation to livestock farming, 58% of farm businesses had temporary and/or permanent grass, which included clover or legumes in grass swards, with 63% of farmers adjusting fertiliser application rates to account for the nitrogen fixation within these swards. These proportions are relatively close to the 70% of livestock farmers in our survey who said they already "Reseed pasture for improved sward nutrient value and/or diversity".

There are, however, at least three reasons why our survey might have over-estimated the UK-wide uptake of the practices identified. One possible explanation for the apparent high uptake of some practices is that the descriptions of them were too broad or generic, encompassing a spectrum of practices, with some farmers remaining close to conventional practice and others at the technological frontier. There is no doubt that interpretations of most of the practices vary among farmers and researchers. Care was taken when designing the survey to use farmer-friendly language, and this included piloting the survey within the farming community (Morris, Jarrett, et al. 2017). Even so, it is almost impossible to communicate complex actions in clear concise wording that can only be interpreted a single way. The interpretations of farmers may thus not reflect the practice that was considered by the group not to be widely adopted. For example, minimum till agriculture is widely adopted, whereas no till agriculture is less widely adopted in the UK, yet the wording "Reduce tillage to minimum or no till" (Table 1) does not distinguish between these and so the data do not separate them. Data on tillage practices in winter wheat grown across England, collected as part of the Crop Monitor project (Fera Science Ltd 2018) show that only 46% of this crop by area was established using reduced tillage methods in 2015, with 41% using reduced cultivation and 5% direct drilled, with no tillage. Townsend et al. (2016) also estimated that 46% of English arable farmers use some form of reduced tillage. The farmers who said they use reduced tillage methods in our survey could have been using them experimentally, on a single field or a small proportion of their land.

Similarly, "Improve the use of agriculturally marginal land for natural habitats to provide benefits such as soil improvement, pollution control or pollination, and allow wildlife to thrive" is a broad statement that encompasses a range of possible approaches (Table 1). The focus of discussion at the workshop was on selecting marginal land for wildlife, with a view to enhancing production-related ecosystem services, thereby optimising productivity as part of the habitat management process (Bommarco, Kleijn, & Potts, 2013; Power, 2010; Pywell et al., 2015). However, the final wording of the practice does not capture this nuance particularly well. As written, it could easily be interpreted more broadly, as simply providing natural habitat for wildlife, which many UK farmers are doing voluntarily under agri-environment schemes such as Entry Level Stewardship. In 2015, when the survey took place, 57% of all English farmland was under Entry Level Stewardship (calculated using the total area of farmland from the June Agriculture Survey (Department for Agriculture, 2017), and the area under Entry Level Stewardship from the UK Biodiversity indicator on agri-environment scheme uptake (JNCC 2018)).

In both examples, more explicit answer options would be needed to establish what respondents had understood each intervention to mean. In the case of the practice related to natural habitats, where motivations for the action are also important, qualitative or semi-structured interviews might also be necessary. Were the farmers managing natural habitat as an active element of farming for ecosystem service delivery, as implied under ecological intensification, or more passively, in response to voluntary government incentives providing additional income at low cost? Previous studies on the motivations of farmers to take up agri-environment schemes or environmental management have repeatedly demonstrated that farmer attitudes to the environment and wildlife, along with utilitarian motivations, such as payment rate and ease of fit within existing farm practice, are important in explaining uptake of environmental measures (Defrancesco, Gatto, Runge, & Trestini, 2008; Sattler & Nagel, 2010; Sutherland, 2010). This evidence tends to support the view that the practice of maintaining natural habitats is widely used for other reasons than the way it was intended here, when selected as a priority practice for SI.

In another example, there might be highly variable opinions as to what precision agriculture entails, ranging from a £700 Geographical Positioning System aid, to a large machine auto-guidance system giving variable rates of input. Kernecker et al. (2017) found a range of interpretations among European farmers for what are considered "Smart Farming Technologies", from real time diagnostics using drones or satellites to improvements in irrigation technology.

A second, alternative interpretation to explain why practices considered not widely adopted by this group of stakeholders turned out to be widely adopted by this set of farmers, is that the stakeholders were not well informed. Perhaps our results represent a disconnect between the world of agricultural research and the actual business of farming, or an exaggeration in the perception of farmers' reluctance to take up new practices. Poor links between research and practice in UK farming were recently identified as an issue by Rose et al. (2018). It should not be the case for the process reported here, since the group who proposed and selected the practices (Table A1) included several people directly involved in managing farms or providing farm advice, and many others whose day-to-day research work is deeply embedded with agricultural industry.

Conversely, it is possible that the high uptake of innovative SI practices in our dataset reflects particularly good links between research and farm practice in our study areas. These seven areas were chosen on the basis of having local research farms and/or well-connected farmer-stakeholder networks. However, the datasets discussed above imply that at least some of these practices are widely adopted across England and Wales.

A third plausible explanation for reported high uptake rates is that the farmers responding to our survey were a biased, self-selected set of farmers interested in, and enthusiastic about, SI. There is some evidence to suggest this is not the case. The surveyed farmers were also asked questions about their understanding and level of engagement with SI (discussed in Morris, Fish, Winter, and Lobley 2017). Many showed very low awareness and poor understanding of the concept, indicating they are not a self-selected group of farmers engaging with sustainability issues. Coupled with the high uptake figures for the priority practices reported here, this raises a question about whether the concept itself matters, when the farming community is innovating to improve productivity and social and environmental benefits anyway.

If the greatest potential for SI is reflected by a larger than expected number of farmers saying they would consider a particular practice, then "Predict pest and disease outbreaks" on livestock farms, and "Provide training for farm staff on how to improve sustainability/environmental performance" on arable farms are where efforts should be focused to enable innovation. However, although statistically significant, the positive residuals are relatively small in both cases (Figure 3), so no practice shows very high potential for rapid increases in uptake on this basis. Also, this conclusion makes the implicit assumption that stated intentions can predict actual future behaviour, which is known not always to be true.

"Predict pest and disease outbreaks" is also in current use on livestock farms less than would be expected by chance, potentially making a stronger case for it to be prioritised for promotion. The same is not true for staff training on arable farms, which is already used slightly more than expected.

For predicting pests and diseases, some kind of decision support tool is likely to be required. As examples, online tools are available for both arable and livestock farmers in the UK to support decision-making around disease and pest control, based on monitoring and forecasting of current problems (https://cereals.ahdb.org.uk/monitoring.aspx; http://www.nadis.org.uk/).

Rose et al. (2016) recently described 15 factors influencing the uptake and use of decision support tools by UK farmers and farm advisers. The factors include cost, ease of use, performance, peer recommendation and level of marketing. Any, several, or all of these factors could explain the difference in use of pest/disease prediction between arable and livestock farms in our survey (Figure 3).

The majority of farmers in our survey do not train staff on how to improve sustainability or environmental performance. Indeed, most (62% of livestock farms and 37% of arable farms) saw this practice as "not applicable". For some farms, this could be because they have very few, if any, staff. It could also be because the focus of training is on compliance with legislation, and environmental training is not an obligation, therefore not considered a priority. This is a concern, because SI is a knowledge- and data-intensive process (Rural Investment Report for Europe (RISE) 2014). Experiential knowledge and training are crucial to promulgating its practice in the farming industry, and both have been shown to improve the implementation of environmental measures on farms (Lobley, Saratsi, Winter, & Bullock, 2013; McCracken et al., 2015; Waddington et al., 2014). We suggest that policymakers keen to enable SI consider ways to encourage or incentivise sustainability training for farm staff.

In summary, this set of priority practices for SI provides policy makers, researchers and farmers with a starting point for thinking about how to implement SI in practice. It does not represent a blueprint for a SI strategy, because different sets of practices are appropriate for different production systems, and another set of stakeholders, at a different time, would be likely to have chosen a different set. However, together with data on uptake on existing farms, this can provide some strategic guidance on which practices might be useful to promote through education, awareness-raising and incentives.

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APPENDIX

List of participants and their roles in the prioritisation process

Table A1 "Sector" column indicates the type of organisation each participant represents. "Role" column indicates whether the participant took part in stage 1 (initial listing, including consultation with wider networks), stage 2 (online voting for top 10) and/or stage 3 (prioritisation down to top 18 at workshop)

First name	Last name	Affiliation	Sector	Role
Frederic	Ang	University of Reading	Research	1, 2, 3
Stephen	Aston	Defra	Government	1, 2, 3
Nick	Birch	James Hutton Institute	Research	1, 2, 3
Nigel	Boatman	FERA	Research	1, 2, 3
Liz	Bowles	Soil Association	NGO	1, 2, 3
Gillian	Butler	University of Newcastle	Research	1, 2
David	Chadwick	Bangor University	Research	1, 2, 3
Lynn	Dicks	University of Cambridge	Research	1, 2, 3
Alex	Dinsdale	URSULA agriculture	Business	1, 2, 3
Sam	Durham	National Farmers' Union	NGO	1, 3
John	Elliott	ADAS	Business	1, 2, 3
Leslie	Firbank	University of Leeds	Research	1, 2, 3
Andrea	Graham	National Farmers' Union	NGO	1, 2
	Anonymous	CN Seeds Ltd	Business	1, 2
Phil	Howell	NIAB	Research	1, 2
Stephen	Humphreys	Bayer	Business	1, 2, 3

(Continues)

TABLE A1 (Continued)

First name	Last name	Affiliation	Sector	Role
Phil	Jarvis	GWCT/Allerton	NGO	1, 2, 3
Dewi	Jones	Welsh Government	Government	1, 2, 3
Daniel	Kindred	ADAS	Business	1, 2, 3
Stuart	Knight	NIAB	Research	1, 2, 3
Alastair	Leake	GWCT/Allerton Project	Farming	1, 2
Michael	Lee	Rothamsted Research: North Wyke and the University of Bristol	Research	1, 2, 3
Carlo	Leifert	University of Newcastle	Research	1, 2, 3
Kim	Matthews	AHDB Beef and Lamb	Business	1, 2, 3
Alice	Midmer	LEAF	NGO	1, 2, 3
Mark	Moore	Agco	Business	1, 2, 3
Simon	Mortimer	University of Reading	Research	1, 2, 3
Thomas Charles	Murray	Harper Adams	Research	1, 3
Keith	Norman	Velcourt	Business	1, 2, 3
Stephen	Ramsden	University of Nottingham	Research	1, 2, 3
Dave	Roberts	SRUC	Research	1, 2, 3
David	Rose	University of Cambridge	Research	1
Laurence	Smith	Organic Research Centre	Research	1, 3
Richard	Soffe	Duchy College	Research	1, 2, 3
Chris	Stoate	GWCT/Allerton	Farming	1, 2, 3
William	Sutherland	University of Cambridge	Research	1, 2, 3
Bryony	Taylor	CABI	NGO	1, 2, 3
Richard	Tiffin	University of Reading	Research	1, 2
Dave	Tinker	IAgrE	NGO	1, 2, 3
Mark	Topliff	AHDB	NGO	1, 2, 3
Susan	Twining	ADAS	Business	1, 2
John	Wallace	Morley Farm	Farming	1, 2, 3
David	Watson	Newcastle University Farm	Farming	1, 2
Prysor	Williams	Bangor University	Research/Farming	1, 2, 3
Paul	Wilson	University of Nottingham	Research	1, 2, 3