Identifying the drivers and constraints to adoption of IPM amongst arable farmers in the UK and Ireland

Research Article

Received: 24 September 2020 Revised: 12 April 2021 Accepted article published: 2 May 2021 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/ps.6452

Identifying the drivers and constraints to adoption of IPM among arable farmers in the UK and Ireland

Henry E Creissen,[a*] Philip J Jones,[b] Richard B Tranter,[b] Robbie D Girling,[c] Stephen Jess,[d] Fiona J Burnett,[a] Michael Gaffney,[e] Fiona S Thorne[f] and Steven Kildea[g]

Abstract

BACKGROUND: Arable crops in temperate climatic regions such as the UK and Ireland are subject to a multitude of pests (weeds, diseases and vertebrate/invertebrate pests) that can negatively impact productivity if not properly managed. Integrated pest management (IPM) is widely promoted as a sustainable approach to pest management, yet there are few recent studies assessing adoption levels and factors influencing this in arable cropping systems in the UK and Ireland. This study used an extensive farmer survey to address both these issues.

RESULTS: Adoption levels of various IPM practices varied across the sample depending on a range of factors relating to both farm and farmer characteristics. Positive relationships were observed between IPM adoption and farmed area, and familiarity with IPM. Choice of pest control information sources was also found to be influential on farmer familiarity with IPM, with those who were proactive in seeking information from impartial sources being more engaged and reporting higher levels of adoption.

CONCLUSION: Policies that encourage farmers to greater levels of engagement with their pest management issues and more proactive information seeking, such as through advisory professionals, more experienced peers through crop walks, open days and discussion groups should be strongly encouraged.

Supporting information may be found in the online version of this article.

Keywords: integrated pest management; IPM metric; sustainable agriculture; arable farming; farmer survey

1 INTRODUCTION

Integrated Pest Management (IPM) is a holistic approach to managing pests that combines biological, cultural and physical techniques to minimize agrochemical use and so mitigate health and environmental risks, as well as potentially reducing costs.[1] IPM can potentially reduce the need for pesticides through the additive benefits that occur when multiple alterative pest control measures are combined. Several European studies have shown that IPM can reduce reliance on conventional pesticides while maintaining crop yields and profitability.[2–5] IPM adoption is widely accepted as being crucial for the sustainability of crop production in Europe and consequently it has been written into European policy.[1] While several studies have suggested that IPM may lead to a reduction in crop productivity and profitability,[6–8] the weight of empirical evidence suggests that careful application of IPM practices can be a viable way to prevent the overuse and unnecessary application of pesticides without incurring significant yield losses.[2–5]

Arable crops in the UK and Ireland are amongst the most intensively managed in Europe in relation to pesticide use, with farmers

* *Correspondence to: HE Creissen, Scotland's Rural College (SRUC), Peter Wilson Building, Kings Buildings, West Mains Road, Edinburgh EH9 3JG, UK. E-mail: henry.creissen@sruc.ac.uk*

a *Department of Agriculture, Horticulture and Engineering Sciences, Scotland's Rural College, Edinburgh, UK*

b *Centre for Agricultural Strategy, School of Agriculture, Policy and Development, University of Reading, Reading, UK*

c *Centre for Agri-Environmental Research, School of Agriculture, Policy and Development, University of Reading, Reading, UK*

d *Agri-Food Sciences Division, Agri-Food and Biosciences Institute, Belfast, UK*

e *Horticultural Development Department, Teagasc, Ashtown, Dublin, Ireland*

f *Agricultural Economics and Farm Surveys Department, Teagasc, Ashtown, Dublin, Ireland*

g *Crop Science Department, Teagasc Oak Park Crops Research Centre, Carlow, Ireland*

applying, on average, more than triple the amount used elsewhere in other European countries.[9] Due to the increasing problem of pesticide resistance, combined with loss of active ingredients, the need for higher levels of IPM uptake is ever more important if these production systems are to remain viable. It is therefore imperative that the drivers and barriers to IPM uptake in these arable systems are well understood. The first steps in the process are to ensure levels of IPM practices are reliably measured. Creissen *et al.*[10] report the development of an IPM metric to quantify the level of uptake of IPM by arable farmers, accounting for individual differences in approach to pest management, in temperate arable farming systems. The construction of this metric involved first the identification of pest control practices that could be identified with IPM through stakeholder engagement and farmer surveys (see Methodology section below).

Using the novel composite IPM metric developed, which differs from previously reported single activities that are generally used as proxies for IPM,[11–14] Creissen *et al.*[10] observed considerable differences in level of IPM adoption within the arable farming communities in the UK and Ireland. Although all of the farms surveyed had adopted some IPM measures, there were a range of scores, from 33 to 91 on the metric's 100-point scale, with only 15 of 225 farmers surveyed achieving more than 85% of the maximum possible score.[10] This range in the level of IPM adoption was anticipated, because IPM measures are all individually viable, allowing farmers to adopt them in an *ad hoc* fashion, or in a step-wise fashion over space and time when consciously pursuing IPM.[15] Similar levels of IPM adoption were recently identified by Sterio *et al.*[16] amongst Norwegian arable farmers using a slightly different approach to capture IPM levels. Irrespective of measurement method both studies clearly demonstrate that there is scope to increase levels of IPM adoption in arable cropping systems. However, while both studies can be used to identify the different components of IPM that need to be improved, both stopped short of identifying factors that influence, either positively or negatively, levels of adoption.

IPM is a knowledge-intensive process in which farmers are able to select from a range of scientifically-proven measures to counter specific pest challenges, that are technically feasible and which meet the multiple objectives of maintaining crop productivity, profitability and reducing environmental impacts.[17] It is reasonable to assume, therefore, that farmers will need to develop a relatively high level of understanding of IPM, or have access to such knowledge, before high levels of IPM adoption could be achieved. As farmer information-seeking behavior and, in particular, engagement with experts, has been shown to increase technology adoption in other areas of farm management, it is likely that the same factors will be influential in determining enhanced adoption of IPM.[18–21]

In the European Union context, drivers of the uptake of IPM are multifactorial and can be found in the areas of: agronomy, for example, increased resistance of pests to agrochemicals; the market, for example, consumer demand for sustainably produced food; and policy, for example, national and EU environmental regulation. In 2009 the EU set rules for the sustainable use of pesticides (Directive 2009/128/ European Commission, 2009).[1] As a requirement of this Directive, all countries must create an IPM program, known as a national action plan (NAP), in which objectives are set to reduce risks associated with pesticide usage. As part of each NAP, national targets relating to IPM adoption and a reduction in pesticide usage should be set, and progress towards these targets monitored.[12] However, EU member states differ in their national approaches to encouraging IPM uptake and reducing pesticide usage. For example, the UK has no mandatory IPM goals, but has instead adopted a largely voluntary approach to encouraging its use.[22] Ireland has a mandatory IPM record sheet which all professional pesticide users must complete.[23] Germany has adopted a voluntary-incentive approach, offering farmers payments for adopting IPM measures.[24] Denmark has adopted a taxation-based approach, where farmers are penalized with tax increases if their practices result in a high estimated pesticide load.[25]

For realistic policy objectives to be set for IPM uptake, and effective plans devised to meet them, policy makers must first understand where farmers are starting from, that is, the current perception, and general levels of adoption of IPM. Although some focused studies have been conducted in the past,[26,27] very little contemporary generalizable data exists to illustrate this baseline in the UK and Ireland. Without such data, it is extremely difficult to establish properly targeted NAPs and assess their effectiveness, in terms of driving increased IPM adoption. The study reported here uses the data captured by Creissen *et al.*[10] to address this knowledge gap, and has the following objectives: (i) to further explore the trends in IPM adoption levels identified, and (ii) identify potential drivers and barriers to adoption of IPM practices in arable cropping systems in temperate climates such as the UK and Ireland.

2 METHODS

2.1 Collection of survey data and the development of a metric to quantify IPM uptake

To collect the primary data required for this study, a survey of arable farmers was undertaken in 2016 and 2017 in England, Scotland, Northern Ireland and Ireland as previously described by Creissen *et al.*[10] (see also Supplementary Appendix S1).

Arable farmers were selected for interview at random using official national data sets as sampling frames in each of the four study countries (Supplementary Appendix S2).[10] Farms were designated as ‘arable’ based on their Farm Accountancy Data Network farm type classification, indicating a significant area of arable cropping on the farm. This designation does not preclude the presence of livestock on the farm, but any livestock will constitute minority enterprises. Data collection was by face-to-face interviews in England, Northern Ireland and Ireland, these being carried out by experienced farm data recorders; data collection in Scotland was by means of a postal questionnaire.

The survey questionnaire (Supplementary Appendix S3) contained 14 questions related to (farmer) perception of IPM and level of adoption and a further eight socioeconomic questions focused on the farmer and the farm business to allow for comparisons across defined sociodemographic groups. The questions related to farmer IPM adoption were also used to create the metric of IPM adoption reported by Creissen, *et al.*[10] This same metric was deployed in this study to quantify level of IPM adoption on each sample farm. This IPM metric is a composite indicator based on six key questions that capture the range of IPM practice. A panel of stakeholders weighted these questions in terms of their importance to the achievement of IPM. The resultant metric is a rating scale with a 0 to 100 range, indicating level of IPM practiced. For more information on these farmer and stakeholder surveys and the design of the IPM metric, see Creissen *et al.*[10] and also Supplementary Appendix S1.

2.1.1 Socio-economic data

The socio-economic variables employed were designed to ensure compatibility with the national farm surveys regularly conducted in each of the study countries. These included respondent's position on the farm, for example, owner (Survey Question 15); the area farmed (Survey Question 16); the scale of different farm enterprises (crop and grassland areas) (Survey Question 17); respondents age (Survey Question 18); level of education (Survey Question 19) and; off-farm income (Survey Question 20); whether a successor had been identified (Survey Question 21); and biodiversity/conservation scheme membership (Survey Question 22). See Supplementary Appendix S3 for the survey questionnaire.

2.2 Use of rating scales

Within the survey, a number of questions, including some contributing to the IPM metric, used rating scales. For example, respondents were asked to state the frequency with which they used a range of agronomic management actions relevant to IPM and express their opinions about these practices with rating scale answers. In other cases, farmers were asked to reveal their attitudes on particular issues, that is, respondents were provided with one or more statements that define a particular action or condition and were asked to rate their level of agreement with this, or the importance of it. In these latter cases a five-point Likert-type scale was used where 1 = Strongly agree and 5 = Strongly disagree.

A different rating scale approach was used to determine the respondent's relationship with their crop protection adviser. Here, respondents were presented with a set of six statements reflecting, from least to most, an increasing level of dependence on a crop protection adviser and were asked to identify the statement that best reflected their own situation.

Additionally, respondents were asked to indicate the nature of the pest control challenge on their farms. In these cases, rating scales were also used.

2.3 Statistical approaches

In order to address the goals of the study, analysis of the survey data followed a stepwise approach, as follows: (i) general overview of the sample; (ii) analysis of IPM levels within the sample, including comparisons between countries; (iii) identification of potential drivers or barriers to IPM practices (including familiarity with IPM), potential national differences in their expression and differences between high scorers (upper quartile) and low scorers (lower quartile).

For a description of all variables used in the statistical tests reported below, please see Supplementary Appendix S4 and the full questionnaire at Supplementary Appendix S3.

All data processing and statistical procedures were undertaken using the analytics package SAS.[28] To identify the drivers of IPM score, a general linear model (GLM) was fitted of the form:

$$y = \mu + x'\beta + \epsilon$$

using Proc GLM in SAS (Table 1). Where y is the dependent variable (IPM score), μ is the intercept (constant), x' is a vector of independent variables, β are the parameters to be estimated and ϵ is the random error. All socio-economic variables present in the dataset were regressed on IPM score, except those variables used in the construction of the IPM metric itself. Those variables that did not produce significant effects were then removed until a sub-set of the variables, which were all found to be statistically significant, remained. This was deemed to be the most efficient statistical model.

Proc GLM was chosen to generate the linear regression model in this case for several reasons, that is, GLM does not require the assumption of normality of distribution of the dependent variable; GLM handles missing values without losing observations; and also allows for the inclusion of categorical (Class) explanatory variables in the regression model. To identify the divers of familiarity with IPM, with this being an ordinal variable, an Ordered Probit model was used (Proc Probit in SAS). In the case of the Ordered Probit model the dependent variable y^* replaces y in the fitted form above, where y^* represents a latent and continuous measure of familiarity with IPM (underlying the observed ordered responses). The GLM and Ordered Probit models contained a mix of binary, ordinal and interval-scale variables. In the model solutions, in the case of the ordinal and binary variables, for example, Sources of pest management advice and Relationship with crop adviser, the model interprets the last level in each of the class variables as the reference level and so sets the 'estimate' for this level to zero. The parameter estimates for the remaining levels of each class variable represent the difference in IPM score (or familiarity with IPM) for these level(s) compared to the reference level, that is, the change in the dependent variable value that results from a change from the reference level of a classification variable to any other levels.

Where tests were conducted to explore differences in the levels of socio-economic parameters between countries (a classification variable with four levels), several different statistical tests were used. Where interval scale dependent variables were involved, Analysis of variance (ANOVA) were used; where ordinal variables were involved Kruskal-Wallis non-parametric ANOVAs were used; and where binary (categorical) variables were involved, Chi-Square tests were used to examine the significance of country differences. Where two-sample tests of ordinal variables were required, for example comparing between subgroups with high and low IPM uptake, Wilcoxon two-sample tests were used, using PROC NPAR1WAY in SAS (this approximates the Mann–Whitney U test). A series of comparisons of pairs of the measures used to construct the IPM metric were undertaken using the Wilcoxon Matched-Pairs (Signed Ranks) test. Finally, a test of the extent of the correlation between Familiarity with IPM and IPM score (both ordinal measures) was undertaken using the Spearman's Rho test as the latter metric is a measured at the ordinal scale.

3 RESULTS

3.1 General characteristics of the surveyed sample

Respondents to the survey were primarily the business owner or tenancy holder, accounting for between 84% and 100% of respondents depending on country (Supplementary Appendix S2). The next largest class of respondents were farm employees (which includes farm managers), from 16% in Scotland to zero in Ireland. Farms varied considerably in area, with the largest farms found in Scotland (363 ha (ha) on average), and the smallest in Ireland (101 ha on average).

In all countries most participants were over 50 years of age, although in Northern Ireland, around 25% were under 40 years. The highest level of educational attainment of most farmers in England, Scotland and Northern Ireland was a diploma/certificate connected to farming. However, in Ireland the significant majority did not have farming-specific education, but rather a school

Table 1. Tests for country differences in the six variables/questions that when combined create the composite IPM metric

Description	DF	Statistic	*P*-value
		χ^2	$P > X^2$
Proportion of land in continuous cereals production	3	58.65	$P < 0.001$
Membership of agronomy/crop discussion group	3	3.56	$P = 0.313$
		F	$P < F$
Reasons for using an arable rotation	3	11.58	$P < 0.001$
Influences on choice of cereal/oilseed variety	3	1.95	$P = 0.122$
Preventative measures used to control weeds	3	9.13	$P < 0.001$
Preventative measures used to control diseases	3	6.12	$P = 0.001$
Preventative measures used to control insects/nematodes/molluscs	3	3.68	$P = 0.013$
Factors considered when deciding on a pest management plan	3	10.95	$P < 0.001$

Statistical methods used: χ^2 and $P > \chi^2$ relate to Kruskal-Wallis Test (Proportion of land in continuous cereals production) and Chi Square test (Membership of agronomy/crop discussion group). F and $P >$ F relate to ANOVA.

leaving certificate, approximately equivalent to A-levels in the UK. In England and Scotland, around 20–25% of farmers had a university degree of some kind, but this proportion was less than 10% in Northern Ireland and Ireland. While no data were available on the proportion of farmers who had off-farm sources of income in England, around 30–40% of farmers reported having off-farm income in Northern Ireland and Scotland, but in Ireland this was less than 20%. Only in Northern Ireland had the majority of farm businesses identified a likely successor (no data were available on this metric for Ireland). Rates of biodiversity-promoting scheme membership were highest in England (83%), moderate in Ireland (43%), but relatively low (<30%) in each of Scotland and Northern Ireland (Supplementary Appendix S2).

3.2 Level of IPM uptake

All farmers were undertaking some level of IPM activity, but very few, that is, just 15 (6.7%) of the sample, scored more than 85 out of a possible maximum of 100. Over the whole sample, the mean IPM score was 67.1 with a standard deviation of 13.1 (coefficient of variation 19.6%).[10] Significantly higher IPM scores were found in England and Scotland compared to Ireland and Northern Ireland (Fig. 1). These country differences were found to be significant ($F = 20.79$; $DF = 3$, $P < 0.0001$), with Tukey *post hoc* tests showing that most pairings of countries were significantly different from one another, that is, all pairings except England *versus* Scotland and Ireland *versus* Northern Ireland.

3.3 National differences in scores on the six questions of the IPM metric

Table 1 shows the main effects of country on each of the six questions contributing to the IPM score. Each of these is a composite measure, made up of a number of sub-components capturing different types of pest management activity, or different options. The sub-components of each question are weighted to reflect their relative contribution to IPM just as the questions themselves are subsequently weighted in constructing the IPM metric (further detail on the construction of the IPM metric and its component questions can be found in Creissen *et al.*[10]). The results of the analysis of each of these six questions is individually presented below.

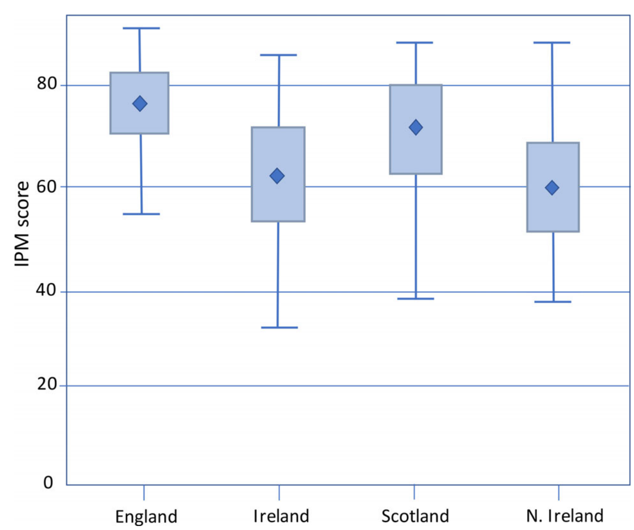

Figure 1. Level of IPM adoption (IPM score) for each of the study countries. Diamonds = mean score within country; boxes represent 75% range and whiskers represent 95% range. n = 225.

3.3.1 *Reliance on continuous cereal production (survey question 3)*

Continuous cereal production is defined in the questionnaire as 'growing cereals on the same land for five or more consecutive years without growing a (non-cereal) break crop'. The lower the area of continuous cereals production the more IPM-consistent the management was deemed to be. There were significant country differences in this practice, with the observed country main effect (Kruskal-Wallis test) attributable to higher proportions of farmers adopting this practice in Ireland (median percentage range 26–50%) and Northern Ireland (median percentage range 1–25%) compared to either of England (median percentage range 0%) or Scotland (median percentage range 1–25%) (Table 1; Supplementary Appendix S5).

A number of explanations for keeping land in continuous cereal production were given (Supplementary Appendix S6), with the most common being a lack of market for non-cereal crops, although there were no significant country differences (Chi-square test) in terms of the frequency of use of this reason. However, Chi-square tests revealed that there were significant differences between countries in terms of the other reasons given for adopting continuous cereals production, that is: 'the land is unsuitable for other crops' ($\chi^2 = 50.51$, DF = 2, $P < 0.0001$); 'the climate is unsuitable for other crops' ($\chi^2 = 8.95$, DF = 2, $P = 0.0299$); 'greater risks growing other crops' ($\chi^2 = 9.71$, DF = 2, $P = 0.0213$); and 'end-market requirements' ($\chi^2 = 15.03$, DF = 2, $P = 0.0018$) (Supplementary Appendix S6). The proportion of land under continuous cereals production was found to be negatively correlated with farm area (Rho = −0.33371, $P < 0.001$), indicating that the larger farms, for example, in England and Scotland, had a lower likelihood of this practice.

3.3.2 Reasons for adopting an arable rotation (survey question 4)

Farmers in each country were asked to indicate why they typically used rotations (Supplementary Appendix S7). In the IPM metric, the composite variable representing use of rotations combines and weights these different reasons, applying higher weights where this is done to control pests or improve soil condition. Higher scores on this composite variable therefore reflect both greater use of rotations and use of them to control pests and manage soil condition. There was a significant country main effect (ANOVA; Table 1) on this composite variable, primarily due to differences between the scores for England and all other countries, with England scoring highest. Problems with blackgrass (*Alopecurus myosuroides*), a pest often controlled by use of rotation, were specifically highlighted by respondents in England, while there were negligible concerns in the other countries (Supplementary Appendix S8).

3.3.3 Influences on choice of cereals/oilseeds variety (survey question 5)

This composite variable is weighted highest when respondents reported that choice of cereals and oilseed variety was influenced by its level of crop disease resistance and direction from recommended lists (of varieties). However, in the sample, the most commonly cited influence on choice of cereal/oilseed variety was yield potential, followed by recommended lists, then disease resistance and consistency of performance. There was no main effect (ANOVA; Table 1) of country on score for this composite variable.

3.3.4 Preventative measures used to control pests (survey question 8)

3.3.4.1. Weeds. All preventative measures to control weeds captured by this composite variable were considered by expert stakeholders to contribute positively to achievement of IPM, with the exception of infrequent crop inspections.[10] There was a significant main effect (ANOVA; Table 1) of country on this variable. Tukey post-hoc tests revealed that scores in England were significantly higher for this measure (i.e., more of the IPM-consistent weed control measures were being undertaken) than in both Ireland and Northern Ireland. Details of the specific measures adopted in each country are provided in Supplementary Appendix S9.

3.3.4.2. Diseases. As with the weeds composite variable above, all preventative measures to control diseases captured by this composite variable were considered to contribute to achievement of IPM, with the exception of infrequent crop inspections.[10] There was a significant main effect (ANOVA; Table 1) of country on the score for the variable, with Tukey *post hoc* tests revealing a lower score in Northern Ireland than in either England or Scotland, with both of these national differences significant at the 5% level. Details of the specific disease control measures adopted in each country are provided in Supplementary Appendix S9.

3.3.4.3. Insects, nematodes and molluscs. All preventative measures to control insect pests, nematodes and molluscs captured by this composite variable were considered to contribute positively to achievement of IPM, with the exceptions of soil testing for insect pests and infrequent crop inspections.[10] There was a significant main effect (ANOVA; Table 1) of country on this variable, with Tukey *post hoc* tests revealing that there was a lower use of preventative measures to control insect pests, nematodes and molluscs in Northern Ireland than in England, with this national difference significant at the 5% level. Details of the specific control measures adopted in each country are provided in Supplementary Appendix S9.

3.3.5 Factors considered when developing a pest management plan (survey question 9)

All specific factors that might be taken into consideration when developing a pest management plan, for example, anti-resistance strategies and weed maps, were considered equally important.[10] There was a significant main effect (ANOVA; Table 1) of country on this variable, with Tukey *post hoc* tests revealing a lower score for this measure, that is, lower use of pest management plans, in Northern Ireland than in any other country. These national differences were significant at the 5% level.

3.3.6 Membership of an agronomy/crop discussion group (survey question 14)

For this, the last of the variables contributing to the composite IPM metric, a positive contribution to IPM is made when there is such membership and a zero contribution when there is not. There was no significant effect of country (Chi-Square Test; Table 1) on this variable.

3.4 Drivers of IPM score

Regression analysis (Proc GLM in SAS) was used to identify those factors that determined IPM score. As Table 2 shows, of the 39 variables tested (listed in Supplementary Appendix S10), five variables were identified as being significant determinants of IPM score, these being: Level of familiarity with IPM; Importance attached to biological control methods; Attitude to recommendations provided by crop adviser; Total farmed area; and Country. The GLM was significant (F = 8.67; $P < 0.001$) and had an R-square of 0.305, that is, around 31% of the variation in the dependent variable (IPM score) could be explained by the sub-set of variables contained in this model.

Attitude to recommendations provided by crop advisers was found to be a significant determinant of IPM score, with those relying on, and acting upon, the advice of a crop protection adviser having a higher IPM score than those that did not ($P < 0.001$) (Table 2). Those farmers who understood the importance of biological control methods (i.e., growing competitive crops, establishing beetle banks *etc.*) to IPM also tended to have higher IPM scores ($P = 0.03$). There was also a significant positive relationship between the area of the farm and IPM score, that is, those with larger farms tended to adopt more IPM practices ($P = 0.012$). Level of familiarity with IPM also showed a significant positive relationship with IPM score ($P = 0.009$; Fig. 2).

Table 2. General Linear Model to identify the determinants of the IPM score

Description of determinants	DF	Estimate	T-value	Pr > t
		53.05	12.77	<0.0001
Level of familiarity with IPM	1	2.01	2.67	0.0086
Relationship with crop adviser (I rely on them and act on their suggestions)		5.81	3.62	0.0004
Relationship with crop adviser (I do not rely on them or act on their suggestions)	1	0.0		
Considers biological control methods an important component of IPM	1	1.82	2.24	0.0268
Total area of farmed land	1	0.013	2.56	0.0115
England		3.09	1.47	0.1444
Ireland		−1.43	−0.58	0.5646
Northern Ireland		0.4039	0.15	0.8808
Scotland	3	0.0		

R-Square = 0.305382; Model F = 7.98; $P > F = <0.0001$.

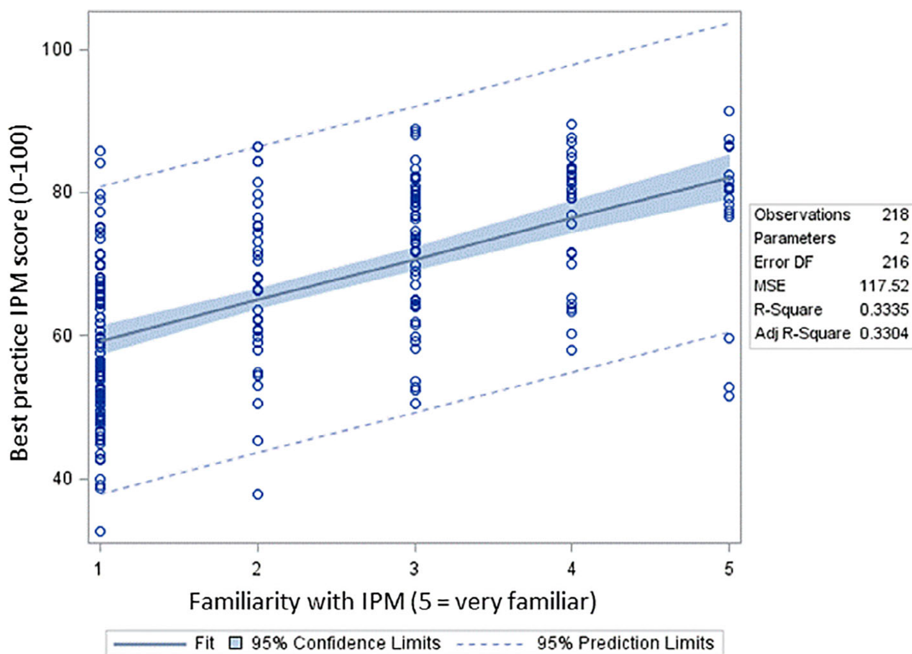

Figure 2. Relationship between familiarity with IPM (rating score, where 1 = not at all familiar, 2 = somewhat familiar, 3 = moderately familiar, 4 = familiar, 5 = very familiar) and IPM uptake (IPM score). Solid line = mean IPM score at each level of familiarity. Rho = 0.55532; $P < 0.0001$. n = 225.

3.4.1 *Country differences in drivers of IPM score*

There was a main effect of country on IPM score. There were two high-scoring countries, that is, England and Scotland (IPM scores = 76 and 71, respectively) and two lower scoring countries, that is, Ireland and Northern Ireland (IPM scores = 64 and 61, respectively). The IPM scores for most pairs of countries were found to be significantly different from one another using Tukey *Post Hoc* tests ($P < 0.05$) with the exceptions of England *versus* Scotland and Ireland *versus* Northern Ireland. It is hypothesized that the country differences in IPM score in the regression analysis were caused by underlying socio-economic differences between countries, that is, country acts as a proxy for these variables. Support for this hypothesis would come in the form of significant country differences in the values of the socio-economic variables found to be drivers of IPM score (Table 2). Table 3 partly confirms this hypothesis, with country differences observed for the following variables: Familiarity with IPM and Total farmed area – both these variables had positive relationships with IPM score. There were, however, no significant country differences for: Relationship with crop adviser; or Importance attached to use of biological control methods.

3.4.2 *What do farmers consider the most important aspects of IPM?*

To further understand potential drivers of IPM, the view of farmers with respect to the most important aspects of IPM was examined. This analysis showed that there was some apparent consensus among farmers that most of the elements of IPM were important, as expressed in terms of the importance ratings provided by them across the measures (Fig. 3(a)), with preventative measures and surveillance deemed slightly more important than the rest. However, all of the score differences between the measures were found to be statistically significant using Wilcoxon's Matched Pairs Signed Ranks tests (Supplementary Appendix S11), with the exception of the comparison between preventative measures

Table 3. Tests for country differences in the socio-economic variables found to be significant determinants of the IPM score

Variable description	DF	Statistic	*P*-value
		χ^2	$P > \chi^2$
Level of familiarity with IPM	3	59.96	$P < 0.001$
Considers biological control methods an important component of IPM	3	5.17	$P = 0.16$
		F	$P > F$
Relationship with crop adviser	3	2.10	$P = 0.101$
Total area farmed	3	35.12	$P < 0.001$

Statistical methods used: χ^2 and $P > \chi^2$ relate to Kruskal-Wallis Test; F and $P >$ F relate to ANOVA.

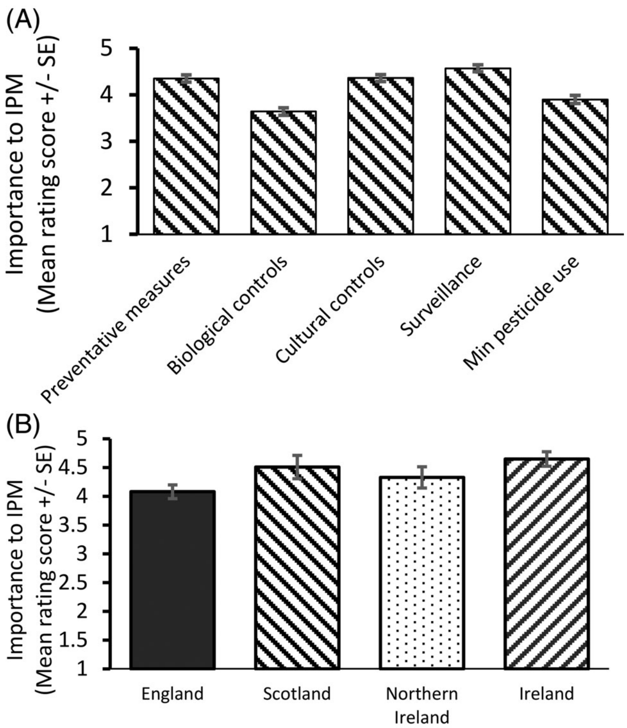

Figure 3. Average rating scores (where 1 = Not at all familiar, 2 = Somewhat unfamiliar, 3 = Moderately familiar, 4 = Familiar, 5 = Very familiar) reflecting: (a) Farmer beliefs about the relative importance of aspects of IPM (average across the whole sample); (b) National differences in farmer belief about the importance of preventative measures to IPM. Preventative measures (hygiene practices such as cleaning equipment, sourcing clean seed *etc.*), biological control methods (growing competitive crops, beetle banks *etc.*), cultural control methods (altering drilling dates to reduce disease, increasing seeding rate to control weeds, rotating crops *etc.*) monitoring and surveillance of insect pest, weed and disease levels (crop walking, reacting to high disease/pest pressure alerts *etc.*). n = 225.

and cultural control methods. There were no significant differences between countries in terms of the importance ratings assigned to any of the IPM elements. The element which came closest to showing significant country differences is the use of preventative measures (DF = 3; F = 2.64; $P = 0.0520$; Fig. 3(b)).

3.4.3 Differences between high and low IPM scorers

The final question asked in this analysis in relation to scoping out potential drivers of IPM was: are all IPM measures equally likely to be adopted, or do some of them present more barriers to adoption than others? To address this question two sub-groups were drawn from the sample, that is, High IPM-score (>79 points i.e., the upper quartile) and Low IPM-score (<56 points, i.e., the lower quartile). If certain types of IPM measures were only deployed by farmers with High IPM scores, then this would support the notion that there are greater barriers to the adoption of these measures than those measures that Low IPM score farmers frequently adopted. It was impractical to compare each individual pest control measure that farmers might adopt, so this comparison was undertaken on the basis of the six specific questions encapsulating IPM and used to generate the IPM score.[10]

High score adopters of IPM had higher rating scores than Low score IPM adopters for each of the five rating-type survey questions that contribute to the IPM score (Fig. 4). Of the farmers that were members of an agronomy or crop discussion group (not represented in Fig. 4), 24 farmers were members in the High IPM score group and just one was in the Low IPM score group. All of the observed differences shown in Fig. 4 were found to be statistically significant at the $P < 0.001$ level using Wilcoxon's (two sided) Two Sample Test (Supplementary Appendix S12). In terms of membership of agronomy/crop discussion group, there was a statistically significant difference between the High and Low IPM score groups ($\chi^2 = 27.7634$, DF = 1, $P < 0.001$). While all group differences were statistically significant, the results suggest that the barriers to the adoption of preventative measures to control pests are smaller than is the case for some other IPM activities, notably the number of factors considered when deciding on the pest management plan. When looking at the specific measures that members of the High and Low IPM score groups took into account when preparing pest management plans, the Low IPM score group were much more likely to report not using such a plan than the High IPM score group. The High IPM score group correspondingly tended to report taking all factors into account more often than the Low IPM score group. All of these group differences were found to be statistically significant ($P < 0.05$) using the Wilcoxon Two-Sample Test. Within the High IPM score group, the measures most often taken into account when preparing pest management plans were rotation and variety resistance, while factors accounted for least often were yield maps and soil-borne pathogens.

It is also instructive to note the differences in the valuations put on different information sources between the High and Low IPM score groups. As Fig. 5 shows the High IPM score group valued farm open days, discussion groups and independent agronomists as sources significantly more ($P < 0.05$) than the Low IPM score group, based on Wilcoxon's Two-Sample (two-sides) test. Conversely, the Low IPM score group valued other farmers, merchant agronomists and the farming press significantly more ($P < 0.05$) than the High IPM score group (Supplementary Appendix S13).

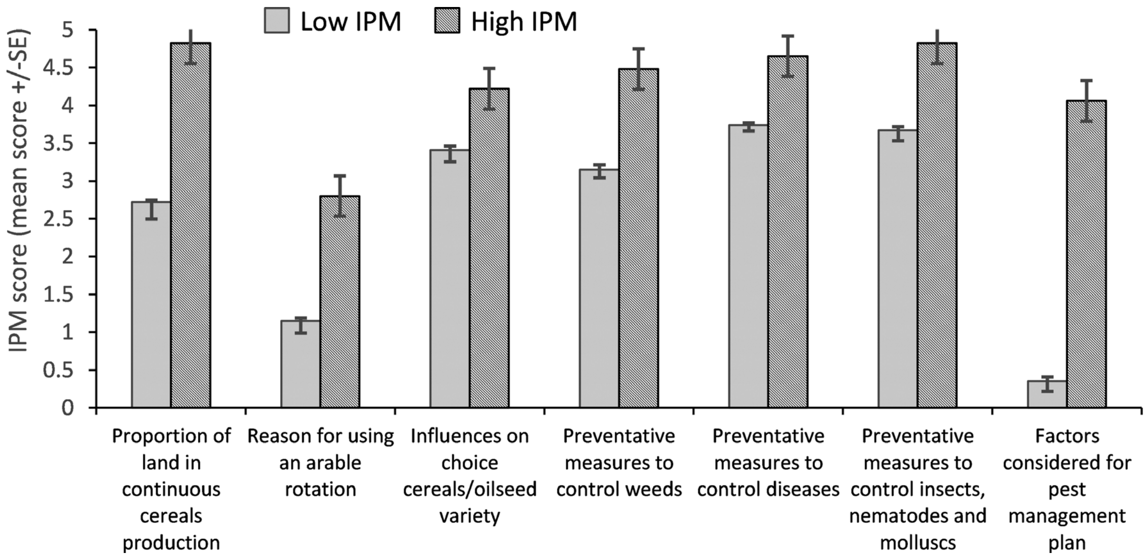

Figure 4. Mean IPM score (where 0 = lowest score and 5 = highest score) for activities acting as sub-components of IPM for high IPM-score (>79 points) and low IPM-score (<56 points) sub-samples. All of the observed differences shown were statistically significant at the $P < 0.001$ level. n = 225.

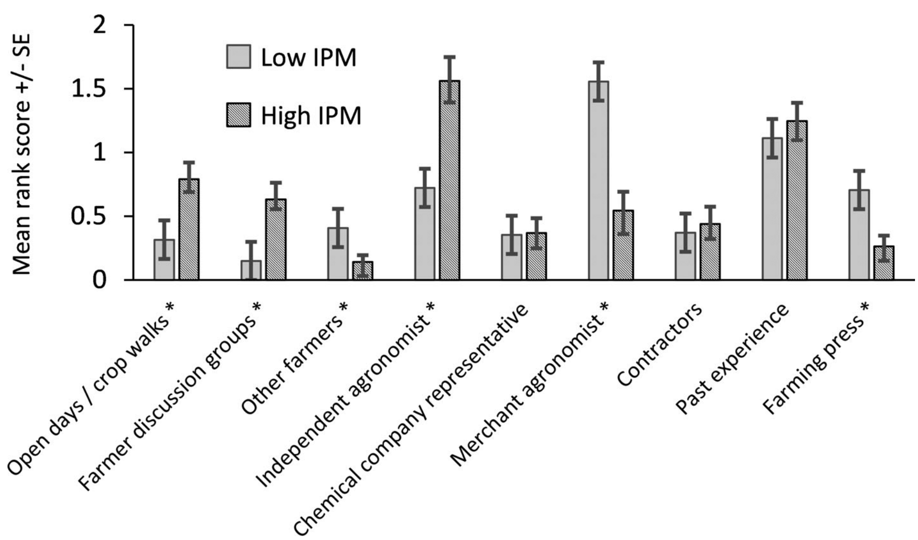

Figure 5. Comparison of mean rank scores of importance (farmers were asked to rank their top 3 sources of pest advice) of different information sources for high IPM-score (>79 points) and low IPM-score (<56 points) sub-samples. The asterisks on the category labels indicate that differences between the High and Low IPM groups are significant at the 1% level or better. n = 225.

There were also numerous significant ($P < 0.05$) country differences in the importance attached to the different information sources (tested using ANOVA, Supplementary Appendix S14) but the only trend that can be discerned in this data is that the rank scores attached to the information sources in Ireland tend to be marginally divergent from those of other countries.

3.5 Familiarity with IPM

Self-reported familiarity with the concept and practice of IPM varied significantly by country ($F = 23.38$, $DF = 3$, $P < 0.001$; Fig. 6). Tukey *Post Hoc* tests found significant differences between most pairs of countries, with the exception of England *versus* Scotland and Scotland *versus* Ireland. While familiarity with IPM appears to be a determinant of IPM score, logic suggests that familiarity may also capture the effects of other more foundational socio-economic variables that remain unidentified. To test this hypothesis, a regression analysis (Ordered Probit) was run, with familiarity with IPM as the dependent variable and all socio-economic variables in the dataset, including country, as regressors. Perhaps unsurprisingly, the subset of socio-economic variables identified as determinants of familiarity with IPM (Table 4) relate to use of particular sources of crop protection advice and the value placed on these sources. In the case of the variable representing the value placed on open days and farm walks, the sign of the coefficients indicates that the higher the rating score (the more these events are valued) the higher the level of familiarity with IPM. Level of education was also identified as a significant driver of IPM familiarity, that is, those respondents without a Bachelor's degree had a significantly lower IPM score than those who did.

Table 4. Ordered Probit Model to identify the determinants of familiarity with IPM				
Description	DF	Estimate	Chi Square	Pr > t
Intercept	1	−2.1644	28.84	<0.0001
Intercept 2	1	0.5347	40.25	<0.0001
Intercept 3	1	1.3266	117.40	<0.0001
Intercept 4	1	2.0743	166.84	<0.0001
Rank of value of open days and farm walks (not ranked in top 3)	1	0.9458	9.26	0.0023
Rank of value of open days and farm walks (low rank)	1	0.3888	1.21	0.2715
Rank of value of open days and farm walks (medium rank)	1	0.2948	0.64	0.4244
Rank of value of open days and farm walks (high rank)	0			
Qualifications achieved (no Bachelor's degree)	1	0.8261	11.29	0.0008
Qualifications achieved (possess Bachelor's degree)	0			
England	1	−0.3553	2.59	0.1073
Ireland	1	0.1497	0.43	0.5131
Northern Ireland	1	1.2441	28.83	<0.0001
Scotland	0			

Proc Probit is modelling the probabilities of levels of Q1 having lower ordered values in the response profile table.

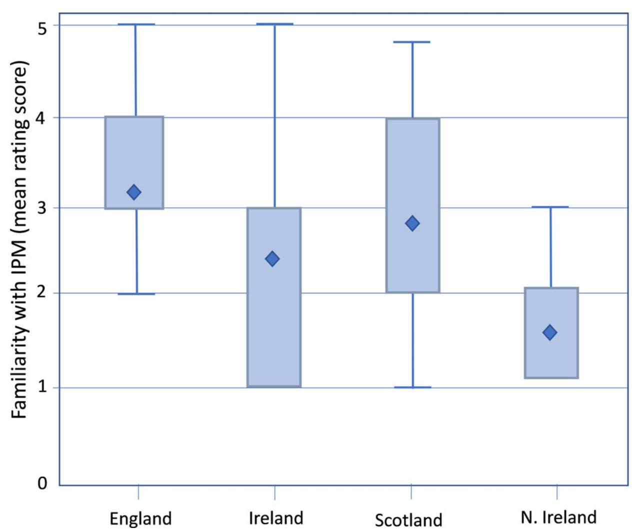

Figure 6. Familiarity with IPM, by country distribution of rating scores. Mean rating score = diamond symbols (where 1 = Not at all familiar, 2 = Somewhat unfamiliar, 3 = Moderately familiar, 4 = Familiar, 5 = Very familiar); boxes represent 75% range and whiskers represent 95% range. n = 225.

4 DISCUSSION

Significant differences in level of adoption of IPM were found between the countries, with the highest levels recorded in England and Scotland and lowest in Ireland and Northern Ireland. The only socio-economic variable identified as a driver of IPM was farm area (ha), the values of which differed considerably between the study countries, with average farm areas much smaller in Ireland and Northern Ireland than in both England and Scotland. Other variables that have been historically identified as impacting rate of adoption of novel technologies and management practices in agriculture, such as farmer age, were not found to be drivers of IPM adoption in this study.[15,29] Such findings demonstrate the need to take the local context into account, not only when measuring IPM adoption, but also when identifying variables impacting adoption. The reason for the relationship between farm area and level of IPM adoption cannot be ascertained from the survey. However, similar relationships have previously been identified in Polish arable farms.[30] It can be hypothesized that farmed area may be acting as a proxy for a number of other factors that can influence the capacity to undertake IPM. For example: (i) larger farms may have to capacity to grow a greater number of crops and consequently are better able to adopt more complex arable rotations; (ii) larger farms, with their greater financial resources are able to buy-in more independent professional advice; (iii) with larger work-forces, larger farms are able to undertake more of the tasks required as part of IPM (e.g., intensive crop monitoring); (iv) farmers with larger farms have the capacity to take greater risks and so are likely to be less risk averse. Risk aversion is likely to be a factor contributing to reliance on continuous cereal production, something that is practiced most extensively in Ireland and Northern Ireland, where farms are smaller; (v) larger farms are more likely to be run by professional managers with higher levels of both general education and agricultural training.

In addition to farmed area (and country), three other determinants of IPM uptake were identified, that is, familiarity with IPM; relationship with crop adviser; and considering biological control as an important component of IPM. Interestingly, of these, only level of familiarity with IPM differed between the study countries. The relationship between familiarity with IPM and level of IPM practiced is quite understandable because familiarity with a technique is a necessary precursor to adoption.[20,31,32]

While the statistical relationship between level of IPM familiarity with level of IPM adoption has been confirmed here, this causal relationship is not a simple linear one, as evidenced by the fact that within each level of familiarity reported by respondents, a wide range of IPM scores were observed. This observation may have two explanations. First, familiarity with IPM does not guarantee a desire to adopt the technique, that is, there may continue to exist meaningful obstacles to adoption, such as poor expectations for outcomes, risk aversion, or lack of necessary equipment.[31,33–35] Second, some of those declaring a low level of IPM familiarity may actually be engaging in relatively high levels of IPM without being aware that the activities they are undertaking are regarded as components of IPM.

As familiarity with IPM is likely to be a proxy for other informational and motivational factors, further analysis of the factors influencing levels of familiarity with IPM was conducted. As previously highlighted, significant differences in familiarity with IPM between the four countries were identified, with the greatest difference between respondents in England and in Northern Ireland. Unlike the case of IPM adoption, area of land farmed was not identified as a significant contributor to familiarity. However, level of education was identified as a contributor, with respondents holding a Bachelor's degree likely to have a higher level of familiarity with IPM than those without. The number of respondents educated to degree level is almost three times greater in England than Northern Ireland. A similar difference was observed between the number of respondents with degrees in Scotland and Ireland, although the difference in level of familiarity between these countries was not significant. Although specific details, such as degree subject, were not recorded, it can be assumed that irrespective of the nature of their higher education, through the process of attaining a degree, the respondents will have gained increased capacity to question, research and formulate their own ideas; skills that would undoubtedly aid them in understanding the knowledge intensive process that is IPM.

Unsurprisingly, attitudes towards different sources of information on pest management and the relationship between the respondent and their crop protection adviser were key drivers of IPM adoption and familiarity. While most respondents reported that other farmers, the farming press and open days/crop walks were their main information sources, there was some statistical association between type of source favored and level of IPM familiarity and uptake. Respondents *actively* seeking information on IPM, such as through open days, crop walks, discussion groups, engagement with agronomists *etc*. tended to have a higher level of familiarity and adoption. These respondents also tended to place a lower value on *passively* obtained information on IPM, from sources such as the farming press or indeed other farmers. Reliance on these passively acquired sources of information can therefore be seen as a barrier to both familiarity and adoption of IPM. At this juncture, however, it is not known whether this statistical association between information source favored and IPM adoption is caused by attitudinal differences in these respondents, or differences in the quality of information received from the sources. The significance of the relationship between sources of IPM information used, and IPM score, is consistent with the findings of studies that showed advice of independent agronomy advisers to be a determinant of IPM adoption, with farmers that are proactively seeking, accepting and acting on such advice tending to show increased levels of adoption.[14,36] The unique influence of discussion groups should also be highlighted here, due to the elevated exposure to peer pressure in this context, that is, past studies have shown that the actions of other farmers can greatly influence a farmers' intention to reduce pesticide use.[37]

While reliance on a crop adviser and acting on their advice was a significant driver of level of IPM adoption, this does not apply equally to all types of adviser. A significant difference was observed between the type of adviser most predominantly used by those practicing high and low levels of IPM. Those categorized as practicing lower levels of IPM tended to place a higher value on advice from merchant agronomists, while those practicing higher levels of IPM often placed a higher value on independent agronomists. As stated above, this difference will not necessarily indicate differences in the quality of advice provided by these different groups of advisers, but it does further emphasize the fact that those actively seeking impartial information on IPM pest control are also more likely to understand and implement it at a higher level. In most instances the cost of advice provided by merchant agronomists will be included in the cost of the pesticide, while those using an independent adviser have to first seek out this advice, then pay for it and subsequently acquire the pesticide inputs independently of the advice. It is likely that larger farms are better able to accommodate this additional cost and complexity than those with smaller farms and, as a consequence of obtaining this independent advice, they may use more IPM measures than smaller farms. This may partially explain the farm size effect on IPM score.

The final attitudinal variable identified as a determinant of level of IPM adoption is a belief that biological control measures are important components of IPM. This result is somewhat surprising, as the importance ratings attached to this component of IPM were not statistically different to the importance ratings attributed to any other component. This statistical association may be caused by confusion about what constitutes biological control, that is, many of the preventative or cultural practices relevant to IPM, such as crop rotation and variety selection, may also be thought of as being 'biological'.

One issue not considered in this study was farmer perception of the cost effectiveness of IPM and the possible role of this perception as a barrier to adoption. As highlighted in the present study and by Sterio *et al*.[16] adoption of IPM in arable systems is highly complex, however the fact that end market requirements and increased risks associated with alternative crops were identified as key factors in reasons for farmers growing continuous cereals suggests economic performance may play a critical role. The collection of economic performance data alongside levels of IPM adoption for Irish and UK arable farms is ongoing, with a view to providing such analysis.

5 CONCLUSION

With the exceptions of farmed area and level of education, factors historically identified as impacting the adoption of novel technologies and management practices in agriculture, such as farmer age and predominant farm enterprise do not seem to play a vital role in the likelihood of adoption of IPM practices in the study countries. In these cases, the factors determining IPM uptake are attitudinal and therefore are more tractable as barriers to uptake can be overcome through incentivizing farmers to actively engage and educate themselves on IPM practices through initiatives supported by policy. This finding has implications for policy makers looking to encourage further adoption of IPM as a route to reducing pesticide usage and increasing sustainability of arable systems. Increasing uptake must, therefore, be understood as being achievable through improving: (i) farmer familiarity with IPM, and (ii) creating a culture of innovation and best practice within the arable sector. Whatever specific actions are taken, these need to result in a greater willingness, among farmers, to engage with their pest management challenges and actively seek information on best practice from impartial and informed sources.

ACKNOWLEDGEMENTS

We acknowledge the financial and logistical support of the: Scottish Government Strategic Research Programme; Rural Business

Research (England); Department of Agriculture, Food and the Marine (Ireland) (RSF 14/S/879); and the Department of Agriculture, Environment and Rural Affairs (Northern Ireland) in enabling the study reported here. We thank all who contributed to the design of the survey and all involved in data collection processes, including the Teagasc National Farm Survey recorders, Farm Business Survey recorders, Science and Advice for Scottish Agriculture, Census and Single Farm Payment data recorders. We would also like to thank the stakeholders involved in developing the IPM metric and all the farmers who participated in the survey.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

1 European Union, Directive 2009/128/EC of the European parliament and of the council of 21 October 2009 establishing a framework for community action to achieve the sustainable use of pesticides. *Off J Eur Union* **52**:71–86 (2009). https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:309:0071:0086:EN:PDF.

2 Jacquet F, Butault JP and Guichard L, An economic analysis of the possibility of reducing pesticides in French field crops. *Ecol Econ* **70**: 1638–1648 (2011).

3 Boussemart J-P, Leleu H and Ojo O, Exploring cost dominance between high and low pesticide use in French crop farming systems by varying scale and output mix. Working Papers IESEG School of Management. Available: http://my.ieseg.fr/bienvenue/DownloadDoc.asp?Fich=231112724_2012-ECO-11_Leleu.pdf [11 June 2014] (2012)

4 Lechenet M, Bretagnolle V, Bockstaller C, Boissinot F, Petit MS, Petit S *et al.*, Reconciling pesticide reduction with economic and environmental sustainability in arable farming. *PLoS One* **9**:e97922 (2014).

5 Lechenet M, Dessaint F, Py G, Makowski D and Munier-Jolain N, Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nat Plants* **3**:1–6 (2017).

6 Di Tullio E, Camanzi L, Fontolan F, Volpato C and Zucconi S, *The Assessment of the Economic Importance of Azoles in European Agriculture: Wheat Case Study*. Nomisma, Bologna (2012).

7 Hossard L, Philibert A, Bertrand M, Colnenne-David C, Debaeke P, Munier-Jolain N *et al.*, Effects of halving pesticide use on wheat production. *Sci Rep* **4**:4405 (2014).

8 Jess S, Kildea S, Moody A, Rennick G, Murchie AK and Cooke L, European union policy on pesticides: implications for agriculture in Ireland. *Pest Manag Sci* **70**:1646–1654 (2014).

9 Sharma A, Kumar V, Shahzad B, Tanveer M, Sidhu GPS, Handa N *et al.*, Worldwide pesticide usage and its impacts on ecosystem. *SN Appl Sci* **1**:1446 (2019).

10 Creissen HE, Jones PJ, Tranter RB, Girling RD, Jess S, Burnett FJ *et al.*, Measuring the unmeasurable? A method to quantify adoption of integrated pest management in temperate arable farming systems. *Pest Manag Sci* **75**:3144–3152 (2019).

11 Ecophyto R&D: which options to reduce pesticide use? INRA (2010). http://www.endure-network.eu/content/download/6137/45600/file/Ecophyto%20R&D.pdf

12 Barzman M and Dachbrodt-Saaydehb S, Comparative analysis of pesticide action plans in five European countries. *Pest Manage Sci* **67**: 1481–1485 (2011).

13 Lamine C, Transition pathways towards a robust ecologization of agriculture and the need for system redesign cases from organic farming and IPM. *J Rural Stud* **27**:209–219 (2011).

14 Kudsk P and Jensen JE, in *Experiences with Implementation and Adoption of Integrated Pest Management in Denmark: Integrated Pest Management*, ed. by Peshin R and Pimentel D. Springer, Dordrecht, pp. 467–486 (2014).

15 Lefebvre M, Langrell SRH and Gomez-Y-Paloma S, Incentives and policies for integrated pest management in Europe: a review. *Agron Sustain Dev* **35**:27–45 (2015).

16 Steiro ÅL, Kvakkestad V, Breland TA and Vatn A, Integrated pest management adoption by grain farmers in Norway: a novel index method. *Crop Protect* **135**:105201 (2020).

17 Byerlee D, Modern varieties, productivity, and sustainability—recent experience and emerging challenges. *World Dev* **24**:697–718 (1996).

18 Jørgensen LN, Nielsen GC, Ørum JE, Jensen JE and Pinnschmidt HO, Integrating disease control in winter wheat – optimizing fungicide input. *Outlooks Pest Manage* **19**:206–213 (2008). https://doi.org/10.1564/19oct04.

19 Tatlidil FF, Boz I and Tatlidil H, Farmers perception of sustainable agriculture and its determinants: a case study in Kahramanmaras province of Turkey. *Environ Dev Sustain* **11**:1091–1106 (2009).

20 Kabir MH and Rainis R, Determinants and methods of integrated pest management adoption in Bangladesh: an environment friendly approach. *Am Eurasian J Sustain Agric* **7**:99–107 (2013).

21 Leach AB, Hoepting CA and Nault BA, Grower adoption of insecticide resistance management practices increase with extension-based program. *Pest Manag Sci* **75**:515–526 (2018).

22 Hillocks RJ, Farming with fewer pesticides: EU pesticide review and resulting challenges for UKagriculture. *Crop Prot* **31**:85–93 (2012).

23 Guidance Notes on Integrated Pest Management For Use On Irish Farms. Department of Agriculture, Food and the Marine. https://www.pcs.agriculture.gov.ie/media/pesticides/content/sud/Guidance%20Notes%20on%20Integrated%20Pest%20Management.pdf.

24 European Commission. Overview report on the implementation of member states' measures to achieve the sustainable use of pesticides under directive 2009/128/EC. (2017). https://op.europa.eu/en/publication-detail/-/publication/99a5c931-afc0-11e7-837e-01aa75ed71a1/language-en/format-PDF/source-50439784

25 Kudsk P, Jørgensen LN and Ørum JE, Pesticide load - a new Danish pesticide risk indicator with multiple applications. *Land Use Pol* **70**:384–393 (2018).

26 Bailey AS, Bertaglia M, Fraser IM, Sharma A and Douarin E, Integrated pest management portfolios in UKarable farming: results of a farmer survey. *Pest Manag Sci* **65**:1030–1039 (2009).

27 Sharma A, Bailey A and Fraser I, Technology adoption and pest control strategies among UKcereal farmers: evidence from parametric and nonparametric count data models. *J Agron Econ* **62**:73–92 (2011).

28 SAS Institute Inc. 2013. Base SAS® 9.4 Utilities: Reference. Cary, NC: SAS Institute Inc. https://support.sas.com/documentation/cdl/en/lebaseutilref/64791/PDF/default/lebaseutilref.pdf

29 Parsa S, Morse S, Bonifacio A, Chancellor TCB, Condori B, Crespo-Pérez V *et al.*, Obstacles to integrated pest management adoption in developing countries. *Proc Natl Acad Sci U S A* **111**:3889–3894 (2014).

30 Sawinska Z, Świtek S, Głowicka-Wołoszyn R and Kowalczewski PŁ, Agricultural practice in Poland before and after mandatory IPM implementation by the European Union. *Sustainability* **12**:1107 (2020).

31 Jørs E, Aramayo A, Huici O, Konradsen F and Gulis G, Obstacles and opportunities for diffusion of integrated pest management strategies reported by Bolivian small-scale farmers and agronomists. *Environ Health Insights* **11**:1178630217703390 (2017).

32 Despotovic J, Rodi V and Caracciolo F, Factors affecting farmers' adoption of integrated pest management in Serbia: an application of the theory of planned behaviour. *J Clean Prod* **228**:1196–1205 (2019).

33 Diagne A and Demont M, Taking a new look at empirical models of adoption: average treatment effect estimation of adoption rates and their determinants. *Agric Econ* **37**:201–210 (2007).

34 Alwang J, Norton G and Larochelle C, Obstacles to widespread diffusion of IPM in developing countries: lessons from the field. *J Integr Pest Manag* **10**:1–8 (2019).

35 Moss S, Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides. *Pest Manag Sci* **75**:1205–1211 (2019).

36 Lamichhane JR, Dachbrodt-Saaydeh S, Kudsk P and Messean A, Toward a reduced reliance on conventional pesticides in European agriculture. *Plant Dis* **100**:10–24 (2015).

37 Bakker L, Sok J, Van Der Werf W and Bianchi F, Kicking the habit: what makes and breaks farmers' intentions to reduce pesticide use? *Ecol Econ* **180**:106868 (2020).