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An interdisciplinary method for assessing IPM potential: case study in Scottish spring barley

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Abstract

A method is proposed which considers Integrated Pest Management (IPM) through several lenses, in order to obtain a more holistic view of the potential for IPM, and is described using a case study of Scottish spring barley. Long-term experimental field trial databases are used to determine which management methods are best suited to the system at hand. Stakeholder engagement provides insight into which of these methods are most likely to be taken up by farmers. Finally, a database of commercial practice allows an estimate of the potential for improving management patterns, based on current levels of IPM uptake across a wider sample of Scottish farmers. Together, these diverse sources of information give a more complete view of a complex system than any individual source could and allow the identification of IPM methods which are robust, practical, and not already in widespread use in this system. Bringing together these sources of information may be of particular value for policy and other decision makers, who need information about strategies which are both practical and likely to have a large positive impact. In the case of Scottish spring barley, there is good potential to reduce the need for fungicide use through the increased use of highly resistant barley varieties.

Keywords: Integrated Pest Management, Farmer decision making, Disease resistance, Stakeholder engagement, Interdisciplinary methods, Varietal disease resistance

Introduction

Pesticide has been widely used in agricultural systems since the Green Revolution (McLaughlin and Mineau 1995; Robinson and Sutherland 2002), as a way of reducing damage to crops due to pests, pathogens, and weeds (Cooper and Dobson 2007); yet its use carries the potential for concomitant negative effects, such as reduced soil health and ecosystem function (Chen et al. 2001; Min et al. 2002; Vieira et al. 2007) and non-target toxicity linked to biodiversity loss (Beketov et al. 2013; Geiger et al. 2010; McLaughlin and Mineau 1995). Despite pesticide use being relatively little-studied in comparison with other agricultural inputs (Bernhardt et al. 2017), alternatives to the standard pesticide spray programmes have been suggested in the form of Integrated Pest Management (IPM) for over fifty years (Stern et al. 1959). IPM (defined here as per the FAO) is an ecosystem approach which combines diverse management practices in order to minimize the use of pesticides while protecting crops from pest, pathogens, and weeds (FAO 2017), and has been found to improve the overall environmental sustainability of farms, as compared to conventional pesticide use (Lefebvre et al. 2014). IPM can encompass a number of methods, including forecasting disease intensity and adjusting spraying programmes accordingly, sowing highly resistant crop varieties, and using crop rotation.

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IPM effectiveness is often assessed via field experiments which aim to consider the impact of IPM on yield, crop quality, biodiversity, and other key agro-ecological factors (Bailey et al. 2001; Deike et al. 2008; Detheridge et al. 2016; Flower et al. 2017; Hysing et al. 2012). While field experiments provide important insights, such work remains essentially theoretical without engagement with stakeholders (including farmers, policy makers, agronomists, and other agri-food actors). Decision making is a complex process, which will necessarily involve the weighing of risks when choosing management strategies (Dandy 2012; Ilbery et al. 2013; Ingram 2008), and may result in stakeholder decisions which are not fully aligned with experimental outputs. This is particularly important, as farmer decisions are often more strongly influenced by market forces and the marketing of pesticides than by IPM recommendations (Magarey et al. 2019). Despite the potential benefits of collaboration with stakeholders, relatively few published studies have conducted social science engagement alongside scientific analysis for IPM, though post-hoc studies to understand whether given methods were taken up several years after governmental recommendations were put forward have been carried out in the UK (ADAS 2002; Bailey et al. 2009). While the use of social science research in order to understand the complexities of plant disease risks is becoming more common (Bailey et al. 2009; Ilbery et al. 2013; Maye et al. 2012; Sherman and Gent 2014), few studies bring together which farmer opinions, actual practice, and experimental research into IPM as part of a single research project. This study addresses this gap by using three types of data (long-term experimental field trials, stakeholder surveying, and actual practice reporting) to assess the potential for IPM to reduce the need for fungicide use in the case study crop of Scottish spring barley, in order to identify IPM methods which are of interest both in terms of scientifically measured outputs and to farmers in this system.

Barley: a crop of global and local importance

Barley is one of the top five crops in the world in terms of hectares harvested, at over 47 million in 2017 (FAO 2019), and is of particular importance in Scotland, where spring barley is the main cereal crop, accounting for approximately 50% of arable land (excluding permanent grassland) in 2016 (Scottish Government 2016). The dominance of spring barley in Scotland is largely due to the malting industry, which offers a price premium, although most barley is ultimately destined for feed (Scottish Government 2015) after failing to meet stringent malting requirements. Fungal pathogens are key pests of barley, which have been estimated to cause a total yield loss of 15% worldwide (Oerke and Dehne 2004) and 14% in the USA (James et al. 1991). To combat these diseases, over 160,000 kg of fungicide was applied to Scottish spring barley in 2016 (over an average of 1.8 fungicide applications applied to 93% of the crop area), representing 42% of the total amount of pesticide applied to the crop (Monie et al. 2017). Fungicide use in Scottish spring barley therefore provides an opportunity to assess the potential for reducing pesticide use, in a system which is of both local and global importance.

Materials and methods

Two IPM methods—crop rotation and varietal resistance—were considered in terms of their impact on yield and disease levels for three of the most important diseases in the Scottish spring barley production system (Ramularia leaf spot (RLS), caused by *Ramularia collo-cygni*; scald, caused by *Rhynchosporium commune*; and powdery mildew, caused by *Blumeria graminis* f. sp. *hordei*). Each source of data was assessed individually before being compared to gain insights into the potential for IPM uptake, producing a more unified picture of disease management.

Stakeholder survey

A stakeholder survey of 43 farmers and 36 agronomists who were involved in the production of Scottish spring barley was conducted at four locations across Scotland, through a convenience sample of attendees at the Agronomy 2016 events, (co-hosted by Scotland's Rural College (SRUC) and the Agriculture and Horticulture Development Board (AHDB)) in order to obtain a relatively large sample at low-cost. The agronomists presented a varied group, with some based in the Scottish Agricultural College advisory service (linked with SRUC), and others from the private sector. The farmers in attendance at these events presented a group which was more highly educated than the norm, had larger farm sizes, and were voluntarily attending an event where disease management was being discussed. The results from these stakeholders should therefore be considered as coming from an early adopter of innovation group—as per age, farm size and education characteristics (Diederen et al. 2003; Rogers 1961). In addition to key socio-economic and grouping information, data were collected regarding variety use on farm from 2011 to 2015, previous rotations, fungicide use, main diseases on farm, and opinions regarding fungicide use in future. Data from this survey were used to assess the current level of uptake of key IPM methods, and openness towards IPM use in future. Farmers were found to have low levels of uptake of crop rotation and varietal disease resistance, but to be open to using these in principle. More information regarding methodology, results, and a copy of the survey used has been previously published and is available in Stetkiewicz et al. (2018). Survey results were then compared with experimental field data and commercial data in order to provide context-specific information regarding farmer perceptions and use of IPM—this process is described in detail below.

Experimental Field Trials database

Data for 1996–2014 from a long term experimental Field Trials database collected by SRUC for spring barley were analysed to determine: the management and environmental factors which influenced the difference in untreated and (best-practice) treated yields from 1996 to 2014; the effect of using fungicide on spring barley yields from 2011 to 2014 for varieties sown by surveyed farmers in those years; and the potential difference in profit between treated and untreated barley production, using Field Trial yield data for 2011–2014 and barley price data from the AHDB. These data were used to provide information regarding the potential of IPM methods to reduce the need for fungicide use, without decreasing yields. Disease resistance level and wet weather were found to be important in determining the level of impact on yield of treatment. While the average yields of treated plots were 0.62t/ha higher than untreated plots, in a majority of the cases assessed (65%), the impact of fungicide treatment on yield was not statistically significant. Yield varied both regionally and annually throughout the database. Fungicide treatment had the greatest positive impact on yield in the database in the Lothians in 1998, where average treated yields were 2.3 t/ha higher than average untreated yields in the same trial. However, in the Scottish Borders in 2006, average untreated yields were in fact 0.68 t/ha higher than the average treated yields in the same trial. Overall, 93 trials in the database included years where treated trials had higher yields than untreated trials (although only in 63 of these trials were the differences greater than 0.5 t/ha), while in 7 trials untreated yields were higher than treated yields. More detailed information about the Field Trials database used, variation in yield across time and geographical location, as well as the analysis undertaken and results obtained has been previously published and is available in Stetkiewicz et al. (2019).

Commercial practice database: Adopt-a-Crop

The third source of data used in this interdisciplinary comparison was the Adopt-a-Crop (AAC) database, which provides information regarding current practice on Scottish commercial farms.

Scope and purpose of the Adopt-a-Crop database

The AAC was initially funded by the Scottish Government as an advisory activity, designed to provide warnings about current and emerging pest, disease, and weed levels in crops to both farmers and government. Data were collected for immediate, rather than long-term use, and this project represents the first attempt to analyse the information collected in the AAC as a long-term database. The AAC contains information from 1983 onwards for a range of arable crops, collected from across Scotland. Information regarding location, sowing date, crop and variety planted provides a large amount of data about actual practice on Scottish commercial farms for the past three decades. Which farms are included in the AAC database varies from year to year, as these are selected by SRUC/Scottish Agricultural College (SAC) consultants, based in local SAC offices throughout the country. Advisors choose farms to include in the survey, with a maximum of 50% being client farms, in order to broadly reflect the acreage of each crop grown in their local area. The AAC is compiled through the Crop Health Advisory Activity, which is funded by the Scottish Government through its Veterinary and Advisory Service Programme (re-launched in 2016 as the Farm Advisory Service).

Following extensive cleaning and preparation of the AAC and the incorporation of additional information regarding varietal disease resistance from the Scottish Cereal Recommended Lists (SAC and HGCA 2012, 2011, 2010, 2009, 2015; SRUC 2013; SRUC and HGCA 2014), data from 2009 to 2015 was analysed, as a useful overlap with the farmer survey variety data, which covered 2011–2015. The AAC data were used to estimate the current levels of uptake of rotations and varietal disease resistance in the Scottish spring barley farmer population, using a larger and more geographically diverse sample than in the stakeholder survey, where the sample was necessarily limited in scope. Results from the AAC data and stakeholder survey were compared to understand how representative the surveyed farmers were in relation to the broader sector, and thus to what extent results from this survey can be used to gauge wider farmer attitudes.

Data analysis: comparisons across data sources

Varietal information from the AAC was analysed both to assess the disease resistance profiles of the fields included in the database, as well as to provide a comparison with the stakeholder survey and Field Trials data. As such, a number of metrics were produced, including: the proportion of varieties sown which were included in the Recommended List for that year, the proportion of varieties sown which were highly resistant to each disease and/or to two or more of the diseases, the most frequently sown varieties, and the percent of varieties sown which were listed as being suitable for a given market in the Recommended List (see Table 1 for a summary of each metric presented in this paper). A comparison was then made between the datasets for each metric, and correlations were used to assess association between the spring barley varieties listed in the stakeholder survey and AAC. As information was not available from the AAC regarding the intended market of the spring barley grown, the potential market(s) for each variety was determined using the Recommended List for a given year. A comparison of the varieties sown in the AAC with the 'best possible' varietal choice (calculated as the fully approved distilling variety with the highest mean resistance for RLS, scald, and powdery mildew in that year) was made, along with the proportion of varieties in each year which fell below the 'best possible' varietal choice, and therefore represent the potential to improve varietal disease resistance on-farm. A similar approach was taken to analyse rotation information. The proportion of fields reported to have had continuous barley or cereals in the AAC was calculated, and the potential for a link between previous crop and the use of highly resistant varieties was explored. These were then compared against stakeholder survey results, to provide a summary of the opportunities existing for improving rotational practice on commercial farms. Geographical location was assessed at regional level, to provide a comparison with the stakeholder survey results, Field Trial data, and Scottish Government farming statistics (Scottish Government 2015), to ensure that the data being compared were not heavily skewed by region, as this may have implications for farm size and structure, and thus farm management decisions. The regions and sub-regions used are those from the Scottish Government's Economic Report on Scottish Agriculture (ERSA) (2015), and are shown in Fig. 1, below.

Results

Varietal information

Frequently sown varieties

Of the varieties sown in the AAC, 22.1% were not found in the Recommended List for that year, as compared to 4.6% of varieties in the stakeholder survey. Eight entries in the AAC listed mixed variety sowing, where two or more spring barley varieties were sown in the same field

Table 1 Summary of metrics produced assessing the Adopt-a-Crop (AAC) and the sources to which each was compared

AAC metric:	Compared with	Analysis notes	Relevant table/ figure
Proportion of varieties sown which were on the Recommended List for that year	Stakeholder survey	Percentage	
Most frequently listed varieties	Stakeholder survey	Top ten most commonly listed for each source; correlations test for association between the two sources	Table 2
Disease resistance rating for each disease	Stakeholder survey; Field Trials database	Percentage highly resistant to one or more diseases; percentage highly resistant to two or more diseases	Table 3
Mean disease resistance by market	Stakeholder survey	Mean resistance rating for each disease; proportion resistant to one or more diseases	
Resistance rating by year	Stakeholder survey	Percent of varieties with each disease resistance rating by year; percent highly resistant per year; percent below best choice per year	Table 4
Potential market	Stakeholder survey	Percent of varieties with the potential (assessed via Recommended Lists) to be used in each barley market	
Previous crop	Stakeholder survey	Percent of fields with continuous barley/cereals in each source	Figure 3
Impact of previous crop on resistance rating	Stakeholder survey	Mean disease resistance rating for continuous and non-continuous barley	Table 5
Variation in sowing of continuous barley/cereals by year		Percent of fields in AAC with continuous barley/cereals each year	
Geographical spread	ERSA 2015; stakeholder survey; Field Trials database	Number and percent of farms in each sub-region of Scotland for each source	
Variation of farming practice by region		For each sub-region: percent of varieties highly resistant to two or more diseases, percent of fields with continuous barley, percent of fields with continuous cereals	
Regional variation in main market	ERSA 2015	Percent of fields with varieties of each market type, by sub-region	

at the same time. These entries were removed from all comparisons and proportions, as variety mixes cannot be directly compared to individual varieties in terms of resistance rating, and there were too few data points to analyse varietal mixing separately. It is interesting to note, however, this presence of varietal mixing on commercial farms, which was not found in the stakeholder survey.

The ten most frequently listed varieties in the AAC and stakeholder survey are shown below in Table 2. Three of the five most popular varieties were the same in both the AAC and stakeholder survey, and were also present in the Field Trials database. A number of varieties listed in the top ten for each source are also common to both sources. All of the top ten varieties in the stakeholder survey were listed in the AAC, and seven of the top ten in the AAC were listed in the stakeholder survey, and the varieties listed in the survey and AAC were strongly correlated (with a coefficient of 0.81) suggesting substantial overlap and comparability between the two data sources. This was taken to imply that IPM methods relating to variety choice which could be of use for one set of farmers (those surveyed) are likely to be applicable to the second set (the wider group of farmers in the AAC).

Disease resistance

The proportion of varieties which were highly resistant to each disease (a score of seven or higher on the standard nine point scale used by the SRUC/AHDB, where one is the lowest resistance and nine is the highest resistance is used throughout this paper (SRUC and AHDB, 2017)), as well as those highly resistant to two or more diseases is presented in Table 3. This showed fewer fields with highly resistant varieties to powdery mildew in the AAC than the stakeholder survey (although the figure was consistent with the Field Trials), but more fields with highly resistant varieties to RLS in the AAC than in the survey or Field Trials. The stakeholder survey had a higher percentage of varieties with high resistance to two or more

Table 2 Ten most frequently sown varieties in the AAC and survey, and their presence in the Field Trial databases*

	Number of times listed in AAC	Number of times listed by farmers in survey	Present in Field Trials database 1996–2014
Concerto	132	125	Yes
Optic	102	35	Yes
Waggon	79	23	Yes
Oxbridge	30	8	Yes
Propino	16	14	
Belgravia	15	28	Yes
Maresi	15		
Decanter	12		
Riviera	11		Yes
Westminster	11	Present	Yes
Odyssey	Present	17	
Chronicle	Present	7	
Golden Promise	Present	4	
Catriona	Present	3	

*Number of times listed in either the AAC or survey is only included where these varieties fall in the top ten for that given source; otherwise, 'Present' is used

Table 3 Proportion of varieties which were highly resistant to each disease*

	RLS (2012 onwards)	Scald	Powdery mildew	Two or more diseases	Any Resistance**
AAC	26.1%	14.2%	58.1%	17.4%	74.5%
Survey (farmer)	17.8%	19.3%	84.3%	28.7%	84.3%
Field Trials 2011–2014 (survey varieties only)	14.3%	13.6%	59%	15.9%	59.2%
Field Trials 1996–2014 (all varieties)	5.3%	15%	59%	12%	63%

*Proportion based on: total number of varieties for which varietal information is available (i.e. discounts varieties not in the Recommended Lists and variety mixtures). RLS proportions are based on the varieties in each dataset from 2012 onwards, when resistance ratings were first published. In this paper, 'highly resistant' is defined as a rating of 7 or above, on the standard 1–9 disease resistance scale

**Any Resistance is defined as the variety having a rating of 7 or above for one or more of the three diseases of interest diseases than the AAC or Field Trials. However, the proportion of varieties which were highly resistant to RLS, scald, or 'two or more diseases,' was below one third of the total in all cases. The proportion highly resistant to powdery mildew, by contrast, was over half in every source. Differences in disease resistance between malting and feed barley were similar in both the stakeholder survey and AAC, with more feed varieties being resistant to one or more diseases than malting varieties: 100% of AAC and 100% of survey feed varieties were resistant to one or more diseases, as compared to 67% of AAC and 82.5% of survey distilling varieties. For all three diseases, on average more than half of the fields in the AAC had a variety which was below the 'best choice' distilling variety for that year—for scald nearly 90% of varieties sown were below the best choice (see Fig. 2 and Table 4).

Barley market

The percentage of varieties which could be used in each market was comparable between the AAC and survey data, with a large majority having the potential (as determined by the Recommended List) to be sold for Distilling/Grain Distilling in both the AAC (73%) and the stakeholder survey (84%).

Crop rotation

Despite a substantial amount of variation in previous crop, the majority of fields in the AAC had been sown with consecutive cereals (420 out of 479), of which most were consecutive barley (339 out of 479); winter wheat was the second most frequently sown cereal crop (79 out of 479), with spring wheat and oats making up the remainder of the cereal crops. This mirrored the stakeholder survey results (see Fig. 3), with both sources showing over two thirds of farmers to be sowing consecutive barley in some fields each year. Mean disease resistance rating did not vary depending on previous crop sown for AAC fields, which is similar to the lack of variation in disease resistance rating from survey respondents who stated they often/always sowed consecutive barley versus those who did not (see Table 5). While the percentage of fields with continuous barley or cereals varied across years—continuous barley having a minimum of 60% (2013) and maximum of 76% (2010), and continuous cereals a minimum of 83% (2009 and 2013) and maximum of 93% (2012)—there was no clear trend showing any increase or decrease in this practice.

Regional variation

The AAC data were distributed in a way which is relatively representative of barley farming in Scotland; in all but two sub-regions, the proportion of farms included in the AAC was within 10% of that reported in the 2015 Economic Report on Scottish Agriculture (Scottish Government 2015). Both exceptions had a higher proportion of farms reported in the AAC than in the ERSA, but were within 20% of the ERSA figures: North East: + 18.7%, and Tayside: + 10.2%. Geographical spread in the AAC also matched well with that reported in the stakeholder survey, with both showing higher proportions of farmers located in the North East than in ERSA figures; however variation between proportions for Tayside were substantial, with 18.8% of AAC farms coming from the region, as compared with only 1% of surveyed farmers. The Field Trials 2011–2014 database had a much higher percentage of farms in the Lothian sub-region, and a much lower percentage in the North East and Highland areas than was seen in either the AAC or the ERSA.

Some differences in varietal resistance across regions were evident, with fluctuations from a low of 0% of varieties being highly resistant to two or more diseases (Fife) to a high of 30% (Ayrshire). Only one sub-region in the AAC had less than 50% of farmers sowing consecutive barley (Scottish Borders), suggesting that this is a common practice across the country. The minimum proportion of farmers sowing consecutive cereals in the AAC was 60% (Ayrshire) again suggesting this is common across all sub-regions. The majority of AAC fields in each sub-region sowed varieties which are listed in the Recommended List as distilling/grain distilling or brewing varieties—the exceptions being Ayrshire (55% feed barley), Clyde Valley (87.5%), and Orkney (60%).

Comparability of the data sources

Overall, the three data sources show a similar range of varieties in use, and thus resistance ratings and possible markets. The AAC and survey both have high proportions of fields with consecutive cereals or barley, and do not show an impact of this on the choice of disease resistance levels in the current crop. Geographical spread is also broadly similar between the sources, albeit with a trend in the Field Trials data towards more data from the South East of Scotland. The three sources were therefore deemed broadly comparable for the purposes of this study.

Discussion

Key opportunities to improve commercial practice

Considering current practice as recorded in the AAC, the potential for improving IPM decisions regarding varietal choice and crop rotation is appreciable. Less than one third of varieties in the AAC were highly resistant to RLS, scald, or two or more diseases, and less than two thirds were highly resistant to powdery mildew. The AAC data had a lower proportion of varieties in the Recommended List in a given year as compared to the farmer survey

Table 4 Best choice versus actual uptake of varieties in the AAC (expressed as a percentage of varieties recorded)*

Disease rating (1–9)	2015			2014		
	Powdery mildew	Scald**	RLS	Powdery mildew	Scald	RLS
3					41%	
4		83%			39%	
5				14%		14%
6	9%	**17%**	**71%**			51%
7					**20%**	**36%**
8	6%		29%	44%		
9	**86%**			**42%**		
AAC: Highly resistant***	92%	0%	29%	86%	20%	36%
AAC: Below Best choice****	15%	83%	0%	58%	80%	65%
Survey: Highly resistant				90%	31%	22%
Survey: Below best choice				68%	69%	78%

	2013			2012			2011	
Disease rating (1–9)	Powdery mildew	Scald	RLS	Powdery mildew	Scald	RLS	Powdery mildew	Scald
3		37%			23%			19%
4		41%			72%		1%	66%
5	13%		14%	21%		75%	23%	1%
6		4%	51%			**26%**		
7		**18%**	**34%**		2%		3%	9%
8	55%			53%	**2%**		44%	**6%**
9	**32%**			**26%**			**29%**	
AAC: Highly resistant	87%	18%	34%	79%	4%	0%	76%	15%
AAC: Below Best choice	68%	82%	65%	74%	97%	75%	71%	95%
Survey: Highly resistant	90%	23%	23%	76%	18%	9%	70%	28%
Survey: Below best choice	75%	77%	77%	76%	90%	5%	78%	100%

Disease rating (1–9)	2010		2009	
	Powdery mildew	Scald	Powdery mildew	Scald
3		8%		8%
4		61%		38%
5	47%		41%	12%
6		7%		10%
7	14%	17%	26%	26%
8	14%	**7%**	9%	**6%**
9	**25%**		**24%**	
AAC: Highly resistant	53%	24%	59%	32%
AAC: Below best choice	75%	93%	76%	94%

*Bold text indicates the rating of the 'best' choice variety for that year/disease combination (this will be the highest rated variety which has full recommendation for distilling in the Recommended List)

** Note: Scald is presented as 'Rhynchosporium' and RLS is presented as 'Ramularia' in the Recommended List; both have been updated in this table in line with the nomenclature used throughout this paper

*** 'Highly resistant' rows show the percentage of varieties for that year/disease combination with a disease resistance rating of 7 or more (on the standard 1–9 scale)

*** 'Below best choice' rows show the percentage of varieties for that year/disease combination which have a disease resistance rating below the maximum possible for that year/disease combination. This is of particular value for those years/disease combinations where no varieties have a resistance rate of 7 or more, such as for scald and RLS in 2015

data, suggesting a possible difference between the AAC and survey groups. However, market possibilities, mean disease resistance ratings, and variety popularity showed strong similarities between the two data sources.

Table 5 Impact of continuous sowing of barley on disease resistance rating on recorded varieties in the AAC and survey

	Mean resistance rating			
	Previous crop barley (AAC)	**Previous crop not barley (AAC)**	**Often/always sow consecutive barley (survey)**	**Sometimes/rarely/never sow consecutive barley (survey)**
Powdery mildew	7.4	7.6	7.5	7.9
Scald	4.5	4.6	4.4	4.6
RLS	6.2	6.3	6.2	6.1

Disease resistance rating runs from 1 (least resistant) to 9 (most resistant)

As a majority of farmers in both the AAC and survey sowed consecutive barley and/or cereals, there is also a possibility for widespread uptake of more varied rotations in Scotland. There is no evidence in the AAC data that farmers are 'trading off' one IPM method for another (e.g. more resistant varieties are not being sown after consecutive barley/cereals), so adoption of both more robust rotations and more highly disease resistant varieties could, in theory, happen in concert, reducing disease intensity on farm. Previous analysis of the Field Trials database considered in this paper has found that while fungicide use on spring barley in these trials did not statistically significantly impact yields in a majority of cases, varietal disease resistance plays a key role in determining yield difference (Stetkiewicz et al. 2019).

The lack of diversity in rotations used was noted by the Scottish Government (2012) in their survey of agricultural production methods, where it was found that 79% of arable land (excluding permanent crops and grass) was not in a crop rotation. This is in contrast to survey results, where a majority of UK cereal farmers self-reported as using crop rotations to control pests, diseases and weeds (ADAS 2002), and where UK wheat farmers considered rotations to be an important disease management tool (Maye et al. 2012). It is possible that Scottish and UK-wide practices differ, or that wheat farmers have taken up crop rotation more widely than other arable farmers. Conversely, self-reported data from farmers may not be a reliable indicator for this practice. Relatedly, a meta-analysis of self-reported pro-environmental behaviours found that although self-reported behaviour was generally highly associated with objective behaviour measures ($r=0.46$), 79% of the variance in association between the two remained unexplained (Kormos and Gifford 2014). Work assessing the validity of self-report measures for pesticide exposure found that, for orchardists asked to recall pesticides used over twenty years previously, sensitivity of recall was good to excellent (0.6–0.9) for the broad categories of insecticides, herbicides, fungicides, and for heavily used chemical classes, though lower and more variable for specific pesticides (0.1–0.6) (Engel et al. 2001). The limitations of relying solely upon self-reported data are evident from the variability of these results, making the connection between stakeholder survey data and commercial farm practice data particularly valuable.

Comparison of the three data sources

The analysis undertaken of the Field Trials database suggests that season rainfall and disease resistance are important factors when considering the impact of fungicide use on yields, see Stetkiewicz et al. (2019). Stakeholder survey results indicate that some farmers are willing to take up disease resistant varieties, rotations, and forecasting disease intensity—there is therefore no inherent attitudinal problem which prevents farmers from using these IPM methods (see Stetkiewicz et al. 2018). The AAC results add to this picture, by confirming that in a larger sample of farmers, rotation practices and varietal resistance usage could, at least in theory, be substantially improved upon. Further analysis including forecasting of disease intensity would be useful in expanding this work linking commercial practice with stakeholder surveys, but information regarding weather-related decisions was not recorded in the AAC. The AAC does, however, give a snapshot of current practice on commercial farms across Scotland, and highlights the opportunities for improving IPM practice in spring barley production.

Limitations of the research

Using long-term information creates both difficulties and opportunities for research, as does the attempt to triangulate three separately collected datasets. While long-term data may be useful in order to convince farmers and policy makers of the widespread applicability of research outputs (Wiik 2009), collecting and collating such data requires an unusual level of institutional commitment over a prolonged period. Comparing long-term datasets is likely, as was the case in this work, to raise issues around the adequacy of data collection procedures, due to the necessary involvement of many individuals in data collection (Clutton-Brock and Sheldon 2010), and the lack of directly comparable metrics, particularly where datasets have been collected for purposes other than those of the project at hand. Due to the way in which the long-term databases used in this analysis were collected, and their original purposes, this analysis was only able to concern itself with a small subset of potential issues of relevance to IPM. Additional information, particularly in relation to other IPM components of relevance such as tillage systems (including minimum tillage), crop

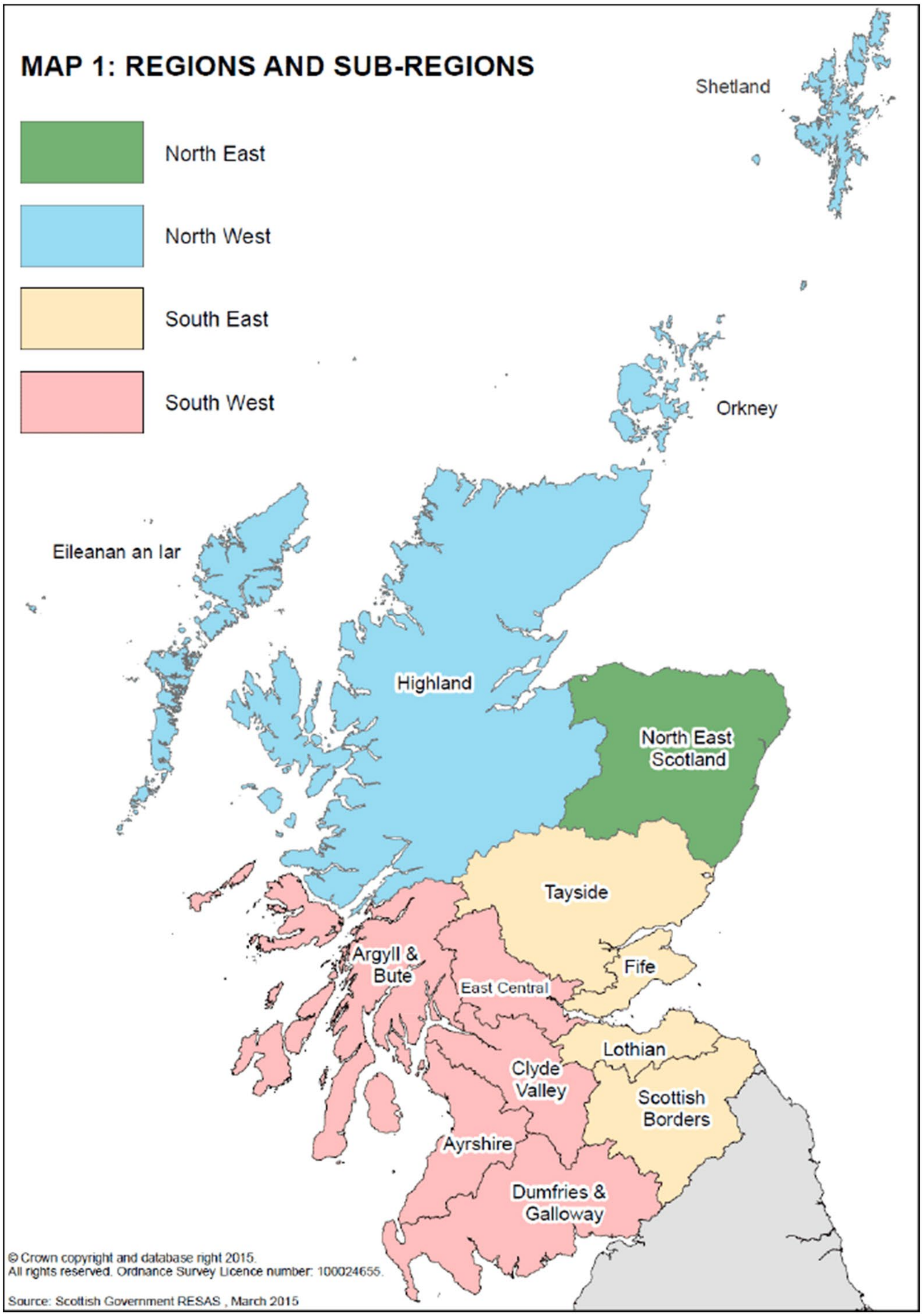

Fig. 1 Regions and sub-regions of Scotland, taken from Scottish Government (2015)

management tools and technology, differing types of rotation practice, fertilizer use, other (non-fungicidal) plant protection products used would have added substantial depth to this analysis.

It is also important to bear in mind that the sample of farmers surveyed is likely biased by discussion of IPM as an artefact of the survey methods (which aimed to maximise response rate), as the events at which the

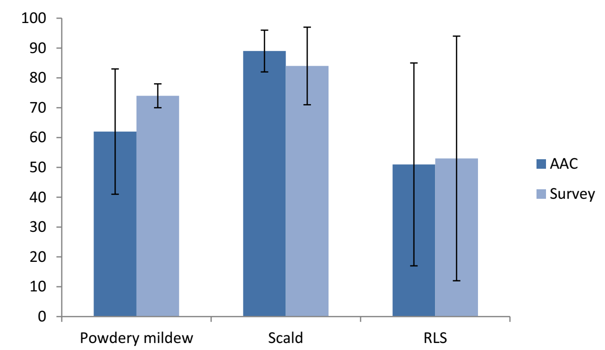

Fig. 2 Percent of varieties in AAC and Survey which are below the best choice for that year (mean across all years) for the specified disease*. *Error bars indicate standard deviation. It is worth noting here that RLS resistance ratings are not included in the 2019 season's recommended list, due to concerns over consistency (SRUC and HGCA 2019)

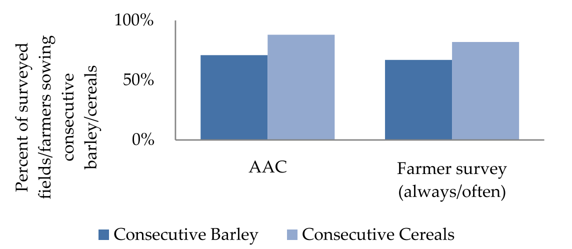

Fig. 3 Comparison of percentage of AAC fields and farmer survey responses indicating consecutive barley/cereals

survey took place were also fora for discussing crop protection, see Stetkiewicz et al. (2018) for more detail. This does mean that survey results should be interpreted as a 'best case' scenario in terms of openness to IPM uptake, and that the results cannot be assumed to be representative of all Scottish farmers. However, the use of the AAC data, which was not collected at disease-related events allowed for further analysis of IPM uptake to be undertaken without this bias at play, though introduced its own sources of bias, such as being sourced in large part from SAC client farms. As similar results were obtained in terms of use of resistant varieties and continuous barley/cereal growing, this suggests that although the survey sample may have been biased, results gathered regarding farm practice still provide a generally accurate reflection of management. Expanding this snapshot picture of farmer opinion in future work could give a broader understanding of IPM potential.

The gap between the 'best possible' and actual varieties sown by farmers in both the stakeholder survey and AAC work highlights that the existence of highly resistant cultivars of spring barley which are suitable for distilling is not enough in itself to ensure that disease resistant varieties are widely sown. Further research into what is preventing the widespread uptake of these varieties is needed to pinpoint the barriers to uptake. Barriers to uptake of highly resistant varieties exist, particularly for the distilling industry, where there is a preference for varieties which malt in a consistent manner and produce high spirit yields (Bringhurst and Brosnan 2014). Using new varieties can therefore pose a risk to their production systems. Previous work (Vanloqueren and Baret 2008) on the under-adoption of highly resistant varieties of wheat in Belgian systems has found twelve key factors which prevent uptake, several which might be of relevance to the Scottish spring barley sector; in particular breeding objectives of seed companies being skewed towards producing high yielding varieties, and the potentially contradictory objectives of companies which both develop new varieties and the fungicides which are applied to them.

It is important for growers to have confidence in resistance breeding ratings, so that when growing a highly resistant variety, they are able to reduce input use. RLS resistance ratings are relatively new, having been added to the SRUC/HGCA recommended lists in only 2012. In addition, resistance ratings were not included in the 2019 recommended list, due to concerns over consistency (SRUC and HGCA 2019); farmers may therefore have less confidence in the resistance rating for this disease. However, more confidence may be felt towards other resistance rating scores. In scald, for example, research has confirmed that for highly resistant varieties, farmers can spray one time fewer, removing the T1 (stem extension) fungicide application without negatively impacting yield (Bingham et al. 2020). Work must be done, therefore, to not only breed highly resistant varieties which meet key product specifications, but to elicit confidence in farmers around disease ratings in order to alter spraying practices.

Development of a wide range of highly resistant, high yielding, and market-appropriate varieties may need to be undertaken with the involvement of all stakeholders, including breeders, Recommended List committees, end-users such as maltsters, brewers, and farmers themselves, to ensure that new varieties provide viable alternatives to current varieties, which match the needs of both farmers and industry.

Interdisciplinary method

While interdisciplinary research has been recognised as being of particular use in optimising IPM (Birch et al. 2011), the use of a diverse range of data to assess IPM potential is novel—synthesizing stakeholder engagement, commercial farm data, and modelling of long-term data in a single research outcome does not yet appear to have been reported in relation to IPM. Calls have been made for more integration of stakeholder engagement into agricultural and environmental research to improve research quality and relevance (Gramberger et al. 2015; Lamichhane et al. 2016; Lefebvre et al. 2014; Murray-Rust et al. 2014; Phillipson et al. 2012), yet there remain relatively few stakeholder surveys of pest and disease control attitudes and methods amongst cereal farmers.

This project presents the first synthesis of farmer surveying, long-term experimental results, and commercial farm data. This gives the opportunity to assess key questions regarding IPM uptake and the future of IPM in this sector from multiple viewpoints, and to consider these in an unusually integrated manner. It also allows for some of the difficulties inherent in using long-term databases collected for other purposes to be mitigated, as the three separate sources of information can be combined to overcome the weaknesses inherent in each. However, the difficulty of finding or creating three comparable sources of data for a given farm system is not to be underestimated. As described above, when attempting to compare data from sources not designed to be used in this way, it is crucial to ensure broad comparability of the data before attempting to draw conclusions. In some instances, it may not be feasible to acquire economic, field experiment, and social survey data for a particular system. However, where possible, such a synthesis can be of use in encouraging farmers to take up IPM measures, and policy makers to appreciate the potential benefits of IPM, as it provides information about a range of scenarios and across a number of farm conditions, and takes into account both biological and social data.

Conclusions

The findings of this project support the idea that there is potential for IPM uptake to be improved in Scottish spring barley production, thereby reducing fungicide use without negatively effecting yield levels, based on a combination of modelling of long-term data, stakeholder surveying, and commercial practice data. For the studied system, there is clear potential for reducing the need for fungicide use through the increased sowing of highly resistant barley varieties. Use of crop rotations (particularly those with non-continuous cereals) could also be substantially expanded upon in the sector, potentially leading to reduced disease pressure. In addition, the novel interdisciplinary approach taken in this work provides a template that may be useful in assessing IPM in other contexts around the world.

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Author contributions
CT, AB, FB, RE, and SS were involved in designing the study and analysing and interpreting the data. FB was integral for acquiring the AAC and Field Trials data used in this work. AB, CT, and SS worked together to develop the stakeholder survey used. SS drafted the manuscript, which was revised by CT, AB, FB, and RE. All authors read and approved the final manuscript.

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Availability of data and materials
Some of the data described in this paper are confidential and not available for public access. For more information about which data are confidential, and to view the publicly available data, please see the lead author's electronic thesis (Stetkiewicz 2017).

Declarations

Ethics approval and consent to participate
Ethics approval was waived for the farmer and agronomist stakeholder survey based on the University of Edinburgh's School of Biological Sciences Ethics Assessment Form via self assessment on 4 November 2015. A Scottish Government Rural and Environment Science and Analytical Services Division Research Approvals Proforma for the same survey was approved on 6 November 2015.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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