An interdisciplinary assessment of the potential for improving Integrated Pest Management practice in Scottish spring barley

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Declaration

This is to certify that that the work contained within has been composed by me and is entirely my own work. No part of this thesis has been submitted for any other degree or professional qualification.

Contents

Table of Figures

Table of Tables

Terms Used

AAC – Adopt a Crop Database. The Adopt a Crop database is a database of commercial practice, with information gathered from farms across Scotland. Information about key arable crops, such as varieties sown, sowing date, and previous rotation on the field is collected in this database.

Absolute Yield Difference – the value obtained by subtracting untreated yield from treated yield values for a given field trial. This is used as both a plot-level calculation in Chapter 2 and a means level calculation in Chapter 3.

ANOVA – Analysis of variance. A statistical test used to determine if there are statistically significant differences between the means of three or more independent groups.

Any Resistance – used to denote a variety which is highly resistant to at least one of the three diseases studied in this thesis

AUDPC – Area under the disease progress curve. This value provides a quantitative summary of disease severity over a given period of time. Here calculated using the standard trapezoidal method (for more detail on the calculation, see section 2.2.2).

GLM – Generalised linear model. A model that uses the basic methods of general linear regressions, but which allows for response variables with a non-normal error distribution, by basing the analysis on maximum likelihood instead of least squares.

Highly disease resistant – varieties with a disease resistance rating of seven or more (out of a possible nine as determined by the SRUC/HGCA Cereal Recommended Lists)

Independence maintainer – here used to refer to a farmer whose primary financial goal is to achieve the level of profit necessary to avoid being dependent. The particular dependence in question may vary, but could include the need for income from outside the farm, or reliance on loans.

Integrated Pest Management (IPM) – an ecosystem based approach to pest and disease management which aims to minimise pesticide use through a combination of management techniques

mlo gene – recessive alleles of the barley Mlo locus caused by mutation, which gives broad spectrum resistance to mildew (caused by *Blumeria graminis* f.sp. *hordei*)

Pest – in this thesis, 'pest' is used to denote an organism (fungal, viral, bacterial, or animal) which attacks a crop.

Pesticide – here used to refer to a commercially available chemical compound which is applied to a crop in to reduce damage inflicted by a pest (can be applied preventatively, before the pest attacks the plant, or curatively, after the pest attacks the plant).

Profit-maximiser – here used to refer to a farmer whose main financial priority is not achieving a specific profit, but rather making the largest profit possible (this may be over the short or long term).

Profit-satisfier – here used to refer to a farmer who has a specific goal regarding amount of profit (s)he wants to achieve in a given year, and once this goal is met, will do little to increase profit further, as compared with a profit-maximiser.

R^2 – (also known as the coefficient of determination). A statistical measure of the distance between the observed values and the fitted regression line.

Relative Yield Difference – represents the absolute yield difference as a proportion of the treated yield.

REML – Residual maximum likelihood. A method used to estimate the parameters of a statistical model (based on maximising the likelihood of obtaining the observed values), which is particularly well suited to analysis when there are unknown parameters in a model or unbalanced data is being used.

Risk – here used to refer to the probability of a given, negative outcome or event occurring.

Season rainfall – the anomaly classification of the average amount of rainfall in a growing season of February to August (inclusive), such that a given growing season is classed as ‘wet,’ ‘dry,’ or ‘average’.

Season temperature – here defined as the anomaly classification of the average temperature in a growing season of February to August (inclusive), such that a given growing season is classed as ‘wet,’ ‘dry,’ or ‘average’.

Win-win – here defined as a situation in which multiple benefits or steps towards multiple goals are achieved by a single action or decision; in the context of this thesis, this is normally when a given management practice both reduces the need for fungicide inputs, while maintaining or increasing yields/profits

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Abstract

Integrated Pest Management (IPM) has long been promoted as a means of reducing reliance on pesticide inputs as compared to conventional farming systems. Reduced pesticide application could be beneficial due to the links between intensive pesticide use and negative impacts upon biodiversity and human health as well as the development of pesticide resistance. Work assessing the potential of IPM in cereal production is currently limited, however, and previous findings have generally covered the subject from the perspective of either field trial data or social science studies of farmer behaviour. This thesis attempts to help to address this knowledge gap by providing a more holistic assessment of IPM in Scottish spring barley production (selected because of its dominance in Scotland's arable production systems), in relation to three of its most damaging fungal pathogens: *Rhynchosporium commune*, *Blumeria graminis* f.sp. *hordei*, and *Ramularia collo-cygni*. Several IPM techniques of potential relevance to the sector were identified, and the prospects of three in particular – crop rotation, varietal disease resistance, and forecasting disease pressure – were assessed in several ways.

Preliminary analysis of experimental field trial data collected from 2011 – 2014 across Scotland found that the majority of spring barley trials in this period (65%) did not show a statistically significant impact of fungicide treatment on yield, with the average yield increase due to fungicide application being 0.62 t/ha. This initial analysis was expanded upon using stepwise regressions of long-term (1996 – 2014) field trial data from the same dataset. Here, the difference between treated and untreated yields could be explained by disease resistance, average seasonal rainfall (whereby wetter seasons saw an increased impact of fungicide use on yield), and high combined disease severity.

Stakeholder surveying provided information about current practice and attitudes towards the selected IPM techniques amongst a group of 43 Scottish spring barley farmers and 36 agronomists. Stakeholders were broadly open to taking up IPM measures on farm; sowing of disease resistant varieties was most frequently selected as the best technique in terms of both practicality and cost, though individual preference varied. However, a disparity was seen between farmer perception of their uptake of IPM and actual, self-reported uptake for both varietal disease resistance and rotation. Farmers and agronomists

also overestimated the impact of fungicide use as compared with the field trials results – the majority of stakeholders believed fungicide treatment to increase yields by 1 - 2 t/ha, while the majority of 2011 – 2014 field trials had a yield difference of under 1 t/ha. The reasons behind these differences between perception and practice are not currently known.

Finally, an annual survey of commercial crops, gathered from 552 farms across Scotland (from 2009 – 2015), highlighted two gaps where IPM practice could be improved upon. Firstly, relatively few of the varieties listed in the commercial crops database were highly resistant to the three diseases – 26.1% were highly resistant to Ramularia, 14.2% to Rhynchosporium, and 58.1% to mildew. Secondly, 71% of the farms included in the database had planted barley in at least two consecutive seasons, indicating that crop rotation practices could be improved.

The overarching finding of this project is that there is scope for IPM uptake to be improved upon and fungicide use to be reduced while maintaining high levels of yield in Scottish spring barley production. Incorporating experimental field data, stakeholder surveying, and commercial practice data offered a unique view into the potential for IPM in this sector, and provided insights which could not have been gained through the lens of a single discipline.

Lay Summary

Integrated Pest Management (IPM) can potentially reduce reliance on pesticides, and thus the negative impacts on biodiversity and human health which are linked with intensive pesticide use, while still maintaining high crop yields. Three IPM techniques were assessed in this project in relation to spring barley in Scotland – crop rotation, using highly disease resistant varieties, and forecasting disease pressure. Three key diseases of spring barley were studied: mildew, Rhynchosporium, and Ramularia.

The work presented in this thesis indicates two key points. Firstly, there is a gap between the willingness to take up IPM in surveyed farmers and the actual uptake of IPM measures. Secondly, there is potential for IPM measures to reduce the need for fungicides while maintaining high yields. Fungicide treatment did not significantly increase crop yields in a majority (65%) of field trials run from 2011 – 2014, although fungicide treated plots did have higher yields on average than untreated. This average difference between treated and untreated yields was studied in more detail using field trial data from 1996 – 2014, and was linked to wetter seasons, disease severity, and varieties with low disease resistance.

Farmers were open to taking up all three IPM techniques, though they overestimated how often they currently used crop rotation and disease resistant varieties, as compared to their own self-reported farm history data. Farmers and their advisors also overestimated the impact of fungicide use on yield as compared to the field trial experiments.

Finally, an annual survey of commercial crops was studied for 2009 – 2015. Less than one-third of varieties listed by farmers in the database were highly resistant to either Rhynchosporium or Ramularia, and more than two-thirds of farms in the database had planted barley in the same field at least two years in a row- which can increase disease burden. It is therefore possible to improve current commercial practice for both disease resistance and crop rotation.

The overarching finding of this project is that there is scope for IPM uptake to be improved upon, and fungicide use to be reduced while maintaining high levels of yield in Scottish spring barley production. Incorporating experimental field data, stakeholder

surveying, and commercial practice data offered a unique view into the potential for IPM in this sector.

Chapter 1 General introduction

1.1 Importance of Integrated Pest Management

Pesticide use became widespread during the Green Revolution (McLaughlin & Mineau, 1995; Robinson & Sutherland, 2002) as a means of increasing crop yields by limiting pest and disease damage (Cooper & Dobson, 2007). The application of pesticide has the potential to lower greenhouse gas emissions intensities by increasing yields without significantly altering greenhouse gas emissions caused by producing the crop itself, (Berry et al., 2008; Cooper & Dobson, 2007), and has additional benefits such as reducing disease vector populations (Cooper & Dobson, 2007). Pesticide use has been shown to reduce disease severity (AHDB, 2017a; Wegulo et al., 2012; Hysing et al., 2012). The effect of pesticide on yields, however, is far from clear: while some field studies show overall increases in yield (Paul et al., 2011; Willyerd et al., 2015; Kelley, 2001), others find no increase (Swoboda & Pedersen, 2008; Poysal et al., 1993), and many present highly mixed results (Priestley & Bayles, 1982; Cook & King, 1984; Wiik, 2009; Cook et al., 2002; Mycroft, 1983; Gaspar et al., 2014). Intensive pesticide use also has a variety of concurrent detrimental effects, such as negative impacts on soil health and soil ecosystems (Chen et al., 2001; Min et al., 2002; Walia et al., 2014; Vieira et al., 2007), or non-target toxicity linked to biodiversity loss in agricultural areas (McLaughlin & Mineau, 1995; Robinson & Sutherland, 2002; Geiger et al., 2010; Beketov et al., 2013). Where residue levels are high, pesticides can also cause direct harm to humans via consumption, in which case potential for toxic exposure is higher than for those involving drinking water or inhalation (Margni et al., 2002). The use of pesticides also carries with it the risk of entering the 'pesticide treadmill,' whereby spraying for a specific disease removes natural competition, and thus promotes an increase in other, normally milder diseases (Van den Bosch, 1978). Pesticide use also puts intense selection pressure on the target organism, often leading to resistance development, and thus the need to develop new pesticides for control (Brent & Hollomon, 2007). Reducing pesticide use, therefore – if this can be achieved without impacting yields – could offer an opportunity to reduce the negative environmental and health impacts associated with crop production, slow pesticide resistance development in pathogen populations, and reduce the cost of production.

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 is an ecosystem approach which combines diverse management practices in order to minimize the use of pesticides while protecting crops from pests and pathogens (FAO, 2017), and has been found to improve the overall environmental sustainability of farms, as compared to conventional pesticide use situations (Lefebvre et al., 2014). IPM can encompass a number of techniques to reduce pathogen population levels, including spraying pesticide where appropriate (Environmental Protection Agency, 2016). Three IPM techniques which may reduce the need for fungicide use are focused on in this thesis: crop rotation, disease resistance, and forecasting disease pressure.

1.1.1 **Previous rotation**

Crop rotation has a long history as a farm management technique, going back thousands of years (Curl, 1963), and can help to maintain the fertility of soils (Taylor et al., 2006; Watson et al., 2002), reduce pathogen pressure (Curl, 1963; Kirkegaard et al., 2008; van Bruggen, 1995), increase yields (Mazzilli et al., 2016; Bailey et al., 2001; Deike et al., 2008) and reduce farmer reliance on fungicides (Andert et al., 2016). For fungal pathogens which overwinter, crop rotation can reduce pathogen population build up, by preventing overwintering organisms from having a food source in the following growing season; this then reduces the number of pathogens present when the next host is planted, reducing the number of potential inoculum sources (Curl, 1963). For crop rotation to be successful then, in terms of disease reduction, it is important to rotate crops in such a way that non-host crops follow host crops for the duration of the pathogen’s potential survival in crop debris, soil, or volunteers. This can be difficult in areas where the number of commonly produced crops for use in an arable rotation is low, such as Scotland, where the only combinable crops with sufficient market share to be recorded by the Scottish Government in 2016 were barley, wheat, oats, rye, oilseed rape, and peas/beans (Scottish Government, 2016b), and where all but the oilseed rape, rye, and peas/beans are potential hosts for *Ramularia collo-cygni* (see 1.2.3, below). Diverse crop rotations may also be difficult in practice, given the long-term nature of fixed rotation plans; farmers have ranked long rotations as a production risk, due to the instability of market prices (Ridier et al., 2012). Farmers are aware, however, of the benefits that crop rotation can bring, and many attempt to integrate rotations or break crops into their farm management strategies (Bailey et al., 2009; Maye et al., 2012).

1.1.2 Disease resistance

Genetic disease resistance is another IPM tool which has potential to reduce the need for fungicide use. Research into resistance genes has resulted in cultivars which are bred to have high levels of disease resistance for a number of key diseases, including mildew, Rhynchosporium, and Ramularia. While disease resistance can break down over time (Burdon et al., 2014; Poland et al., 2009), new varieties and new resistance techniques (Burdon et al., 2016) continue to provide resistant varieties for farmer use. SRUC in conjunction with the Agriculture and Horticulture Development Board (AHDB) – previously the Home Grown Cereals Authority (HGCA) – produces annual Cereal Recommended Lists for Scotland. These Recommended Lists provide farmers with information about a range of characteristics for oat, wheat, and barley varieties which are on the market, including disease resistance levels. Disease resistance is calculated based on 3-5 years of data from untreated trials across Scotland (HGCA, 2014). Resistance scores are based on a scale of one (lowest resistance) to nine (highest resistance), however the actual disease severity seen on varieties with a rating of, for example, six, may vary from year to year. This is due to the fact that the varieties with the highest/lowest disease severity in a given dataset are used as a reference point for comparing the other varieties (HGCA, 2014). Disease resistance ratings are therefore not directly comparable across years, although an attempt is made to ensure that varieties with a resistance of nine are essentially disease-free every year (HGCA, 2014). High disease resistance ratings have been linked with increased yields and reduced disease levels in untreated fields of wheat (Cook & Thomas, 1990; Loyce et al., 2008) therefore providing a potential opportunity to reduce the need for fungicide use.

1.1.3 Forecasting disease pressure

Forecasting disease pressure based on weather is an IPM technique which attempts to use the links between certain weather conditions and disease severity to determine when applying fungicide is necessary. For example, high levels of moisture at GS 30-39 are linked to higher levels of Rhynchosporium infection/spread (Avrova and Knogge, 2012; Atkins et al., 2010), as described below (see section 1.2.2) so moisture levels at this growth stage are a known risk factor. Forecasted rainfall during this period would therefore increase the risk for Rhynchosporium development, and a reason to apply fungicide to the crop, while dry weather would be seen as meaning application was likely to be unnecessary. The use of meteorological variables as metrics in fungicide decision making is often incorporated into risk algorithms, whereby a set of IPM techniques, potentially including varietal disease resistance levels and crop rotation history, and bio-physical factors are quantified as a numerical description of risk, such that when a given threshold is reached, fungicide application is deemed to be appropriate (Twenström et al., 1998; Makowski et al., 2005; Gladders et al., 2001; Burnett et al., 2012). Some of these tools are more proscriptive, and focus on economic thresholds and returns at a given pest level, while others are more subjective, providing different risk categories such that treatment decisions can be determined by farmer tolerance or aversion to risk. These types of risk algorithm are generally developed for an individual crop-disease combination, taking into account the disease life-cycle, local weather patterns, and previous levels of disease, and are tested against field trial datasets to test their predictive ability.

1.2 Spring barley – a crop of local and global importance

The variability of yield response to pesticide in the literature, and the potential for IPM to reduce disease makes clear the need for additional research to better understand the likely impacts of management changes. In this thesis, yield, pesticide use, and several IPM strategies will be analysed in the context of spring barley production in Scotland. Barley is one of the top five crops in the world, with an average of 53,572,792 hectares harvested each year, globally (FAOSTAT, 2013), 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, 2016b). The dominance of spring barley in Scotland is largely due to the malting industry, which offers a price premium, though most barley is ultimately destined for feed (Scottish Government, 2015a) after failing to meet the stringent malting requirements for nitrogen levels, grain skinning, etc. The key pests of barley are fungal pathogens, which have been estimated to cause a total yield loss of 15% worldwide (Oerke & Dehne, 2004) and 14% in the USA (James et al., 1991). To combat these diseases, a total of 187,173 kg of fungicide was applied to Scottish spring barley in 2014 representing 42% of the total amount of pesticide applied to the crop (Scottish Government, 2014). 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. Three fungal diseases of particular importance to Scottish spring barley production are assessed in detail in this PhD: mildew (caused by *Blumeria graminis* formae specialis *hordei*), Rhynchosporium (caused by *Rhynchosporium commune*) and Ramularia (caused by *Ramularia collo-cygni*).

1.2.1 **Powdery mildew of barley**

Mildews are among the world's most commonly encountered plant diseases and can affect a wide range of hosts (Glawe, 2008; Schulze-Lefert & Vogel, 2000; Panstruga & Schulze-Lefert, 2002). *Blumeria graminis* formae specialis *hordei*, the barley-specific form of the pathogen, may be able to infect wild relatives of barley, but has no other known hosts in the UK (Jarvis et al., 2002), and recent concerns that host expansion might be occurring due to crossing with *B. graminis* formae specialis *triciti* (a pathogen on wheat), appear to be unlikely (Walker et al., 2011). Mildew is the second most commonly targeted disease by Scottish farmers when applying fungicides (Scottish Government, 2014). Yield reduction due to mildew in the range of 11 – 17% for susceptible varieties have been recorded (Lim & Gaunt, 1986; Hysing et al., 2012).

B. graminis f.s. *hordei* is an obligate biotroph, which must colonise the plant in order to obtain nutrients (Duplessis et al., 2014) – its life-cycle is summarised in Figure 1-1. Barley is most susceptible to *B. graminis* f.s. *hordei* at early growth stages, with increasing resistance as the plant ages (Russell et al., 1976), and early infections impact yield potential to the same extent as later infections (there is no compensatory mechanism in the plant for early green leaf area loss) (Lim & Gaunt, 1986). Overwintering is possible, and has been reported in *B. graminis* in the UK on cereal stubble (Turner, 1956). Inoculum from nearby farms growing winter or spring barley is likely to be an important source of infection, as spores of *B. graminis* have been demonstrated to travel approximately 650 km by air-borne dispersal from the UK to Denmark (Hermansen et al., 1978).

Due to this potential for long-range dispersal, crop rotation on an individual farm scale may be able to delay epidemics, by reducing the inoculum present at the start of the growing season, but is unlikely to prevent them (Jenkyn, 1970) as inoculum is likely to arrive in the field at some point during the growing season. The incidence of powdery mildew has been shown to increase with delayed sowing of spring barley (Last, 1957) and later-sown, susceptible varieties show a larger yield reduction from mildew than early-sown trials (Last, 1954). Crop diversification, which involves planting varieties of barley which are susceptible to different races of the pathogen in neighbouring fields, has been suggested as a way of reducing severe epidemics (Oxley & Burnett, 2010), and the Recommended Lists provide diversification scheme information to allow farmers to undertake this (SRUC & AHDB, 2017). Varietal disease resistance is a key way of managing mildew, as a number of varieties are highly resistant – fourteen out of the fifteen varieties on the 2017 Recommended List (SRUC & AHDB, 2017). Mildew resistance currently is primarily conferred by the *mlo* gene, with some more specific resistance from the *mla* gene (Schulze-Lefert & Vogel, 2000); varieties with *mlo* resistance have been widely cultivated since the 1980s, and *mlo* resistance is considered highly durable (Jørgensen, 1992). Varietal resistance is all the more important, as the risk of *B. graminis* f.sp. *hordei* developing resistance to fungicides is high – of the eight categories of fungicides assessed by the Fungicide Research Action Group UK (2015), two had high risk, five moderate, and only one (multi-site activity fungicides) had low risk.

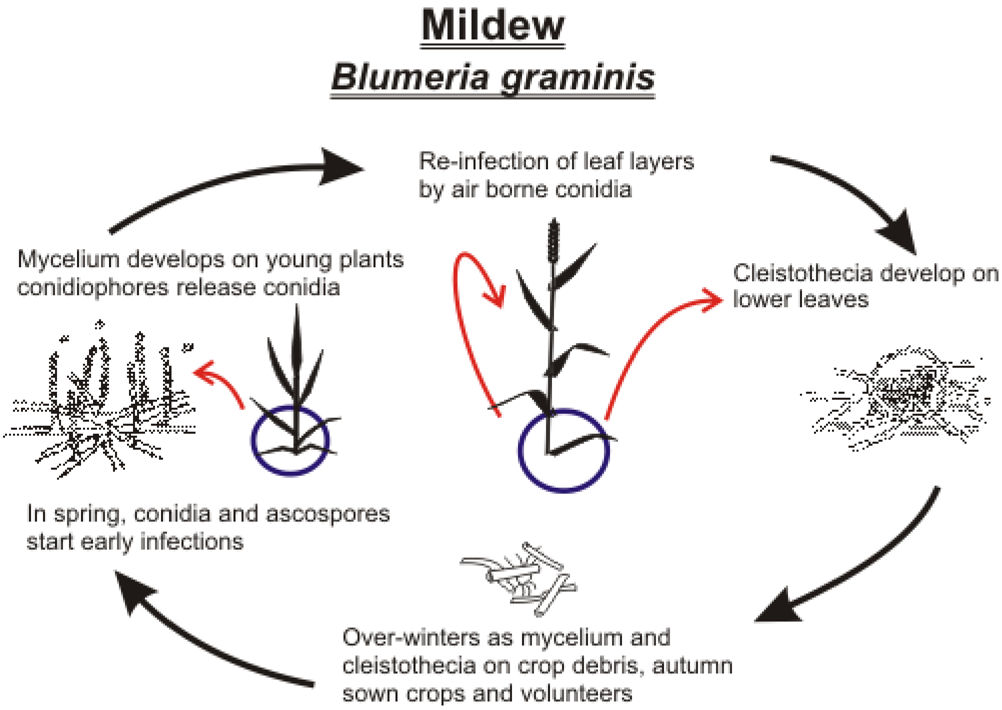


Figure 1-1: Life-cycle of *Blumeria graminis* (cereal mildew)*

*Taken from (AHDB, 2016b)

Weather variables

Mildew thrives in conditions which are warm and humid, with wind required for spore dispersal – however, high levels of humidity and rainfall can reduce disease severity by preventing sporulation (Jarvis et al., 2002; Oxley & Burnett, 2010). Two models have been created assessing the risk factors which lead to mildew epidemics in spring barley in the UK, with Channon's (1981) expanded version of Polley and King's (1973) original model calculating a three day running risk level by summing the number of risk criteria which are met (shown in Table 1-1) on days where relative humidity is over 78% at 9am and identifying days with a value of two or more as high risk. The optimum temperature for *B. graminis* development appears to be 15 – 20°C (Yarwood, 1957; Cherewick, 1944).

Table 1-1: Mildew risk model variables

Weather variable	Models which included this variable	
Relative humidity > 78% at 9am		Channon (1981)
Maximum air temperature > 15.6C	Polley and King (1973)	Channon (1981)
Minimum sunshine: 5 hours	Polley and King (1973)	Channon (1981)
Rainfall maximum: 1mm	Polley and King (1973)	Channon (1981)
Run of wind >246 km	Polley and King (1973)	Channon (1981)

1.2.2 Rhynchosporium

Rhynchosporium commune has long posed a major, global threat to barley production (Avrova & Knogge, 2012), with reported yield reductions of 30 – 40% possible (Shipton et al., 1974, cited in Zhan et al., 2008). *R. commune* is a pathogen on barley and other *Hordeum* species, as well as *Bromus diandrus* (Avrova & Knogge, 2012), a wild grass found throughout Europe (Clayton et al., 2016).

R. commune is currently considered a hemibiotrophic pathogen with a long asymptomatic phase in the plant (Zhan et al., 2008), following the revised guidelines for pathogens put forth by Oliver *et al.* (2004). The disease (Rhynchosporium) can be seed borne, but the most important source of inoculum is likely to result from overwintering on debris and stubble from previous crops (Avrova & Knogge, 2012). *R. commune* is polycyclic (see Figure 1-2), so several generations of spores may be produced in a single barley growing season, providing additional inoculum (Avrova & Knogge, 2012).

DNA of *R. commune* has been reported from barley samples as early as GS 13 (Atkins et al., 2010), which coincides with the GS of infection in other field studies (Salamati & Magnus, 1997; Ryan & Clare, 1975; Rotem, 1976; Xue & Hall, 1992). Secondary infection of upper leaves occurs during stem extension, GS 30 – 39, and it is during this period when rainfall is the most important factor for epidemic development (Atkins et al., 2010).

Crop rotation may reduce epidemics by decreasing the amount of primary inoculum available to infect the crop early in the season (Shipton et al., 1974). Delayed sowing may also be beneficial, as there may be less *R. commune* remaining from the previous season to infect the crop (Zhan et al., 2008). Decreasing sowing density or the rate of nitrogen application may reduce disease severity by decreasing canopy density and therefore leaf wetness within the stand (Hoad and Wilson, 2006, cited in Zhan et al., 2008); however these methods can decrease yields and may not be economically rational. Varieties of spring barley which are highly resistant to *R. commune* have been available for decades, though their prevalence in the Recommended Lists fluctuates over time; in 2015, for example, no varieties had a resistance rating of seven or more (SRUC & HGCA, 2015), though in 2014 six of the fourteen varieties in the list had a rating of seven or above (SRUC & HGCA, 2014). The sudden change between these two years is partially due to the removal of varieties from the list, and partially the gradual downgrading of varieties from one year to the next – several varieties were moved from a seven to a six rating in 2015 (SRUC & HGCA, 2015). In 2017, one variety in the Recommended List is highly resistant to Rhychosporium (SRUC & AHDB, 2017).

Despite the fact that several fungicide groups currently give good control (AHDB, 2017a), varietal resistance is important for the control of this disease, as there is a history of

R. commune overcoming fungicides (Fungicide Resistance Action Committee, 2013). Some fungicide resistance has been reported in two of the seven available groups of fungicides in the most recent Fungicide Resistance Action Group UK report, and a further two fungicide groups are thought to be at moderate risk for resistance developing (2015).

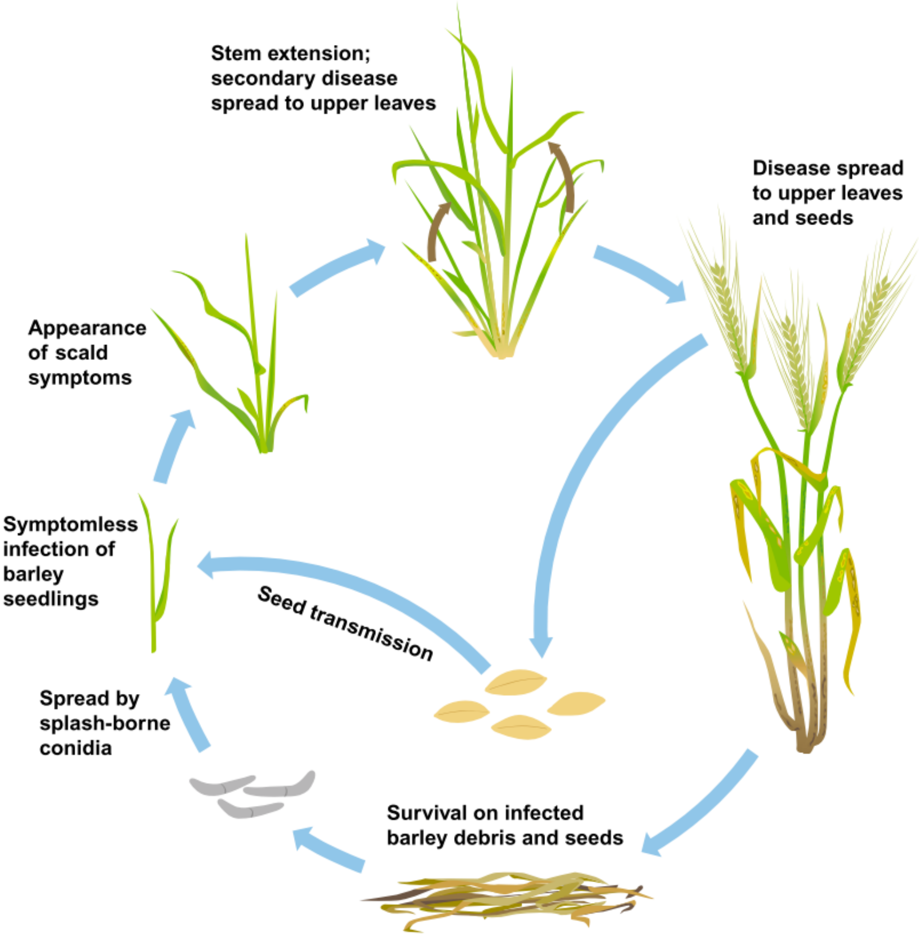


Figure 1-2: Life-cycle of *Rhynchosporium commune* (from Avrova and Knogge, 2012)

Weather variables

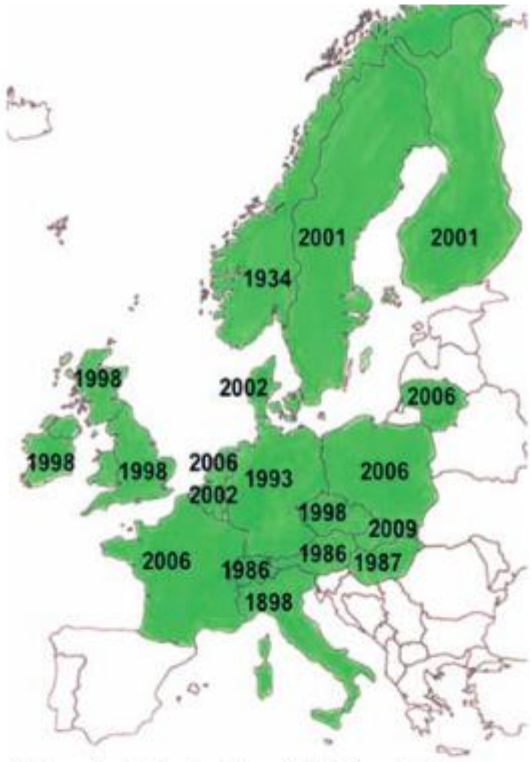
The main weather variables which affect *R. commune* disease progression are high humidity and cool temperatures (Oxley & Burnett, 2010; Salamati & Magnus, 1997; Atkins et al., 2010). Optimum temperature for *R. commune* infection and epidemic progression is generally agreed to be between 18 and 21°C (Salamati & Magnus, 1997; Ryan & Clare, 1975; Xue & Hall, 1992). A number of studies have considered the relationship between temperature, leaf wetness/humidity, and *R. commune* – the shortest reported period of leaf wetness which maintained the disease in inoculation experiments was 2 hours, at near optimal temperature (Ryan & Clare, 1975; Salamati & Magnus, 1997). Optimal leaf wetness periods vary according to temperature; in general, higher temperatures within the natural range for *R. commune* require shorter periods of leaf wetness or high humidity to optimise spore production (Rotem, 1976).

1.2.3 **Ramularia**

Ramularia collo-cygni has only recently attracted research attention (see Figure 1-3 for a summary of the first reported outbreaks of *R. collo-cygni* across Europe) and recognition as a major pathogen on barley (Havis et al., 2015). Yield reductions of up to 70% have been reported due to severe epidemics in South America (Pereyra 2013 cited in Havis et al., 2015), though losses in the UK are in the range of 7 – 13% (Oxley et al., 2008). A number of alternate hosts have been identified, including *Triticum aestivum* (bread wheat), *T. durum* (durum wheat), *Avena sativa* (oats), and several species of wild grass (Frei & Gindro, 2015).

R. collo-cygni's life-cycle is a source of debate, though recent work has considered it to be a hemi-biotrophic pathogen with a prolonged latent phase (Havis et al., 2015). Infection is detectable by GS 10-13, though symptoms typically do not present until GS 75, as shown in Figure 1-4 (Havis et al., 2015). There are likely several important sources of inoculum in the field, including seed borne, wind dispersal, and secondary spore dispersal within the crop life-cycle, though the relative importance of each is uncertain (Havis et al., 2015). In addition, the fungus is able to spread to new tissues within the host plant, without the need for additional external inoculum during the season (Havis et al., 2014).

R. collo-cygni has only recently begun to be researched in earnest and little is known about the relative effectiveness of management choices in reducing disease levels. However, crop rotation has been recommended to reduce primary inoculum levels (Oxley & Burnett, 2010). Varietal disease resistance to Ramularia has been included in the Recommended Lists since 2012 (SAC & HGCA, 2012), and provides farmers with a number of options – nine of the fifteen spring varieties included in the 2017 Recommended List were highly resistant to Ramularia (SRUC & AHDB, 2017). Research on the mlo gene which is often used for resistance to mildew suggested a trade-off with Ramularia resistance in controlled conditions (McGrann et al., 2014), however, all the spring barley varieties which are highly resistant to Ramularia in the 2017 Recommended List are also highly resistant to mildew (SRUC & AHDB, 2017), suggesting that in field conditions any negative associations with mildew resistance are relatively minor. Varietal resistance is crucial, as nearly all strains of *R. collo-cygni* had already developed resistance to one of the four groups of fungicides assessed by the Fungicide Resistance Action Group (2015), with two more groups having high levels of risk for fungicide resistance developing. Recent information from agrochemical company monitoring in Germany suggests further developments in resistance to the main groups of fungicides used to control Ramularia (Fungicide Resistance Action Group UK, 2017).



First reported outbreaks of ramularia leaf spot in Europe

Figure 1-3: First reported outbreaks of Ramularia in Europe, from (Oxley et al., 2010)

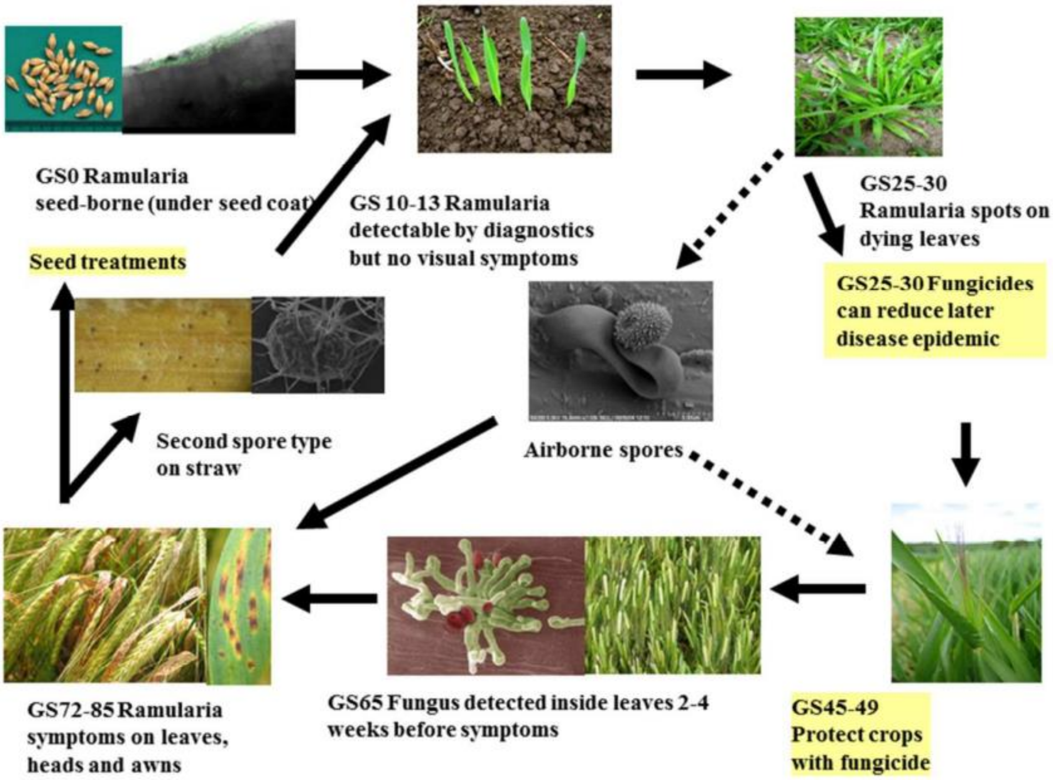


Figure 1-4: Life-cycle of *Ramularia collo-cygni* with suggested treatment opportunities from Havis et al., 2015

Weather variables

Leaf wetness has been proposed as a risk factor in *R. collo-cygni* development, with high humidity around GS 30 – 31 apparently correlating to higher disease levels in both Norway (Salamati and Reitan, 2006 cited in Havis et al., 2015) and Scotland (Havis et al., 2012). A high number of rainy days in the three weeks post heading, GS 51, has also been shown to be positively linked with higher disease expression (Mařík et al., 2011). The optimal temperature for Ramularia may be approximately 15°C, as an increase in spore release was observed when ambient temperature increased from 5 to 15°C (Havis et al., 2015), however more research, including assessing the disease at higher temperatures, is needed to verify this finding. Recent research into developing a Ramularia risk forecast suggests that risk prediction is likely to be complex and involve many factors (Havis, 2017 – personal communication).

1.3 Analysing IPM and disease via long-term datasets

As each of the three diseases discussed above is at moderate or high risk of developing resistance to multiple fungicide groups (Fungicide Resistance Action Group UK, 2015), it is important to find ways of relieving the selective pressure put on these pathogens by fungicide application, while preventing disease epidemics. Fungicide resistance development has implications in terms of the profitability of growing the crop, can lead to increased levels of input with commensurate impacts on costs to the consumer and on any environmental impacts arising from fungicide use. Many studies assessing the IPM methods described above (crop rotation, disease resistance, and forecasting disease pressure) are based on experiments running for less than five years (Twenström et al., 1998; Makowski et al., 2005; Loyce et al., 2008; Mazzilli et al., 2016) Long-term databases can potentially provide useful information regarding IPM efficacy, as data can be collected in a number of weather and agronomic situations, within the same region. However, assessing long-term data can be problematic, as data collection and storage methods are likely to have changed over time, especially where the data has been initially collected for purposes other than long-term analysis. In addition, the institutional funding and dedication required to produce long-term datasets is often lacking, and long-term datasets therefore often provide information with varying levels of quality and consistency (Clutton-Brock & Sheldon, 2010). Despite these drawbacks, the use of long-term data continues to be considered a useful way of teasing apart complex relationships and causality in ecological studies (Clutton-Brock & Sheldon, 2010; Lindenmayer et al., 2012), and can therefore provide a useful starting point for considering disease prevention.

Two such long-term databases exist in relation to Scottish spring barley – the SRUC Field Trials database, and the Adopt-a-Crop database – which will be used as a basis for studying IPM in this thesis.

The SRUC Field Trials database is a dataset, gathered from an annual pathology field trial programme from various funders, which allows consideration of the direct impact of fungicide treatment alongside management decisions. Data from field trials – including yield, fungicide treatment, disease levels, varietal selection and previous crop – have been collected since 1983 at a range of locations around Scotland, and stored electronically since

1996. The trials used a randomised block design to test the efficacy of new fungicides and were conducted for various chemical companies, using commonly sown varieties, and can therefore provide commercially relevant comparisons. For additional information on the experimental design and database, see Chapter 2.

The Adopt-a-Crop (AAC) represents data gathered annually as part of Scottish government funded Advisory Services monitoring in order to provide timely advice. Its crop database provides commercial farm data for spring barley in the form of archived crop monitoring information. Inclusion of farms in the AAC varies from year to year, but each year represents a range of locations across Scotland. Information about varietal choice and previous rotation provides an opportunity to assess the potential for increasing IPM uptake in current Scottish commercial practice. See Chapter 5 for more detailed information regarding the AAC database and its collection.

Using these two databases in tandem, analysis can be undertaken to assess both the effectiveness of IPM techniques in Scottish spring barley (using the Field Trials database), and the potential for increasing uptake of these techniques (using the AAC). However, additional information is necessary in order to understand what barriers may exist to uptake, whether farmers prefer one IPM technique over another, and whether increasing IPM uptake is actually feasible in this sector.

1.4 Opportunities afforded through stakeholder surveying

While field experiments can provide insight into farm management alterations in order to reduce environmental impact and maintain yields, this type of work remains essentially theoretical if there is no engagement with stakeholders. Stakeholder decision making is a complex process, which will necessarily involve the weighing of risks when choosing management strategies (Ilbery et al., 2013; Ingram, 2008; Dandy, 2012). Stakeholder engagement, meanwhile, is often removed from the process of research by time and space (e.g. Bailey et al. 2009; Sherman & Gent 2014), preventing it from becoming part of the iterative process of developing and discovering new ideas and technologies (Gramberger et al., 2015). However, particularly in the environmental domain, a growing body of literature has recognised the need to understand how stakeholders make decisions, in order to improve research outputs (Feliciano et al., 2014; Bailey et al., 2009; Sherman & Gent, 2014; Ilbery et al., 2013; Gramberger et al., 2015; Phillipson et al., 2012). The quality of scientific output may be improved by stakeholder engagement in several ways. First, through avoiding wasting resources on theoretically promising approaches which cannot be implemented on farm for practical reasons, and therefore more resource is available for fully exploring alternatives. Secondly, farmers and agronomists may be sources of new ideas and innovative thinking themselves – through troubleshooting problems on farm they may raise issues which, in turn, bring out new lines of thinking. Lastly, farmers, being the expert on their farm, know better than any researcher the specific difficulties and opportunities they encounter, and the interconnectedness of farm management decisions. Farmers can therefore provide a vital source of information which may include new viewpoints and fresh ideas tempered with realism.

Despite these potential benefits of collaboration with stakeholders, relatively few studies have conducted such engagement alongside scientific analysis, though post-hoc studies to understand whether given techniques were taken up several years after governmental recommendations were put forward have been carried out for IPM (Bailey et al., 2009; ADAS, 2002). While the use of social science research in order to understand the complexities of plant disease risks is becoming more common (Maye et al., 2012; Ilbery et al., 2013; Bailey et al., 2009; Sherman & Gent, 2014), there is a distinct lack of work in which farmer opinions and research into IPM have been conducted as part of a single research project. This gap in the literature provides a space to discover IPM techniques which are both scientifically and practically of interest, and thus to make recommendations which should be acceptable to both the scientific and stakeholder communities.

1.4.1 Diversity among Scottish spring barley farmers and its potential impact on IPM

Farmers are, as a group, heterogeneous. Just as each farm has its own set of practical restrictions and complexities, farmers come from diverse backgrounds and have different business and management goals. In Scottish spring barley production, farm size, and weather patterns vary by region, despite the fact that the majority of arable farming in Scotland takes place along the East coast (Scottish Government, 2015a). In some areas, e.g.

the Scottish Borders, farms over 200ha are common (making up 23.3% of farms in this area), and tenancy levels are relatively high (at 33.75%), while in Aberdeenshire only 6.3% of farms are 200ha or over, while farms under 5ha are common and tenancy rates are 20% (Scottish Government, 2015a; Scottish Government, 2015e). Weather, which may prevent or make more difficult certain types of IPM such as rotation by restricting the types of crops which can be grown, is also variable, with shorter growing seasons and lower temperatures in the North of the country (Met Office, 2016). Topography, soil type, and local markets will also play a part in influencing crop choice and agronomic practices. Sampling must therefore draw on farmers from different regions within Scottish barley farming in order to present a representative picture.

There are a number of other areas where heterogeneity is to be expected in the Scottish spring barley producing population. Some differences are easily quantifiable, i.e. tenancy status and main market, while others are less straightforward but no less informative, such as speed of innovation uptake. Several studies have divided farmers into 'early innovator' and 'late innovator' categories, depending on the amount of time taken to use new technologies or management systems on farm, and thus provide a means of predicting which farmers will fall into each category on the basis of socio-economic factors. While the factors influencing farmer behaviours are complex, and each farmer will differ in their experiences and behaviours, using farmer behaviour frameworks allow some insight into general trends (Pike, 2008). Early innovators, for example, often present a young, highly educated group with a relatively large farm size or stable income base, though this characterisation cannot identify all early innovators (Rogers, 1961; Diederen et al., 2003; Sharma et al., 2011). Willingness to allow some risk to develop on farm in the form of low level disease, is variable not only across innovation groups, but also depends on the crop being affected and the relative potential impact of disease on yields and quality (Maye et al., 2012), with many farmers applying 'insurance' sprays before disease is visible (ADAS, 2002). Farmer perception of risk is therefore a crucial component of the decision making process, as they are faced with both inherent risks (e.g. weather) and risks which can, to some extent, be managed (e.g. seed quality). Plant disease poses the latter type of risk to a farmer – management strategies such as fungicide are available and widely used. Surveys of wheat farmers have found them to be highly concerned with disease as a key risk factor on farm, particularly in light of the increase of fungicide resistance developing in pathogens (Maye et al., 2012), and the prospect of losing key pesticides as a result of EU policy (Ilbery et al., 2013). Although wheat farmer concerns related primarily to the financial implications of epidemics (Maye et al., 2012), cereal farmers have, in other work, shown themselves to be more concerned with keeping up with best practice than maximising short term profits (ADAS, 2002), highlighting the multifaceted and constantly evolving nature of risk management.

1.4.2 Factors influencing farmer decision making

Farmer decision making is complex, and a number of studies have highlighted the fact that so-called 'win-win' options are not taken up at the rate which scientists and policy makers might expect. This could be due, in part, to the fact that these are often identified at the national level, and may not be feasible for individual farmers due to practical constraints (Feliciano et al., 2013; Smith & Oleson, 2010; Moran et al., 2013). These constraints may be physical (e.g. farm size, tenancy status, soil type, location, etc.) or financial – both in terms of market forces driving decisions and the upfront cost of innovations and solutions. Research has often identified win-wins based on the standard profit maximising model of farm behaviour, but it has been suggested farmers may be best understood as profit-satisfiers or independence maintainers instead (Emery & Franks, 2012; Feliciano et al., 2014; Dandy, 2012). Farmer interactions with financial incentives are also complex, as these may be both useful in encouraging land managers to take up given actions (Feliciano et al., 2014; Dandy, 2012; Barrett et al., 2016), or counterproductive, where it reduces altruistic motivations and notions of self as a 'good farmer' (van Dijk et al., 2015). Cost-benefit analysis alone, therefore, is not necessarily a reliable predictor of farmer decision making.

In addition to the readily recognisable financial and physical constraints which may prevent uptake of new strategies, a number of other, potentially less obvious, factors can affect decision making. For example, farmer behaviour and decision making is also influenced by external credibility – whether their actions mean they are perceived as a 'good farmer' by friends and family (Sherman & Gent, 2014; Dandy, 2012; Hallam et al., 2012; Burton et al., 2008; Moran et al., 2013; Barrett et al., 2016) which may influence the choice to spray for highly visible crop diseases, regardless of likely impact on yields. Stakeholders often cite ease of uptake as the main barrier to changing practices (Feliciano et al., 2014; Dandy, 2012; Harrison et al., 1998; Hallam et al., 2012). Governmental regulation, while a potential driver for change , can also become a barrier to uptake, particularly when rules are too complex, or there are multiple rules at cross-purposes (Dandy, 2012; Smith & Oleson, 2010). Sources of information about regulation and research outputs themselves can have an impact on attitudes and uptake of innovation, with a general preference towards information being delivered by successful peers, agronomists (Bailey et al., 2009; ADAS, 2002), and from inter-generational experience (Sherman & Gent, 2014), rather than direct from researchers or government. Attitudes towards the environment and stewardship can be a crucial factor in decision making – with many farmers refuting the idea that their activities are detrimental to the environment (Feliciano et al., 2014; Barnes et al., 2013). Those who are interested in reducing pesticide use on farm often see this as a case of good stewardship of the land, rather than environmental sustainability (Sherman & Gent, 2014). Recognising the tensions between each of these facets of decision making is important when considering decision making; it is highly complex, taking into account rational economic motives, on-farm practicalities, self-perception identity, and personal levels of risk aversion; it is therefore difficult to predict using theoretical models. Social science strategies of stakeholder engagement provide an opportunity to study this process in a way which allows for non-rational, but nonetheless realistic, outcomes.

Due to the complexity of farmer decision making, further research is therefore necessary to understand which IPM techniques are considered suitable by stakeholders in specific crop contexts. Surveying stakeholders about current practice and perception of key IPM techniques, allows for primary data to be collected which is of relevance to IPM in Scottish spring barley. However, stakeholder engagement of this type is necessarily limited to a small number of participants, due to the resource constraints of this PhD. As the Scottish farming population is variable, it is therefore useful to connect small-scale, in-depth surveying with a broader assessment of current commercial practice in Scottish spring barley farming, through the Adopt-a-Crop database. This allows the IPM techniques of interest to be considered in a wider context than would otherwise be possible, while incorporating stakeholder opinions into final recommendations.

1.5 Thesis Aims and Objectives

This thesis aims to generate an interdisciplinary view of the current state of IPM in the Scottish spring barley sector. This will provide insight into which IPM techniques have potential to reduce the need for fungicide use, while also being acceptable to stakeholders, and which are not currently in widespread use. The key questions which will be addressed in this thesis are:

- ⇒ What impact does fungicide treatment have on yields of Scottish spring barley, and what other management and site factors may be influencing yield?
- ⇒ To what extent can IPM techniques and site factors, such as weather, explain the differences in yield between treated and untreated spring barley?
- ⇒ What are stakeholder's attitudes towards key IPM techniques, and what are the current levels of uptake of these?
- ⇒ Are there areas where IPM use could be improved upon in current commercial practice?

The answers to these questions will be used to provide an overview of current IPM practice in Scottish spring barley and to highlight areas where there are opportunities for improvement.

1.6 Thesis Structure

This thesis considers IPM through several lenses, in order to obtain a more holistic view of the potential for IPM in Scottish spring barley to reduce fungicide use. Long-term databases are used to determine which management techniques are best suited to the system at hand (Chapter 2 and Chapter 3). Stakeholder engagement (Chapter 4) provides insight into which of these techniques are most likely to be taken up by farmers. Finally, the AAC database of commercial practice allows an estimate of the potential for improving current management patterns, based on current levels of IPM uptake across a wider sample of Scottish farmers (Chapter 5). 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 techniques which are robust, practical, and not already in widespread use. Bringing together these sources of information can provide answers to a key question in an unusual way, which may be of particular use for policy and other decision makers, who need information about strategies which are both practical and likely to make a positive impact.

Chapter 2 Field Trials database analysis (2011 – 2014): case study of varieties being sown by farmers

2.1 Introduction

In order to reduce fungicide inputs, while maintaining high yields, it is necessary to understand under what conditions fungicide application impacts yields. Applications can then be tailored to situations where a yield increase is likely to occur, and eschewed when yield is unlikely to be impacted. For fungicide use to result in increased yields, several conditions must be met: first, the crop must have the potential to be infected by pathogenic fungi, second the fungicide must reduce the fungal population or prevent infection, and thirdly this reduction must actually reduce yield loss. There are therefore a number of situations in which fungicide application may fail to impact yield in spring barley. Fungal infection may not occur, or may not become severe enough to impact yields, due to a lack of inoculum, inappropriate weather conditions for pathogen development, or factors such as inbred crop resistance. Fungicide application may also not reduce pathogen populations, for example due to the pathogen having developed resistance to a given fungicide. In addition, fungicide application, even where it impacts pathogen population levels, may not influence that season’s yields, for example where the disease affects the plant after grain filling has already occurred. Finally, some fungicides can have negative impacts on yield in certain situations; for example, several of the most commonly applied fungicides in the Field Trials database carry label recommendations against applying where frosts are predicted (BASF, 2014a; BASF, 2015; BASF, 2014b). It is therefore useful to consider the relationship between fungicide application, fungal pathogens, and crop yields in light of the factors which are likely to impact fungicide-yield interactions.

2.1.1 Previous research on the relationships between yield, disease severity, and fungicide use

Proving direct links between fungicide use, yields, management strategies, and disease is difficult. A number of studies have attempted to show that fungicide use decreases disease levels and increases yield; some of these have been successful, while others have shown little measurable impact of fungicide application. For example, several experiments on wheat have linked fungicide use increase yields. Work on fungicide control of powdery mildew (caused by *Blumeria graminis* f. sp. *tritici*) and septoria (caused by *Septoria tritici*) diseases found wheat yield increases of up to 2.7 t/ha (Jørgensen et al., 2000). Cook and King (1984) conducted field surveys of winter wheat, and found yield responses to fungicide use up to 89%, with the most damaging leaf disease being mildew (caused by *Blumeria graminis* f.sp. *tritici*). However, many experiments have reported internally inconsistent results – in wet conditions, for example, fungicide use increased yields in winter wheat grown in the US, while in dry years this was not seen (Wegulo et al., 2012). In a long-term field experiment on wheat in Sweden, only 52% of the years between 1983 and 2007 showed significant increases in yield from fungicide use (Wiik & Rosenqvist, 2010).

Work on barley in Ontario by Sutton and Steele (1983) found a maximum impact of fungicide use of 19.1% of yields. Priestley and Bayles (Priestley & Bayles, 1982), working on spring barley in England found that yield impact from fungicide use varied between years from a 2.4% increase in yield to 13.8%. The links between fungicide use, reduced disease, and increased yields therefore remain unclear, as further evidenced by the number of papers attempting to determine when fungicide use makes economic sense (Hysing et al., 2012; Wiik & Rosenqvist, 2010; Jørgensen et al., 2000; Thompson et al., 2014).

2.1.2 **Long-term field trials**

Analysing data collected across a range of sites, in different fields, with different weather conditions, and different management practices, can offer useful insight into which factors are most influential in determining the impact of treatment on yield. Few studies on long-term data have thus far been conducted which explicitly test the impact of fungicide use on yield and disease levels. Wiik and Ewaldz's (Wiik & Ewaldz, 2009) work on winter wheat in Sweden using data from 1983 – 2005, followed by further analysis done by Wiik (2010) of the data for 1977 – 2005 are notable exceptions, and both suggest that yield increases from fungicide treatments are highly variable. Yield increase from a single fungicide treatment in 1983 – 2007 was statistically significant just over half of the time (13 of the 25 years), with a maximum increase in yields of 1.9 t/ha and a minimum of under 0.3 t/ha (Wiik & Ewaldz, 2009). Information is not available in the 1983 – 2005 analysis as to which years had statistically significant impacts of fungicide on yields overall; however, yield increases did vary widely across years, with the average yearly treated yield observed in 1987 44.2% higher than the untreated, as compared to a difference of 1.9% in 1992 (Wiik, 2009). Wiik (2009) found, via regression analysis, that leaf blotch diseases explained 74% of the yield increase in fungicide treated trials during 1983 – 2005. Similarly, Cook and Thomas (1990), working on winter wheat in the UK, saw fluctuations in yield response to fungicide across years. Though no analysis of the statistical significance of yield impact from fungicide was undertaken, three fungicide applications per season led to an increased yield of a maximum reported 16.4% in 1981, and a minimum of 8% in 1986, while one fungicide application increased yield by up to 12.5% in 1985, but only 4% in 1984 (Cook & Thomas, 1990). These two long-term experiments which have investigated the link between yield and fungicide use, then, showed widespread variation across years. Due to this variability, calls have been made for further analysis of long-term field trials which compare yield, disease, and treatment, to allow optimisation of fungicide use (Wiik, 2009).

2.1.3 SRUC Field Trials data as a platform for analysis

The SRUC Field Trials database can provide a useful insight into the relationship between disease/yield/fungicide use in Scottish spring barley. Data has been collected from these field trials at a range of locations across Scotland since 1983 regarding yield, disease levels and fungicide treatment, along with a range of other management factors. The fungicide treatments used varies over time, but always comprised the best possible treatment available at the time, at the recommended dose, according to expert opinion. Thus, the impact of treatment on disease and yield should be maximised from the perspective of fungicide choice and application, and relevant to standard farm management practices. As the trials included widely used cultivars across this period, the Field Trials database can provide a particularly farmer-relevant set of analyses.

In order to understand the complex relationship between yield, disease, and treatment, however, it is first necessary to undertake exploratory data analysis on a case study: a subset of data chosen for its direct relevance to current commercial farmers. As the literature is inconclusive about the influence that key management factors have on yield, this initial analysis allows possible explanatory variables and patterns to be identified, which can then be used to inform regression models later on in the thesis. Field Trials data from 2011 – 2014 was selected for this purpose, as results from this period provide a snapshot which can be of use for the current sector. In addition, analysing the last five years of the database, focussing on varieties which are in current use (as determined by the farmer survey presented in Chapter 4) can provide information which is relevant to farmer decision making at present. Finally, the data available for this period contains plot-level information, allowing statistical analysis to be done on a single-trial level, while earlier Field Trials data is available only at means level (more detail can be found on this in Chapter 3.

The work presented in this chapter aims to: determine in which trials fungicide treatment had a statistically significant impact on yield; identify patterns in the 2011 – 2014 data which may indicate which factors influence the impact of treatment on yield so that these can be used to elaborate regression models in Chapter 3; and provide a basis for comparison with the farmer survey work presented in Chapter 4.

2.2 Materials and Methods

2.2.1 Introduction to SRUC Field Trials database

The Field Trials database encompasses information collected from trials run by SRUC, primarily focused on testing the efficacy of various fungicides on spring barley. The data that has been collected and the experimental design used in the trials were therefore not intended for the types of analysis in this project. Trials are run by trained scientific staff, and include disease assessments during the growing season, though the timing of these varies. Trials were set up as a randomised block design, with three or four replicates per trial, with plots ranging in size from 20 to 40m^2. A sample plot diagram is shown below in Table 2-1. For each block within the trial, data for one untreated plot was recorded in the database, alongside one fungicide treated: the ‘best practice’ treatment for that year as determined by expert opinion, allowing direct comparison of within-block differences between treated and untreated plots. The ‘best practice’ treatment varied both in chemistry and number of applications across the database. For each trial in the Field Trials database, information is recorded about key farm management decisions (e.g. varietal selection, previous rotation, sowing date, etc.), fungicide use information (type and timing of application – see Appendix A – Fungicide treatments used in the Field Trials database (1996 – 2014) for a full list of the fungicide treatments used in the database), disease information (percentage disease severity for a number of key diseases at several growth stages during the crop growing season), and yield. The number of disease assessments and the growth stages at which these were measured during the growing season varied between trials. Though data regarding the quality of the barley yield was collected for some trials, this was not consistently recorded throughout the database, and so is not considered in these analyses.

As the Field Trials database had not been used for long-term analysis previously, extensive cleaning and data preparation was needed for this project. Re-coding of variables for consistency across years was undertaken, as, for example, the names or codes used for a given location/variety/disease changed several times within the database. Sowing and harvest date information was also standardised, and converted to Julian days, allowing more direct comparison across years. In addition, trials which were missing information of relevance to the analyses were flagged up. An attempt was made to locate the electronic and/or paper copies of these trial records, and the missing information retrieved and added to the database where possible. Where the original records could not be located, these trials were removed from the database. For example, each trial with fewer than four dates of disease assessment fully coded for each of the three diseases was flagged up (this being the maximum number of assessments for a single trial in the database), as were trials with missing yield, disease, location, variety, or previous rotation information. In total, more than seventy trial reports were manually reviewed for over 500 instances of missing information for the preparation of the full database running from 1996 – 2014. Less than twenty trials were removed from the database for lack of sufficient information, and these were spread relatively evenly across the years. In addition, a review of all electronic records (conducted by Master’s intern Sarah Espinosa) led to the addition of four trials which had been overlooked when the database was originally created.

Table 2-1: Sample field trial (adapted from field plan for trial number 1885, conducted in 2014 at Boghall, Lothians)*

Block 1	Treated	Treated	Treated	Treated	Treated	Treated	Treated	**Untreated**	Treated	Treated	**Treated**	Treated	Treated	Treated	Treated
Plot number	45	44	43	42	41	40	39	38	37	36	35	34	33	32	31
Block 2	Treated	Treated	Treated	**Untreated**	Treated	Treated	**Treated**	Treated	Treated	Treated	Treated	Treated	Treated	Treated	Treated
Plot number	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16
Block 3	Treated	Treated	Treated	Treated	Treated	**Treated**	Treated	Treated	Treated	**Untreated**	Treated	Treated	Treated	Treated	Treated
Plot number	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1

*plots shown in red are the treated and untreated plots included in the database for this trial

2.2.2 **Trial data collection and preparation**

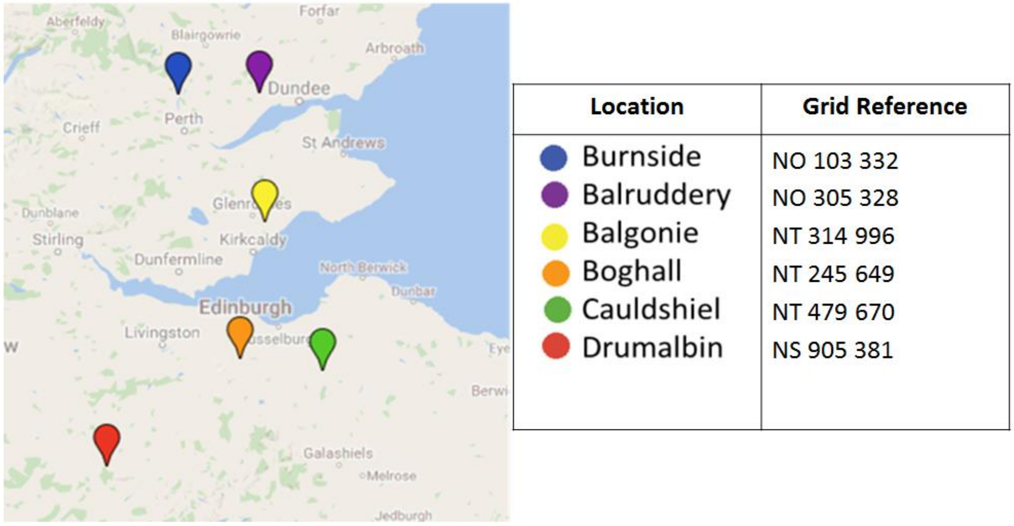
Data for 2011 – 2014 was cleaned and prepared for analysis, as described above. Varietal disease resistance information was added to the database from the SAC/SRUC Recommended Lists produced annually for farmers (SAC & HGCA, 2011; SAC & HGCA, 2012; SRUC & HGCA, 2013; SRUC & HGCA, 2014). Trials which used varieties not sown by surveyed farmers were removed from the database, to ensure comparability between the two. In total, five varieties were removed from the database for this reason (two of which were not Recommended List varieties and therefore could not have been analysed for disease resistance in any case) from a total of 10 trials, leaving 40 trials in the database.

Location was standardised to allow comparison across years, such that trials in different fields on the same farm were considered as coming from the same location. Trials were run at six locations during the years 2011-2014 (see Figure 2-1); the number of trials per location in a given year are summarized in Table 2-2.

Area under the disease progress curve (AUDPC) was calculated for each trial, for each disease, as well as Total AUDPC (a sum of the AUDPC of the three diseases of interest). AUDPC was calculated using the standard trapezoidal method, after Madden et al. (2007), such that:

$$\mathrm{AUDPC} = \sum_{j=1}^{n_j-1} \left(\frac{y_j + y_{j+1}}{2}\right)\left(t_{j+1} - t_j\right)$$

Where t_j is the sample at a given time point *j*, y_j is the disease level at the time point *j*, and n_j is the number of time points.



Location	Grid Reference
● Burnside	NO 103 332
● Balruddery	NO 305 328
● Balgonie	NT 314 996
● Boghall	NT 245 649
● Cauldshiel	NT 479 670
● Drumalbin	NS 905 381

Figure 2-1: Trial locations in 2011 – 2014 Database

Table 2-2: Number of trials in each location by year

	2011	2012	2013	2014	Total
Balgonie	1	1	0	0	2
Balruddery	2	0	0	0	2
Boghall	3	2	2	3	10
Burnside	0	1	0	1	2
Cauldshiel	0	3	1	2	6
Drumalbin	1	2	3	4	10

2.2.3 Statistical analysis of the database

First, overall mean and median difference in yields between treated and untreated plots in the Field Trials were calculated using the within-trial block data, which was then summarised for the variety. A simple cost-benefit analysis was then conducted, using fungicide application cost data from the SAC Farm

Management Handbook calculations, which was available for spring barley in 2013 and 2014 (SAC Consulting, 2014; SAC Consulting, 2013). For 2011 and 2012, fungicide cost data was not recorded separately from total treatment costs, including herbicides, insecticides, growth regulators and trace elements (SAC Consulting, 2011; SAC Consulting, 2012). The average percent of the total application costs for the years 2013 – 2016 which fungicide applications represented was calculated to be 69.2% (SAC Consulting, 2015; SAC Consulting, 2016; SAC Consulting, 2013; SAC Consulting, 2014). The cost of fungicide applications in 2011 and 2012 was therefore assumed to be 69.2% of the total reported treatment costs for those years. Spring barley price information was taken from the AHDB's market data centre, where two-monthly average prices for spring barley was available for both feed and malting varieties (AHDB, 2016c). Average Scottish prices for each market type were calculated by year for use in the analysis. This allowed a simple estimate of the difference in profit per hectare between treated and untreated systems to be calculated.

As an assessment of the impact of treatment on trial yields and disease severity, a one-way ANOVA (analysis of variance) was conducted on each individual trial and variety combination, using Genstat 16 (VSN International, 2013), and using within-trial block (as shown in Table 2-1) as the blocking structure. The impact of treatment was tested for yield, mildew AUDPC, Ramularia AUDPC, Rhynchosporium AUDPC, and Total AUDPC. Significance was set at $p<0.05$. To understand which agronomic factors are linked with fungicide treatment's impact on yield, trial conditions were compared with ANOVA results to identify patterns relating to key management factors.

AUDPC as an explanation for significance of treatment

As the relationship between disease severity, yield, and treatment is complex, a number of analyses were undertaken to identify interactions between them, and possible masking of effects. First, disease presence was considered alongside the significance of treatment on yield, to verify that in trials where there was no significant yield difference between treated and untreated plots that this was not simply due to a lack of disease. To determine whether disease resistance alone could account for the differing impacts of treatment, a simple mean was taken of resistance ratings for varieties in those trials with a significant impact of treatment on yield, as compared to the rest. The variability in the dataset in terms of disease resistance levels which could be tested is summarised in Table 2-3. The significance of impact of treatment on yield was then compared with significance of treatment on AUDPC for each disease, to gauge whether treatment impact on disease alone could account for treatment impact on yields. The percent of trials which showed a significant impact of treatment on yield at each standardised location in the database was then calculated, to gauge the effect of location (including weather, soil, and general management variability) on significance of treatment on yield.

Disease assessed between Growth Stages 24 – 34 was also included in analysis, in order to provide a within-season comparison to total AUDPC. A within-season severity measure may be more useful to farmers, as this can be measured and acted upon during the growing season, whereas AUDPC is calculated using disease for the entire duration of the growing season, and is therefore not directly relevant for farmers’ decisions about spraying. Growth stages 24 – 34 were chosen to represent within-season severity, as they encompass a key growth stage for the development of Rhynchosporium, and are a key spraying time for Rhynchosporium, mildew (AHDB, 2016a), and Ramularia (Havis et al., 2015). Several other growth stages were considered for inclusion in the analysis, but due to the variability in timing of disease assessment in the database, there was not adequate information to include these in the analysis.

Table 2-3: Number of trials with varieties of each disease resistance rating in the 2011 - 2014 Field Trials dataset

Resistance rating	Mildew	Rhynchosporium	Ramularia*
1	0	0	0
2	0	0	0
3	0	6	0
4	0	26	0
5	13	0	4
6	0	0	21
7	0	5	5
8	20	1	0
9	5	0	0

*Ramularia was only included in the Recommended Lists from 2012 onwards

Comparison of trials

Pairs and groups of trials were then compared in order to provide more detailed information at site/year specific levels. The database was checked for groups of trials where both had taken place in the same year, at the same trial location, with the same previous rotation and sowing date, but were run with different varieties, and with difference significance outcomes in terms of fungicide use on yield. This allowed for comparison of varietal impact to be drawn within a framework of reduced noise from outside variables, as little else differed between the trials. In some cases, there were three or four trials which could be compared (e.g. two trials were significant and one or two nonsignificant in the same location and year); these were compared at group level. A total of six pairs/groups were identified that met the necessary conditions, with all years but 2013 represented (see Table 2-4 for summary below). Using group comparisons restricted unexplained variation in the data (e.g. soil variables and weather). However, the groups could not be analysed statistically, as there were not enough data points for a robust comparison; the largest group contained two trials with a significant impact, and two with no significant impact in the same location and year. These groups were, however, useful, for preliminary analysis of trends and a more focused comparison with limited unaccountable variation to mask treatment impacts.

Table 2-4: Pairs/groups selected for direct comparisons

Group number	Year	Trial location	Trial code and variety: No significant* impact of treatment on yield	Trial code and variety: Significant impact of treatment on yield
1	2011	Balruddery	1519 Belgravia	1058 (1105) Optic
	2011	Balruddery	1519 Concerto	1519 Optic
2	2011	Boghall	1547 Waggon	1523 Optic
3	2012	Cauldshiel	1665 Concerto	1625 Optic
4	2012	Burnside	1659 Westminster	1659 Concerto
5	2014	Drumalbin	1873 Concerto	1877(1404) Optic
	2014	Drumalbin	1877(1404) Overture	1884 Concerto
	2014	Drumalbin	1878 Overture	

*Significance was tested at $p<0.05$

Pattern checking across all trials

In order to better compare the numerous variables being considered, tables were created for each year indicating every value for which data was available which was considered relevant based on the initial results from means and pair/group comparisons and a review of the literature. These were then colour coded and manually reviewed to identify overarching patterns.

To include weather as a factor in the pattern discernment, regional weather data for each year were downloaded from the Met Office for the two regions relevant to the trials database; Eastern and Western Scotland (Met Office, 2016). A list of the trial locations in each region is presented in Table 2-5. Average temperature and rainfall for each growing season (March – August, inclusive) and the early growing season (May and June) were calculated for both regions. May and

June were chosen for inclusion as these months generally encompassed key growth stages for each of the three diseases considered; GS 31 – 45 for mildew, 30 – 39 for Rhynchosporium, and 25 – 32 for Ramularia (see Chapter 1 for more detail). As anomaly weather data was not directly available from the Met office for the growing seasons, mean temperature and rainfall were calculated using Met Office weather data for each region from 1981 – 2010, the baseline, for both the full growing season and for May/June. Anomaly values could then be calculated in accordance with the levels used in the Met Office 1981 – 2010 anomaly maps (the most recent available). A growing season or May/June period was therefore classed as 'wet' if the percent of average rainfall in that period was 110% or more, and 'dry' if under 90% of the average; it was classed as 'hot' if more than 0.5°C higher than average, and 'cold' if more than 0.5°C colder than average. For summaries of weather data across growing seasons see Table 2-6 and Table 2-7, and for May/June averages see Table 2-8 and Table 2-9.

Weather varied regionally, with the only location in the West of Scotland, Drumalbin, being wetter in 2013 and drier in 2014 than the other areas. However, weather also varied substantially between years – anomaly maps for June of each year are presented below to summarise this shift (see Figure 2-2 and Figure 2-3). The overall growing season was wet in 2011 and 2012, and dry in 2013 in both the East and West of Scotland (the weather for each year and region is presented below in Table 2-6 and Table 2-7 for the growing season). The year 2014 was hot in both regions over the entire growing season, with variation in rainfall between East and West. In May and June, the two months chosen for their potential impact on disease severity, again, 2011 and 2012 are wet in both East and West Scotland. The most variation between the regions was observed in 2013, with the East being dry, and the West being wet. In 2014, both regions were hot and had average rainfall in May/June (see Table 2-8 and Table 2-9).

Sowing date was also categorised as 'early,' 'late,' or 'average'. To create these categories, the median sowing date within the 2011 – 2014 dataset (Julian day

82) was determined, then a ten day range was fitted around this, such that anything sown on or before Julian day 77 is early, and anything after Julian day 87 is late. This was cross-checked against sowing dates from each of the standardised location to ensure each location had trials which fell within this 'average' sowing period. The overall mean and median sowing dates for the 1996 – 2014 dataset also fell within this time period (Julian days 84.5 and 84, respectively), suggesting the period chosen is also reasonable over the longer term. Rotation practice was taken into consideration by including the prior year's crop on each field. Differences between fields where the last crop was spring/winter barley versus other crops (e.g. grass and winter wheat) were assessed to gauge the impact of rotation on disease and yield. The tables of outcomes and factors were then created, and reviewed for trends and patterns.

Table 2-5: Regions corresponding to trial locations in the 2011 – 2014 database

Region	Trial location
East of Scotland	Burnside BDE
	Balruddery BRY
	Balgonie BIE
	Boghall BLL
	Cauldshiel CEL
West of Scotland	Drumalbin DIN

Table 2-6: Average growing season temperature and average rainfall conditions for the East of Scotland for 2011 – 2014

Year	Region	Temperature (°C)	Anomaly value*	Hot/Cold (difference greater than 0.5)	Rainfall (mm)	% of average	Wet/Dry (over 110 or under 90)
2011	East	9.73	0.20	Average	103.48	132	Wet
2012	East	9.35	−0.18	Average	106.53	136	Wet
2013	East	9.25	−0.28	Average	67.33	86	Dry
2014	East	10.42	0.89	Hot	88.02	113	Wet
Baseline (1981 – 2010)	East	9.53			78.23		

*Anomaly value – difference from the baseline (average temperature for this region from 1981 – 2010)

Table 2-7: Average growing season temperature and average rainfall conditions for the West of Scotland for 2011 – 2014

Year	Region	Temperature (°C)	Anomaly value*	Hot/Cold (difference greater than 0.5)	Rainfall (mm)	% of average	Wet/Dry (over 110 or under 90)
2011	West	10.28	0.20	Average	134.45	118	Wet
2012	West	10.23	0.15	Average	124.65	110	Wet
2013	West	9.70	−0.38	Average	98.20	86	Dry
2014	West	10.98	0.90	Hot	120.50	106	Average
Baseline (1981 – 2010)	West	10.08			113.74		

*Anomaly value – difference from the baseline (average temperature for this region from 1981 – 2010)

Table 2-8: Average temperature and rainfall conditions for the East of Scotland in May and June for 2011 – 2014

Year	Region	Temperature (°C)	Anomaly value*	Hot/Cold	Rainfall (mm)	% of average	Wet/Dry (over 110 or under 90)
2011	East	10.00	−0.14	Average	107.90	150	Wet
2012	East	9.35	−0.79	Cold	107.75	150	Wet
2013	East	10.15	0.02	Average	62.45	87	Dry
2014	East	11.45	1.32	Hot	74.40	104	Average
Baseline (1981 – 2010)	East	10.14			71.74		

*Anomaly value – difference from the baseline (average temperature for this region from 1981 – 2010)

Table 2-9: Average temperature and rainfall conditions for the West of Scotland in May and June for 2011 - 2014

Year	Region	Temperature (°C)	Anomaly value*	Hot/Cold	Rainfall (mm)	% of average	Wet/Dry (over 110 or under 90)
2011	West	10.55	−0.25	Average	172.75	190	Wet
2012	West	10.55	−0.25	Average	128.80	142	Wet
2013	West	10.50	−0.30	Average	105.90	117	Wet
2014	West	11.90	1.10	Hot	94.35	104	Average
Baseline (1981 – 2010)		10.80			90.84		

*Anomaly value – difference from the baseline (average temperature for this region from 1981 – 2010)

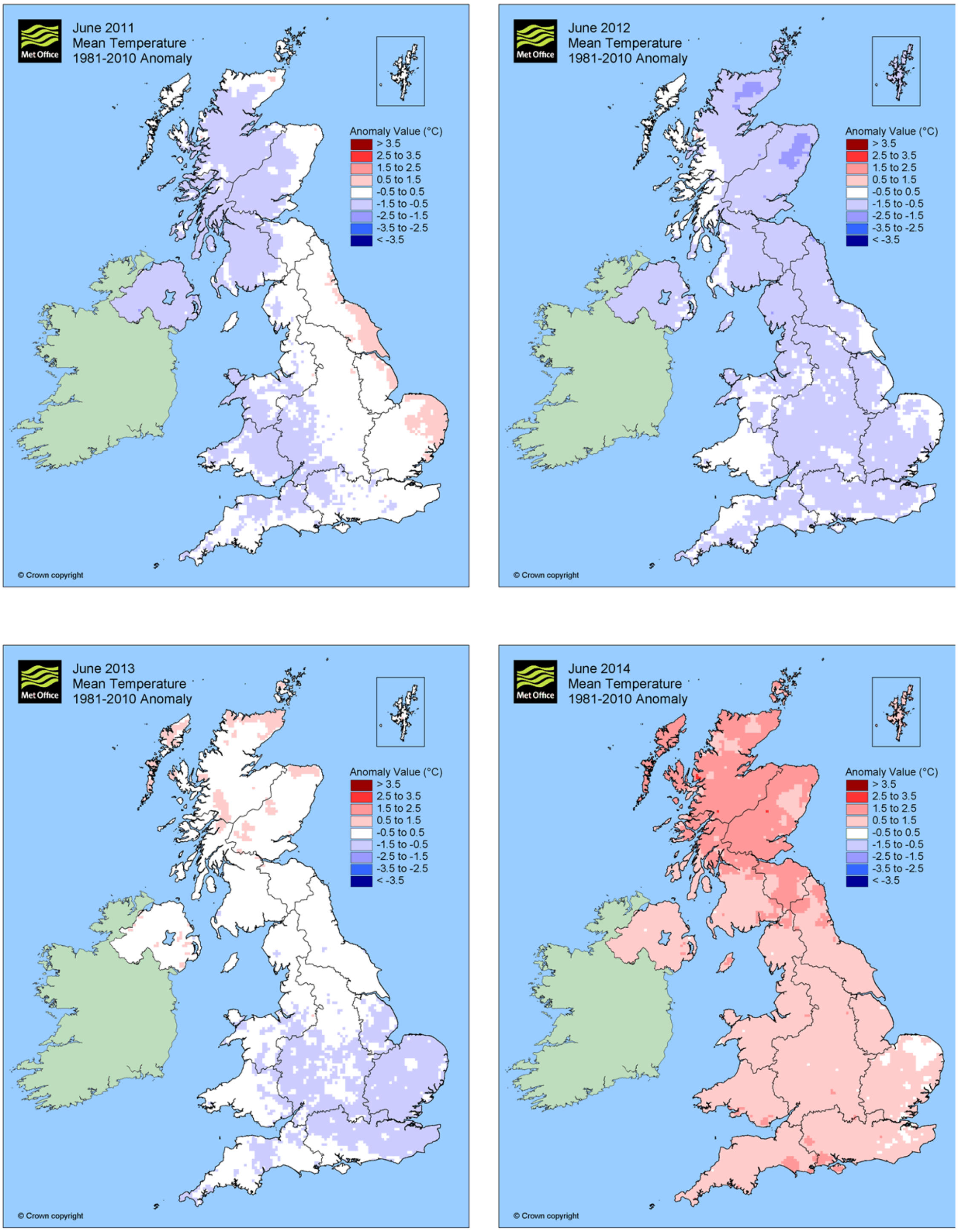


Figure 2-2: Mean temperature anomaly maps for June 2011 – 2014, highlighting variability of weather across this period (Met Office, 2016)

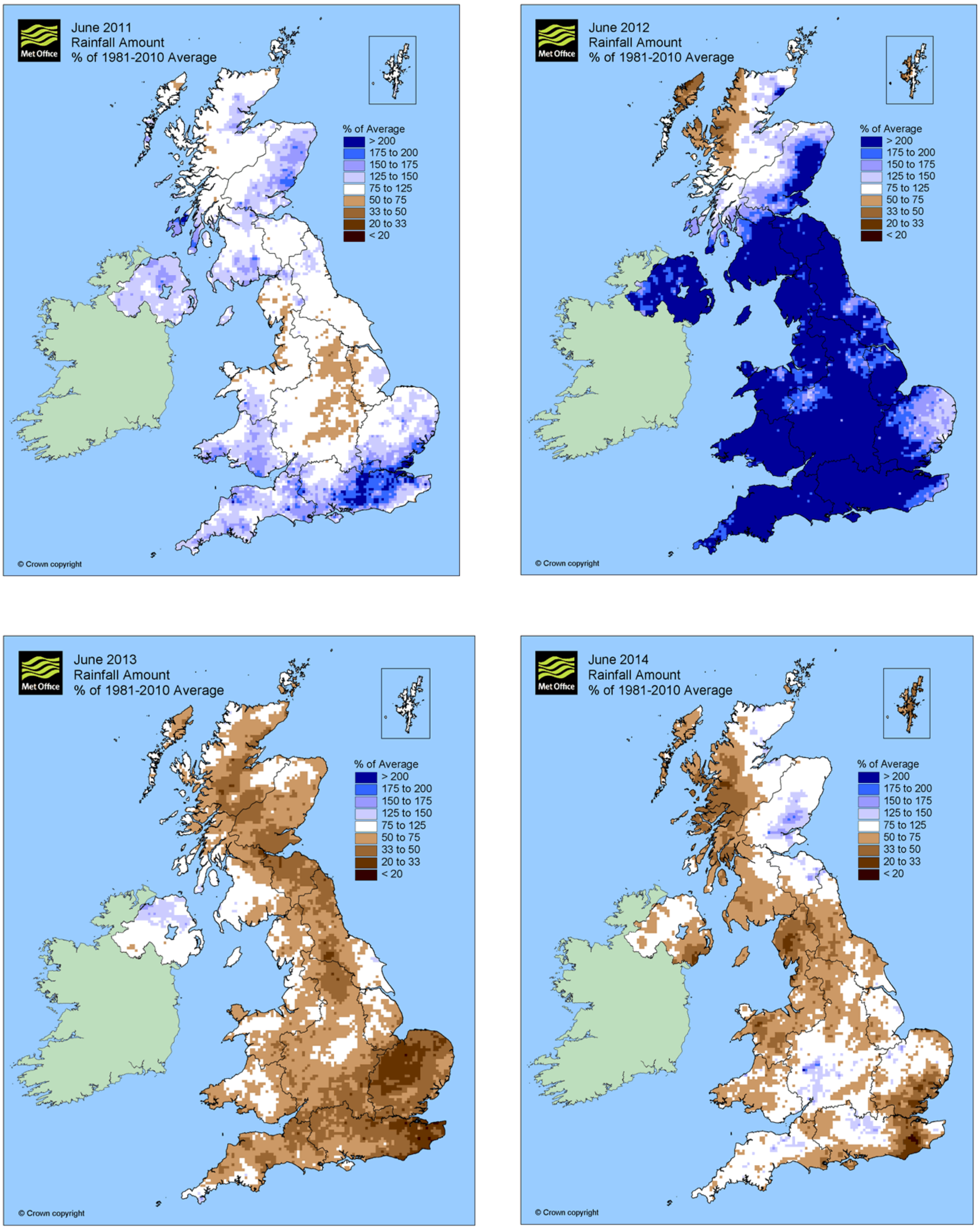


Figure 2-3: Rainfall anomaly maps for June 2011 – 2014, highlighting variability of weather across this period (Met Office, 2016)

2.3 Results

2.3.1 Fungicide treatment does not significantly impact yield in the majority of trials

While treated plots had, on average, higher yields than untreated by 0.62 t/ha (see Table 2-10), the majority of trials (65%) did not show a statistically significant impact of fungicide treatment on yields. In cases where disease was present, disease severity, particularly Total AUDPC, was more likely than yield to be reduced by the fungicide treatment (see Table 2-11, below). The detail of which trials were found to show significant impacts of treatment on yield and AUDPC for each disease is shown in Appendix B – Impact of treatment on yield and disease severity for all 2011 – 2014 trials.

The significance of treatment impact on yield varied across years and locations, with 2013 having no trials showing a significant impact (see Table 2-12). Not all diseases were present in every trial; the majority of instances where a disease was not recorded occurred in trials where treatment did not significantly impact yields (see Table 2-13).

Table 2-10: Mean and median of the treated and untreated yields and the difference between treated and untreated yields of spring barley

	Mean yield (t/ha)	Standard error of mean (t/ha)	Median yield (t/ha)
Untreated	6.23	0.11	6.38
Treated	6.84	0.12	6.82
Difference	0.62		0.44

Table 2-11: Significance of impact of fungicide treatment on yield and disease severity*

	Number of trials significantly different	Number of trials not significantly different	Percent of trials significantly different**	Number of trials with no disease pressure
Yield	14	26	35.0	
Total AUDPC (all diseases)	19	18	51.4	3
Rhynchosporium AUDPC	17	19	47.2	4
Ramularia AUDPC	13	13	50.0	14
Mildew AUDPC	6	11	54.5	23

*Significance at $p<0.05$

**Trials with no disease pressure (a value of zero) are not included in percentage significantly different, nor in the number of trials (not) significantly different

Table 2-12: Significance of treatment impact on yield across years

	Number significantly different*	Number not significantly different	Percent significantly different
2011	4	5	44%
2012	4	8	33%
2013	0	7	0%
2014	4	6	40%

*Significance was tested at p<0.05

Table 2-13: Number of trials without disease pressure

Trials lacking disease in untreated plots	Number of treatments without a significant* effect on yield	Number of treatments with a significant effect on yield
Trials with no Mildew present	17	6
Trials with no Ramularia present	10	4
Trials with no Rhynchosporium present	4	0
Trials with none of the three diseases present	3	0
Total number of trials	40	

*Significance was tested at p<0.05. Note that as a trial with no Mildew or Ramularia present (but with Rhynchosporium present) will be listed in two rows, the total number of trials is not equal to the sum of either column, and is included for reference only.

2.3.2 Fungicide use increases profit only marginally

The simple cost benefit analysis conducted compares the mean reduction in yields from a lack of use of fungicide to the cost saved by not purchasing fungicides. The resulting difference in profit between treated and untreated fields is small, averaging 4.4% (£50.30) for malting varieties and 4.7% (£56.80) for feed varieties (see Table 2-14). Fungicide cost margins do vary by year, with malting varieties having net losses in 2013 and a high of +7.5% difference in profit in 2012. Feed varieties were not included in the Field Trials database for 2013 and 2014, meaning profit margin calculations were not possible for this period. This analysis disregards other possible savings from lack of treatment (e.g. lower labour costs).

Table 2-14: Cost benefit analysis for malting and feed barley from 2011 – 2014 in Scotland, based on Field Trial database yields

	Mean Malting Barley Price (£/t)	Mean Feed Barley Price (£/t)	Difference in fungicide cost margin for malting varieties		Difference in fungicide cost margin for feed varieties	
			£/ha	%*	£/ha	%
2011	193.1	152.1	83.7	6.1	102.4	8.1
2012	200.1	169.4	79.8	7.6	11.1	1.2
2013	145.4	140.2	−24.4	−2.8	-	-
2014	119.3	115.1	62.0	6.9	-	-
Overall	164.5	144.2	50.3	4.4	56.8	4.7

*Percent difference is based on the treated profits

2.3.3 Key agronomic factors may be linked to treatment impact on yield

Low disease severity often coincides with trials where treatment does not have a significant impact on yield

Mean and median disease differences between treated and untreated plots tended to be greater in trials where treatment had a significant impact on yield (see Table 2-15), except in the case of median disease difference for Rhynchosporium. This reversal of the trend is likely due to the relatively high number of trials where treatment did not significantly impact yield but with large (e.g. −100 or more) disease differences for Rhynchosporium (one trial in 2011, three in 2012, two in 2013, and two in 2014), see Tables 2-17 to 2-20 for more detail. Nevertheless, this pattern held true in the pairs/groups analysis, where there tended to be larger differences in disease levels in trials where treatment impacted significantly upon yield for mildew (4 out of 5), Rhynchosporium (3 out of 5), and Total (4 out of 5), but not for Ramularia (1 out of 5) – see Table 2-16. There was not enough information available for these groups to make many comparisons of Rhynchosporium or mildew at GS 24 -34, but where this was possible differences within pairs were not large.

Table 2-15: Mean and median disease differences in AUDPC values for all trials, grouped by the significance of impact of treatment on yield

	Mean disease difference		Median disease difference	
	Significant* impact of treatment	No significant impact of treatment	Significant impact of treatment	No significant impact of treatment
Rhynchosporium	−261.9	−172.7	−39.8	−51.4
Ramularia	−17.6	−11.4	−23.9	−11.0
Mildew	−64.3	−27.3	−56.1	−23.5
Total AUDPC	−313.7	−191.4	−149.2	−107.6

*Significance was tested at $p<0.05$

Table 2-16: Pair/group comparisons encompassing disease resistance rating, AUDPC and early season disease*

Significant impact of treatment on yield?	Trial	Yield difference (mean)	Mildew Rating	Ramularia Rating	Rhynchosporium Rating	Mildew AUDPC difference	Ramularia AUDPC difference	Rhynchosporium AUDPC difference	Total AUDPC difference	Year	Farm
No	1519 Belgravia	0.15	9	-	7	−27.7	−82.3	−18.3	−128.4	2011	BRY**
No	1519 Concerto	0.34	8	-	4	−33.4	−72.8	−12.7	−118.9	2011	BRY
Yes	1058 (1105) Optic	0.62	5	-	4	−70.2	−68.8	−25.9	−164.9	2011	BRY
Yes	1519 Optic	0.84	5	-	4	−199.0	−60.2	−34.6	−293.7	2011	BRY
No	1547 Waggon	0.94	9	-	3	−50.5	−92.5	−503.7	−646.7	2011	BLL
Yes	1523 Optic	1.35	5	-	4	−104.7	4.0	−23.4	−124.2	2011	BLL
No	1665 Concerto	0.33	8	6	4	7.8	−42.8	−53.0	−88.0	2012	CAU
Yes	1625 Optic	0.80	5	6	4	−8.4	−31.9	−93.2	−133.4	2012	CAU

Table 2- 16 (continued)

Significant impact of treatment on yield?	Trial	Yield difference (mean)	Mildew Rating	Ramularia Rating	Rhynchosporium Rating	Mildew AUDPC difference	Ramularia AUDPC difference	Rhynchosporium AUDPC difference	Total AUDPC difference	Year	Farm
No	1659 Westminster	0.17	9	6	8	0	−59.62	202.9	143.3	2012	BDE
Yes	1659 Concerto	0.86	8	6	4	−7.5	−21.12	200	171.4	2012	BDE
No	1873 Concerto	0.79	8	6	4	−2.281	0	−449.1	−451.4	2014	DIN
Yes	1877 (1404) Optic	0.74	5	5	3	*	11	0.325	11.32	2014	DIN
No	1877(1404) Overture	−0.21	8	7	7	*	−44	−85.72	−129.7	2014	DIN
No	1878 Overture	0.66	8	7	7	*	−31.2	−49.8	−73.2	2014	DIN
Yes	1884 Concerto	1.43	8	6	4	*	−33.66	−339.2	−372.9	2014	DIN

* Yield and AUDPC differences are based on block level comparisons of treated vs untreated, calculated as Treated – Untreated.A positive difference for yield means the treated yield was higher than untreated. Negative difference mean the untreated was higher than treated. Difference in this chart is calculated by: Significant trial – Non significant trial on same principle. Significance was tested at $p<0.05$.

**Farm locations are coded as follows: Burnside – BDE, Balruddery – BRY, Boghall – BLL, Cauldshiel – CAU, Drumalbin - DIN

Treatment often impacts both yield and disease severity simultaneously

The significance of treatment on yield appears to be linked to the significance of treatment impact on disease severity, as seen in the master trial comparison results; see Table 2-17, Table 2-18, Table 2-19, and Table 2-20 for yearly summaries. In a majority of trials where there is a significant impact of treatment on yield, there is also a significant impact of treatment on one or more AUDPC values (10 of 14). Nine of these ten trials show a significant impact on Rhynchosporium and All Diseases. Three of these ten trials show a significant impact on mildew, while four reported no mildew being present; five show a significant impact for Ramularia, with two reporting no Ramularia present. Only four trials show a significant impact of treatment on yield without a significant impact of treatment on any disease – two of these three trials have no disease reported for two diseases. However, treatment does seem to impact disease severity, even where treatment does not result in a yield difference. Just 12 of the 26 trials where treatment did not have a significant impact on yield also show no significant impact of treatment on any disease severity (all but two of these 12 fall in 2013 and 2014, the drier/warmer years).

Table 2-17: Master trials comparison chart (2011) showing the impact of treatment on disease severity and yield, and key agronomic factors including weather, previous rotation, and varietal disease resistance ratings*

Trial	Variety	Location	Significance of treatment impact on:					Disease Resistance Rating			Rainfall in:		Temperature in:		Sow Date	Previous rotation	AUDPC Difference				Disease Difference at GS 24 - 34		Absolute Yield Difference
			Yield	Rhynchosporium	Mildew	Total AUDPC	Ramularia	Mildew	Ramularia	Rhynchosporium	May/June	Season	May/June	Season			Rhynchosporium	Ramularia	Mildew	Total AUDPC	Rhynchosporium	Mildew	
1058 (1105)	Optic	BRY	Sig	Sig	Sig	Sig	Sig	5	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 25.9	- 68.8	- 70.2	- 164.9	*	-0.3	0.62
1519	Belgravia	BRY	Not Sig	Not Sig	Not Sig	Sig	Sig	9	*	7	Wet	Wet	Avg	Avg	Avg	SB	- 18.3	- 82.3	- 27.7	- 128.4	*	*	0.15
1519	Concerto	BRY	Not Sig	Not Sig	Not Sig	Sig	Sig	8	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 12.7	- 72.8	- 33.4	- 118.9	*	*	0.34
1519	Optic	BRY	Sig	Not Sig	Sig	Sig	Sig	5	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 34.6	- 60.2	- 199.0	- 293.7	*	*	0.84
1523	Optic	BLL	Sig	Not Sig	Not Sig	Not Sig	Not Sig	5	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 23.4	3.9	- 104.7	- 124.2	*	*	1.35
1524	Optic	DIN	Sig	Sig	Not Sig	Sig	Sig	5	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 172.0	- 26.6	- 76.5	- 275.1	*	*	1.11
1525	Optic	BLL	Not Sig	Not Sig	Not Sig	Not Sig	Sig	5	*	4	Wet	Wet	Avg	Avg	Avg	SB	- 62.0	- 27.0	- 31.4	- 120.3	*	*	0.35
1547	Waggon	BLL	Not Sig	Sig	Sig	Sig	Sig	9	*	3	Wet	Wet	Avg	Avg	Late	SB	- 503.7	- 92.5	- 50.5	- 646.7	*	*	0.94
1557	Optic	BIE	Not Sig	Not Sig	No disease	Not Sig	No disease	5	*	4	Wet	Wet	Avg	Avg	Avg	Unknown	- 14.4	0.0	0.0	- 14.4	*	*	0.34

*Farm locations are coded as: Balruddery – BRY, Balgonie – BIE, Boghall – BLL, Drumalbin – DIN. Other abbreviations used in this table: Significant – Sig, Not significant – Not Sig, Average – Avg, Spring barley – SB, Winter barley – WB, Winter wheat – WW. Significance was tested at $p<0.05$.

Table 2-18: Master trials comparison chart (2012) showing the impact of treatment on disease severity and yield, and key agronomic factors including weather, previous rotation, and varietal disease resistance ratings*

Trial	Variety	Location	Significance of treatment impact on:					Disease Resistance Rating			Rainfall in:		Temperature in:		Sow date	Previous rotation	AUDPC Difference				Disease Difference at GS 24 - 34		Yield Difference
			Yield	Rhynchosporium	Mildew	Total AUDPC	Ramularia	Mildew	Ramularia	Rhynchosporium	May/June	Season	May/June	Season			Rhynchosporium	Ramularia	Mildew	Total AUDPC	Rhynchosporium	Mildew	
1659	Concerto	BDE	Sig	Sig	Not Sig	Sig	Not Sig	8	6	4	Wet	Wet	Cold	Avg	Early	WW	200.0	- 21.1	- 7.5	171.4	4.13	0.25	0.86
1664	Concerto	DIN	Not Sig	Sig	No disease	Sig	Not Sig	8	6	4	Wet	Wet	Avg	Avg	Avg	WB	- 681.4	24.1	0.0	- 657.4	*	*	1.10
1620 (1201)	Concerto	DIN	Not Sig	Not Sig	No disease	Not Sig	Sig	8	6	4	Wet	Wet	Avg	Avg	Avg	WB	- 733.5	87.8	0.0	- 645.6	*	*	0.31
1665	Concerto	CAU	Not Sig	Sig	Not Sig	Not Sig	Sig	8	6	4	Wet	Wet	Cold	Avg	Early	SB	- 53.0	- 42.8	7.8	- 88.0	- 0.13	- 0.50	0.33
1625	Optic	CAU	Sig	Sig	Not Sig	Sig	Sig	5	6	4	Wet	Wet	Cold	Avg	Early	SB	- 93.2	- 31.9	- 8.4	- 133.4		- 0.33	0.80
1659	Optic	BDE	Sig	Sig	Sig	Not Sig	Sig	5	6	4	Wet	Wet	Cold	Avg	Early	WW	193.6	- 71.1	- 42.0	80.5	4.00	- 0.25	1.15
1675	Optic	BIE	Not Sig	Not Sig	No disease	Not Sig	Not Sig	5	6	4	Wet	Wet	Cold	Avg	Avg	Unknown	- 11.5	- 11.0	0.0	- 18.8	0.17		0.36
1620 (1201)	Optic	DIN	Not Sig	Sig	No disease	Sig	Sig	5	6	4	Wet	Wet	Avg	Avg	Avg	WB	- 951.9	144.7	0.0	- 807.3	- 0.33	*	- 0.19
1634	Optic	BLL	Not Sig	Sig	No disease	Sig	No disease	5	6	4	Wet	Wet	Cold	Avg	Early	SB	- 69.4	*	0.0	- 69.4			0.43
1585 (1203)	Optic	CAU	Not Sig	Not Sig	Sig	Not Sig	No disease	5	6	4	Wet	Wet	Cold	Avg	Early	SB	- 24.9	*	- 119.8	- 144.7	*	*	0.56
1626	Waggon	BLL	Sig	Not Sig	Not Sig	Not Sig	Not Sig	9	7	3	Wet	Wet	Cold	Avg	Early	SB	50.0	- 16.0	- 6.2	27.8	- 0.03	- 0.30	0.52
1659	Westminster	BDE	Not Sig	Sig	No disease	Sig	Sig	9	6	8	Wet	Wet	Cold	Avg	Early	WW	202.9	- 59.6	0.0	143.3	4.00	*	0.17

*Farm locations are coded as: Burnside – BDE, Balgonie – BIE, Boghall – BLL, Cauldshiel – CAU, Drumalbin – DIN. Other abbreviations used in this table: Significant – Sig, Not significant – Not Sig, Average – Avg, Spring barley – SB, Winter barley – WB, Winter wheat – WW. Significance was tested at p<0.05.

Table 2-19: Master trials comparison chart (2013) showing the impact of treatment on disease severity and yield, and key agronomic factors including weather, previous rotation, and varietal disease resistance ratings*

Trial	Variety	Location	Significance of treatment impact on:					Disease Resistance Rating:			Rainfall in:		Temperature in:		Sow date	Previous rotation	AUDPC Difference				Disease difference at GS 24 - 34		Yield Difference
			Yield	Rhynchos porium	Mildew	Total AUDPC	Ramularia	Mildew	Ramularia	Rhynchos porium	May/June	Season	May/June	Season			Rhynchos porium	Ramularia	Mildew	Total AUDPC	Rhynchos porium	Mildew	
1791	Belgravia	BLL	Not Sig	No disease	Not Sig	Not Sig	No disease	9	7	7	Dry	Dry	Avg	Avg	Late	SB	- 23.0	*	- 11.6	- 23.1	*	*	- 0.33
1790	Concerto	DIN	Not Sig	Not Sig	No disease	Not Sig	Not Sig	8	6	4	Wet	Dry	Avg	Avg	Late	Grass	44.6	14.0	*	58.6	*	*	0.07
1750	Concerto	DIN	Not Sig	Not Sig	No disease	Not Sig	Not Sig	8	6	4	Wet	Dry	Avg	Avg	Late	Grass	- 22.2	- 3.5	*	- 25.7	*	*	0.34
1763	Concerto	BLL	Not Sig	No disease	No disease	No disease	No disease	8	6	4	Dry	Dry	Avg	Avg	Late	SB	*	*	*	*	*	*	- 0.35
1800	Concerto	CAU	Not Sig	No disease	No disease	No disease	No disease	8	6	4	Dry	Dry	Avg	Avg	Late	WW	*	*	*	*	*	*	0.18
1764	Optic	DIN	Not Sig	Not Sig	No disease	Not Sig	Not Sig	5	5	3	Wet	Dry	Avg	Avg	Late	Grass	- 100.4	4.2	*	- 96.2	-0.50	*	0.60
1790	Optic	DIN	Not Sig	Sig	No disease	Sig	Not Sig	5	5	3	Wet	Dry	Avg	Avg	Late	Grass	- 233.9	- 4.7	*	- 238.5	*	*	0.21

*Farm locations are coded as: Boghall – BLL, Cauldshiel – CAU, Drumalbin – DIN. Other abbreviations used in this table: Significant – Sig, Not significant – Not Sig, Average – Avg, Spring barley – SB, Winter barley – WB, Winter wheat – WW. Significance was tested at p<0.05.

Table 2-20: Master trials comparison chart (2014) showing the impact of treatment on disease severity and yield, and key agronomic factors including weather, previous rotation, and varietal disease resistance ratings*

Trial	Variety	Location	Significance of treatment impact on:					Disease Resistance Rating:			Rainfall in:		Temperature in:		Sow date	Previous Rotation	AUDPC Difference:				Disease Difference at GS 24 - 34:		Yield Difference
			Yield	Rhynchosporium	Mildew	Total AUDPC	Ramularia	Mildew	Ramularia	Rhynchosporium	May/June	Season	May/June	Season			Rhynchosporium	Ramularia	Mildew	Total AUDPC	Rhynchosporium	Mildew	
1884	Concerto	DIN	Sig	Sig	No disease	Sig	Not Sig	8	6	4	Avg	Avg	Hot	Hot	Late	SB	- 339.2	- 33.7	*	- 372.9	*	*	1.43
1873	Concerto	DIN	Not Sig	Not Sig	No disease	Not Sig	No disease	8	6	4	Avg	Avg	Hot	Hot	Late	WB	- 436.9	*	*	- 439.2	- 0.87	*	0.79
1919	Concerto	BLL	Sig	Sig	No disease	Sig	No disease	8	6	4	Avg	Wet	Hot	Hot	Avg	SB	- 905.0	*	*	- 905.0	0.30	*	1.58
1906	Concerto	BDE	Not Sig	Not Sig	Not Sig	Not Sig	Not Sig	8	6	4	Avg	Wet	Hot	Hot	Avg	SB	- 274.5	2.5	- 0.8	- 257.2	*	*	0.30
1885	Concerto	BLL	Sig	Sig	No disease	Sig	No disease	8	6	4	Avg	Wet	Hot	Hot	Avg	SB	-1326.8	*	*	-1207.6	- 0.50	*	1.98
1889	Concerto	BLL	Sig	Sig	No disease	Sig	Not Sig	8	6	4	Avg	Wet	Hot	Hot	Avg	SB	-1145.5	- 15.5	*	-1161.0	*	*	2.01
1908	Concerto	CAU	Sig	Not Sig	No disease	Not Sig	No disease	8	6	4	Avg	Wet	Hot	Hot	Avg	SB	- 44.9	*	*	- 44.9	- 0.57	*	0.30
1877 (1404)	Optic	DIN	Sig	Not Sig	No disease	Not Sig	No disease	5	5	3	Avg	Avg	Hot	Hot	Late	SB	0.3	*	*	11.3	- 0.45	*	0.74
1877 (1403)	Optic	CAU	Not Sig	Not Sig	Sig	Sig	No disease	5	5	3	Avg	Wet	Hot	Hot	Avg	SB	- 25.6	*	- 23.5	- 49.0	- 0.50	*	0.12
1877 (1404)	Overture	DIN	Not Sig	Sig	No disease	Sig	No disease	8	7	7	Avg	Avg	Hot	Hot	Late	SB	- 85.7	- 44.0	*	- 129.7	0.25	*	- 0.21
1878	Overture	DIN	Not Sig	Not Sig	No disease	Not Sig	Not Sig	8	7	7	Avg	Avg	Hot	Hot	Late	SB	- 49.8	- 31.2	*	- 73.2	0.10	*	0.66
1877 (1403)	Overture	CAU	Not Sig	No disease	No disease	No disease	No disease	8	7	7	Avg	Wet	Hot	Hot	Avg	SB	*	*	*	*	- 0.10	*	0.14

*Farm locations are coded as: Burnside – BDE, Boghall – BLL, Cauldshiel – CAU, Drumalbin – DIN. Other abbreviations used in this table: Significant – Sig, Not significant – Not Sig, Average – Avg, Spring barley – SB, Winter barley – WB, Winter wheat – WW. Significance was tested at $p<0.05$.

Linkage between disease resistance and the impact of treatment on yield

Those trials where fungicide treatment did not have a significant impact on yield had, on average, slightly higher disease resistance ratings for all three diseases (see Table 2-21). When pair/group analysis was conducted, a clear pattern of higher disease resistance in the trials which did not show a significant impact of treatment on yield emerged. For five of the six comparisons, mildew resistance rating was higher in the trial without a significant impact (the remaining pair was equivalent). For two out of the four groups with resistance information for Ramularia, resistance was higher in the trial without a significant impact (the remaining two pairs were equivalent). Rhynchosporium resistance rating was higher in the trial with a significant impact of treatment on yield in only one of the six groups. Overall, only in one trial was there a pair where any of the diseases had a higher resistance rating in the trial which showed a significant impact of treatment (2011 in Boghall) and here the difference in Rhynchosporium ratings was only one (see Table 2-16).

The pattern of high disease resistance ratings remains relevant when comparing across the master trials comparison charts, as only one trial with two disease resistance ratings of 7 or above showed a significant impact of treatment on yield. Trials with at least one disease rating of 7 or above generally did not show a significant impact of treatment on yield (17 out of 24). Trials with two disease resistance ratings of 6 or above only showed a significant impact of treatment on yield in 7 out of 22 cases.

Table 2-21: Mean and median disease resistance ratings in trials where treatment had a significant impact on yield versus those where it did not

	Trials with a significant* impact of treatment on yield		Trials without a significant impact of treatment on yield	
	Mean	Median	Mean	Median
Mildew	6.4	5	7.2	8
Ramularia	6.0	6	6.1	6
Rhynchosporium	3.9	4	4.6	4

*Significance was tested at p<0.05

Connections between rainfall and impact of treatment on yield

Wet weather, both across the entire growing season and in May/June, seems to be linked to significance of treatment on yield, with 11 of the 14 trials showing a significant impact on yield occurring in wet growing seasons, and eight of the 14 falling into wet May/June periods. Conversely, 2013, the year with no trials showing a significant impact of treatment on yields, was also the driest year.

Other factors which may be linked to treatment significance on yield

Little variation is available in this database to test previous rotation, however of the seven trials which did not have spring barley as the previous crop, more than half (6 out of 8) did not show a significant impact on yield. For those where the previous crop was grass, rather than wheat, all trials (four) did not show a significant impact of the treatment on yield. Sowing date presented slightly more variation, with 19 'average', 9 'early', and 13 'late' trials. Of these, 8 (out of 19), 4 (out of 9), and 2 (out of 13), respectively, showed a significant impact on yield – indicating a potential benefit from later sowing. Sowing date varies with year, location, and weather, so early sowing was seen only in wet years (2011 and 2012) and late sowing almost only seen in 2013 and 2014, complicating the relationship between sowing and significance. Yield differences of over 0.5 t/ha were seen in trials where treatment had a significant impact on yield more than half of the time (12 out of 19 trials), while yield differences of over 1 t/ha were almost solely seen in trials with a significant impact on yield (7 out of 8).

2.4 Discussion

2.4.1 Key messages

Fungicide treatment impact on yield is variable

The mean impact of fungicide treatment on yields was 0.62 t/ha, with the majority of trials having absolute yield differences of below 1 t/ha – however, the difference in yield between treated and untreated was statistically significant only 35% of the time. Yield differences within trials may be buffered as compared to those seen on commercial farms, as a single plot of untreated spring barley surrounded by numerous plots of treated crops may encounter lower disease pressure than would be seen in a larger system. Conversely, the edge effect in trial plots where plants do not have the same competition for light and other resources on the edge of a trial plot may mean plots are, in fact, more responsive to fungicide treatment. Plot size may also preclude direct extrapolation to commercial farm situations, as larger plot sizes (40x40m vs 20x20m or 10x10m) have been shown to significantly impact disease severity, with higher final disease severity in the larger plots, though not yield, in wheat and barley (Burleigh & Loubane, 1984). Further analysis, particularly of commercial field sized trials, would be needed to quantify the exact loss of yield when fields are left untreated – but this would be confounded by the impossibility of having exact replicates. Preliminary cost benefit analysis suggests that increased profit from sprayed fields is in the range of 4.5% for malting barley, considering only the difference between mean treated and untreated yields, and the cost of applying fungicides. When additional factors, such as labour and machinery costs are taken into account, this figure may decrease. This analysis does make the assumption that all untreated barley in the Field Trials was of sufficient quality for malting, which may be inaccurate. The addition of other criteria, e.g. environmental impacts of various management strategies could also effect the cost-benefit results, as it has been suggested that traditional analyses, which do not consider long term effects underestimate the true cost of pesticide use (Van den Berg & Jiggins, 2007). More in-depth cost-benefit analysis could be paired with stakeholder surveys, to determine whether farmers are overestimating the financial benefits of spraying, and what impact this may have on their decision making. There are, however, instances where fungicide treated yields were substantially (up to 2.01 t/ha) greater than those for untreated plots. In these situations, the scope for fungicide reduction or elimination is likely limited. Further research on cost-benefit and identifying seasons or periods of high risk could give farmers more confidence when deciding whether or not to reduce fungicide inputs.

Fungicide treatment had a positive significant impact on spring barley yields in only 35% of the field trials studied. Approximately half of the trials showed a significant impact of fungicide treatment on Rhynchosporium, Ramularia, mildew, and Total AUDPC levels, however. Fungicide treatment therefore seems to impact disease severity in a large number of trials, but this impact does not translate directly into a significant impact on yield. While the impact of AUDPC on yield is widely reported in the literature (Oerke & Dehne, 2004; Havis et al., 2015; Jarvis et al., 2002; Cooper & Dobson, 2007), there are also a number of studies which fail to find a consistent link between yield and AUDPC, and suggest that more accurate relationships can be described by incorporating leaf area index measurements (Waggoner & Berger, 1987; Lim & Gaunt, 1986; Gaunt, 1995; Paveley et al., 1997), however this information was unavailable for the Field Trials database, and could therefore not be used. Treatment significance varied across year and location, suggesting other factors also impact yield difference.

A general impact of disease on yield difference was suggested by the lower mean disease severity and a higher proportion of trials with no disease present for at least one disease in those trials where treatment did not have a significant impact on yield, as well as the slightly higher disease resistance ratings for those same trials. In studies on wheat, higher disease resistance ratings have been shown to be correlated to lower yield loss for Septoria (caused by *Septoria tritici*) (Berry et al., 2008), leaf rust (caused by *Puccinia triticina*), and fusarium head blight (caused by *Fusarium graminearum*) (Martens et al., 2014). Disease resistance ratings may also impact significance of treatment on yield, as only one trial with varieties which were highly resistant to two or more diseases showed a significant impact of treatment on yield, and 71% of trials with varieties highly resistant to at least one disease did not show a significant impact of treatment on yield. This finding is in line with previously reported research in winter wheat, where yield response varied with disease resistance ratings (Cook & Thomas, 1990).

Weather

Yearly summary tables also indicated a link between the significance of treatment on yield and the significance of treatment on disease severity. Wet weather was also highlighted as being of likely importance to the significance of treatment impact on yield, with 86% of trials with a significant impact of treatment on yield falling into a wet year. Further, 2013, the driest year, was also the only year with no trials showing a significant impact of treatment on yield. Previous work on long-term databases of winter wheat has found precipitation, along with temperature, to be a significant factor in predicting yield and disease severity (Wiik & Ewaldz, 2009).

Absolute yield difference

Absolute yield difference was variable with significance of impact of treatment on yield, with yield differences of over 1 t/ha being found in trials where treatment had a significant impact on yield in all but one case, and trials with yield differences of over 0.5 t/ha being found in these a majority of the time.

2.4.2 Limitations

These initial findings shed light on some of the factors which are likely to impact the significance of treatment on yield; disease resistance ratings, disease severity, and weather conditions. Sowing date and previous rotation were included in the patterns analysis, as both have been recorded as impacting disease in Rhynchosporium (Zhan et al., 2008; Oxley & Burnett, 2010), and the impact of rotation on yield is well established (Kirkegaard et al., 2008; Sieling & Christen, 2015), but due to a lack of variation in the database used for this study few conclusions can be drawn regarding the influence of these factors. Likewise, disease severity early in the growing season, between Growth Stages 24 – 34 was included in the analysis, but not enough data existed to consider the impacts of early disease on yield differences. More information regarding these factors, as well as more detailed weather data, linked to each individual farm or county, rather than data compiled at regional level, could provide more insight into the factors of interest. More information would also have allowed the pairs/group comparisons to be undertaken statistically, which could have provided valuable information about the factors being considered without the potential for interference from unaccountable sources of variation.

Weather data at the resolution of regional level was obtained for each year, in order to provide general background for the trials. Anomaly values were used as a way of quickly providing information about whether the years were wetter/drier than average in a straightforward manner. A wider range of anomaly values were tested, separating years into, for example, 'very hot' (more than 1.5°C higher the baseline average from 1981 – 2010); 'hot' (0.5 – 1.5°C higher than the average); 'average' (within 0.5°C of the average); 'cold' (0.5 - 1.5°C below the average); 'very cold' (more than 1.5°C below the average), but there was insufficient variation in the period analysed for this wider range to be of use. Weather data taken at a more local level would have provided more detailed data, and potentially allowed the use of a wider range of anomaly values to be considered separately. Initially, weather data gathering from Met Office databases for each site was trialled using the method reported by Hill and Wall (2015), whereby data from within 5km would be retrieved for comparison. This method was not feasible, given the geographical spread of the trial sites, and it was determined that extending the range of the nearest weather station to 20km, as would have been required, would not provide accurate enough data for detailed analysis. In addition, getting both temperature and rainfall data from the same weather station might not have been possible for each field trial. Regional level data was therefore used, as the broad weather characterisation could be assessed with confidence. The lack of precision in weather data did not prevent patterns regarding weather's impact on disease levels and yield to be seen. Overarching patterns of the influence of key factors were nevertheless identified, which can be used in more detailed analysis of the Field Trials database in order to quantify the impact of these factors on the interaction between yield and fungicide treatment.

2.5 Conclusions

Fungicide treatment impacted yield levels significantly in just over one third of the trials assessed from 2011 – 2014, though disease levels were significantly reduced in many cases. This variable influence of treatment on yield has been reported before where studies have been conducted over the long-term (Jørgensen et al., 2000; Cook & Thomas, 1990). The lack of a constant influence on yield, and the minimal cost benefit from fungicide treatment, estimated at less than 5% on average suggests there may be an opportunity to reduce fungicide use in this sector. In order to provide more robust recommendations to farmers and policy makers, it is necessary to build on the initial patterns analysis described in this chapter, which suggest certain factors, e.g. disease resistance levels and weather, may be very important considerations for rationalising fungicide use. Assessing these factors using long-term data may provide useful information by comparing a wider range of varieties, weather, and field conditions, which may confirm the patterns seen in this shorter term analysis.

Chapter 3 Field Trials (1996 – 2014): regressions analysis assessing the impact of various factors on yield

3.1 Introduction

In order to rationalise fungicide use, and thus slow development of fungicide resistance and reduce the potential for environmental degradation from arable systems as discussed in Chapter 1, it is important to understand what factors drive the differences in yield between treated and untreated crops. As shown in Chapter 2, fungicide application did not significantly increase yield in a majority of field trials in 2011 – 2014. What is crucial from a decision-making perspective is what distinguished a trial with no significant yield increase from fungicide application from a trial with significant yield increase from fungicides. Knowing which factors influence the impact of fungicide use on yields might allow fungicide use to be reduced where these pressures are not present. Some integrated pest management techniques, such as sowing disease resistant varieties or crop rotation, are decisions which must be taken in advance of the growing season; confidence that these are broadly useful tools for a given crop and environment is therefore important. Analysing such factors in an attempt to explain the difference in yield between treated and untreated barley can help to better understand the scenarios in which fungicide treatment significantly impacts yields in spring barley, and thus guide management recommendations. Factors previously identified in the 2011 – 2014 patterns analysis presented in Chapter 2 (disease severity, disease resistance rating, and weather variables), and those which were not variable enough to be assessed (previous rotation and sowing date) will be considered in more detail in this chapter.

3.1.1 Prior studies

Previous studies have analysed the impacts of fungicide treatments on yields and disease, often in the context of producing decision support tools or risk assessments. The work by Twengström et al. (1998) and Yuen et al. (1996) on sclerotinia stem rot of oilseed rape is an example of an attempt to link yield and disease in a way which produces both a forecast of the likely disease severity and a risk algorithm, using economic thresholds to consider a range of factors, including crop rotation, rainfall, and previous disease incidence.

Here, each factor was assessed first in an individual regression, then a full model was compiled, including all terms, and a given factor removed to determine whether or not its inclusion improved the model's ability to predict epidemics (Twenström et al., 1998). While this work provided a useful tool for farmer decision making, one issue which was specifically raised by Twengström was the lack of data going back further than six years – longer term experimental work was suggested as a way of improving predictive power. In Cook and Thomas's (1990) work on fungicide us in winter wheat, by contrast, long-term data (1979 – 1987) was assessed for a range of site variables alongside fungicide impact (at different doses and number of applications) on yields, though no model was developed. While fungicide application did have an overall impact on yields, the response was highly variable across varieties, years, sowing date, crop rotations, fungicide active ingredient, and geographical location (Cook & Thomas, 1990). Though weather variables were not included in this work specifically, some of the variation across regions and years is likely due to weather differences. This work provides good evidence of the importance of varietal choice, and the variability in fungicide impacts on yield, but does not attempt to rank the various site factors in order to aid farmer decision making or policy recommendations.

In another long-term experiment on winter wheat, Wiik (2009), analysing field trials from 1977 – 2005, used a combination of correlations, ANOVA, regressions, and REML (residual maximum likelihood) to assess the impacts of various diseases and fungicide treatments on yield. Fungicide treatment increased yields overall (mean treated yields were 8.64 t/ha, while untreated were 7.83 t/ha – a difference of 9.4%), largely explained by leaf blotch diseases at late growth stages (Wiik, 2009). However, fungicide use increased yields by over 0.5 t/ha in only 14 of the 23 years studied, and yield increases varied considerably between years and regions (Wiik, 2009). In a more detailed analysis of the influence of weather variables on winter wheat disease and yields, running from 1983 – 2007, Wiik and Ewaldz (Wiik & Ewaldz, 2009) found that monthly means of temperature and rainfall explained over half of the variation in disease severity for a range of diseases, but not yield. Wiik (2009) and Wiik and Ewaldz's (Wiik & Ewaldz, 2009) analyses provide valuable information about the impacts of weather on yield and disease in long-term field experiments, however, neither piece of work assessed the relative impacts of other management or site factors on the impact of fungicide use on yield.

While studies aiming to determine when spraying fungicide is necessary are not new, no work was found which attempts to combine the merits of the various approaches described above for spring barley. Combining the assessment of a large range of potentially important site factors, comparison of individual and stepwise regression models, and use of long-term data allows for a broader picture of the agricultural system to be considered, and may provide more actionable outputs for farmers, by considering management factors within their control (e.g. crop rotation). The work of Twengström et al. (1998) provides a useful tool for farmer decision making for oilseed rape using short-term data; Cook and Thomas (1990) provide assessments of variety and rotation in long-term winter wheat production; and the work of Wiik (2009) and Wiik and Ewaldz (Wiik & Ewaldz, 2009) considers temperature and rainfall in detailed assessments of long-term winter wheat trials. Each of these pieces of work provides a valuable insight into a given part of the crop system. Lacking, however, is an analysis which combines long-term data with weather and crop management decisions to assess the relative importance of each.

3.1.2 Database types

As mentioned above, long-term databases present an opportunity to assess these factors across a wide range of conditions, thus potentially providing more robust results. As long-term data is expensive to collect, and requires proportionally long-term forward planning (and potentially confounded by funding for research proposals generally being for fixed, short periods), many models and decision making tools rely on short-term experiments of less than five years. The SRUC Field Trials provides an opportunity to explore the differences between these types of datasets. For reasons which will be explored further below, the 1996 – 2014 data includes only means level information on yield and disease assessment per treated and untreated crop per trial. A comparison is therefore also possible between short term, high resolution data (2011 – 2014, see Chapter 2) and long-term means level data.

The main purpose of the analysis described in this chapter was to determine whether yield differences between treated and untreated spring barley trials/plots can be explained by key management and site factors. The secondary aim of this chapter is to discover what differences, if any, exist between models developed in the same way but using different dataset types, and in particular the length of time over which the data has been collected.

3.2 Materials and Methods

3.2.1 Data collection and preparation

Data gathering

After an extensive review of old trial reports, the majority of information from 1996 (the year in which reports began to be stored electronically) onwards was retrieved. To avoid potential biases arising from using only the 'most clean' data, the database was split to encompass only 1996 – 2014. In a number of cases for trials prior to 2011, yield and disease severity measurements were recorded only as means for a given treatment, rather than at plot level. Some plot level data was retrieved from trial reports, however in a majority of cases the electronic files did not record plot level data. A means database was therefore created, by taking means of plot level data, where available, in order to render the database internally consistent. Weather anomaly data from the Met Office, varietal disease resistance information taken from the SRUC/SAC Cereal Recommended lists, and AUDPC for each disease were added to the database as described in Chapter 2. A summary of the information available in the final database for each variable can be found in Table 3-1, and the geographical spread of trials across time in the database in Table 3-2. The most frequently used fungicides for each year in the Field Trials database are listed in Appendix C – Most frequently used fungicides in the Field Trials database (1996 – 2014), as are their active ingredients, to highlight the change in the chemicals applied over this period.

Table 3-1: Summary of data available in Means Field Trial database 1996 - 2014

Data	**Number of trials for which this data is available**
Location	112
Variety	112
Rhynchosporium Rating	100
Mildew Rating	100
Ramularia Rating	31
Sowing Date	110
Previous Rotation 1	103
Previous Rotation 2	96
Previous Rotation 3	92
Previous Rotation 4	66
Disease severity (disease observed at least once)	108
Total number of trials	112

Table 3-2: Summary of the geographical spread across sub-regions in the 1996 – 2014 means database

	Clyde Valley	Dumfries & Galloway	Fife	Lothian	North East	Scottish Borders	Tayside	Total number of trials in this year
1996				4		3		7
1997						1		1
1998				7				7
1999		1		2		2		5
2000				3		1	1	5
2001						1	1	2
2002				1			1	2
2003		2		1		1	1	5
2004		3	2	4			2	11
2005			1		1		1	3

Table 3-2 (continued)	Clyde Valley	Dumfries & Galloway	Fife	Lothian	North East	Scottish Borders	Tayside	Total number of trials in this year
2006						3	1	4
2007				2		3	1	6
2008						1		1
2009							3	3
2010				2			1	3
2011	1		1	4			3	9
2012	2		1	6			1	10
2013	4			9			1	14
2014	5			7	1		1	14
Total number of trials	12	6	5	52	2	16	19	

Quantifying absolute yield difference and relative yield difference

Two types of yield difference were calculated as proxy values for impact of treatment on yield. Relative yield difference, calculated as:

$$(\text{Treated} - \text{Untreated})/\text{Treated}$$

after Affholder et al. (2013), and absolute yield difference, calculated as:

$$\text{Treated} - \text{Untreated}$$

Both types of yield difference were analysed for different purposes, as described below.

3.2.2 Regression analysis

Table 3-3 provides a summary of all models developed in this Chapter for ease of reference. More detail is provided regarding the method of model development for each type of model following this summary table.

Table 3-3: Summary of all models developed in Chapter 3 (in the order in which they appear)

Model number	Dataset used	Y variate	Notes	Model results detailed?
1	1996 – 2014	Absolute Yield Difference	Individual disease AUDPC tested	Yes
2	1996 – 2014	Absolute Yield Difference	Total AUDPC tested	Yes
3	2011 – 2014 plot level	Absolute Yield Difference	Individual disease AUDPC tested	Yes
4	2011 – 2014 plot level	Absolute Yield Difference	Total AUDPC tested	Yes
5	2011 – 2014 means level	Absolute Yield Difference	Individual disease AUDPC tested	Yes
6	2011 – 2014 means level	Absolute Yield Difference	Total AUDPC tested	Yes
7	2011 – 2014 plot level	Absolute Yield Difference	Fitting with full dataset model – Individual disease	Yes
8	2011 – 2014 means level	Absolute Yield Difference	Fitting with full dataset model – Individual disease	Yes
9	2011 – 2014 plot level	Absolute Yield Difference	Fitting with full dataset model – Total AUDPC	Yes
10	2011 – 2014	Absolute Yield	Fitting with full dataset model –	Yes

Model number	**Dataset used**	**Y variate**	**Notes**	**Model results detailed?**
	means level	Difference	Total AUDPC	
11	1996 – 2014	Relative Yield Difference	Individual disease AUDPC tested	No
12	1996 – 2014	Rhynchosporium AUDPC	Disease severity	No
13	1996 – 2014	Rhynchosporium disease difference	Disease difference	No
14	2011 – 2014 plot level	Rhynchosporium AUDPC	Disease severity	No
15	2011 – 2014 plot level	Rhynchosporium disease difference	Disease difference	No
16	2011 – 2014 means level	Rhynchosporium AUDPC	Disease severity	No
17	2011 – 2014 means level	Rhynchosporium disease difference	Disease difference	No
18	1996 – 2014	Mildew AUDPC	Disease severity	No
19	1996 – 2014	Mildew disease difference	Disease difference	No
20	2011 – 2014 plot level	Mildew AUDPC	Disease severity	No
21	2011 – 2014 plot level	Mildew disease difference	Disease difference	No

Model number	**Dataset used**	**Y variate**	**Notes**	**Model results detailed?**
22	2011 – 2014 means level	Mildew AUDPC	Disease severity	No
23	2011 – 2014 means level	Mildew disease difference	Disease difference	No
24	2011 – 2014 plot level	Ramularia AUDPC	Disease severity	No
25	2011 – 2014 plot level	Ramularia disease difference	Disease difference	No
26	2011 – 2014 means level	Ramularia AUDPC	Disease severity	No
27	2011 – 2014 means level	Ramularia disease difference	Disease difference	No

Absolute yield difference regressions (Models one through ten)

Stepwise regressions using GLM (generalised linear model) in Minitab 16 (2010) were elaborated for three databases: the full means Field Trials database (1996 – 2014), the plot level Field Trials database (2011 – 2014), and a subset means Field Trials database (2011 – 2014). These regressions were fitted for a number of fixed-effect factors: sowing date; previous rotation – barley or non-barley; any resistance – disease resistance rating of seven or more to at least one of the three diseases; Rhynchosporium AUDPC; mildew AUDPC; Ramularia AUDPC; Total AUDPC; and season rainfall and temperature anomaly levels of wet/dry/average, as calculated in Chapter 2. A normal error distribution and identity link function were used, as residuals were distributed relatively normally (as determined by a review of standardized residual histograms and half-normal plots). Errors likely to arise due to aliasing were identified, and these interactions were excluded from the analysis. The outputs of these three models were then compared to provide assess the difference between long and short term datasets, as well as high resolution (plot level) vs lower resolution (means level) data on regression outputs. In addition to a full stepwise regression, each factor was tested in an individual GLM regression against each dataset, for comparison.

Assessing Total AUDPC (calculated as the sum of all three diseases) in addition to individual disease severity was necessary as, in a number of instances, a lack of data for mildew AUDPC through incomplete recording of data meant trials without this information were removed from the analysis. The impact of testing Total AUDPC instead of mildew on the number of trials/plots which can be assessed is shown in Table 3-4 for each of the three databases. These models provide a comparison with those created using individual disease levels. The potential restriction arising from other factors included in the model was assessed, however only disease severity decreased the percent of trials/plots available for analysis below 89% (see Table 3-5). The final model developed for the full 1996 – 2014 dataset was then used to compare the predicted versus actual values for each of the three datasets, to assess goodness of fit.

Table 3-4: Impact of including mildew AUDPC vs Total AUDPC on the total number of trials/plots included in regression analysis for each dataset

	Total Number of trials/plots	Number of trials/plots including mildew AUDPC)	Number of trials/plots including Total AUDPC
1996 – 2014 data	224	71	212
2011 – 2014 means data	39	21	35
2011 -2014 plot level data	132	75	123

Table 3-5: Impact of including each factor on the total number of trials/plots included in regression analysis for each dataset

	Full means dataset (1996 – 2014)	2011 – 2014 means dataset	2011 – 2014 plot level dataset
Season rainfall	224	39	132
Season temperature	224	39	132
Any Resistance	200	39	132
Non-continuous Barley	206	35	126
Sow Date	220	39	132
Rhynchosporium AUDPC	204	37	123
Mildew AUDPC	73	23	82
Ramularia AUDPC	*	24	96
Total AUDPC	214	37	125
Total number of trials	224	39	132

Relative yield difference regressions

A stepwise model was then elaborated using relative yield difference, in order to provide a measure of the impact of a static theoretical maximum yield measurement on model output. For a summary of the model developed testing relative yield difference, see Table 3-6.

Table 3-6: Model developed testing relative yield difference

Dataset used	**1996 – 2014 dataset**
Model number	**Model 11**
Model type	Stepwise regression
Y variate	Relative Yield Difference
X variates tested	Season rainfall Season temperature Any Resistance Sow Date Non-continuous Barley Mildew AUDPC Rhynchosporium AUDPC

Disease severity and disease difference regressions

Stepwise regressions were then carried out for each of the three datasets, testing as well as individual factor regressions, fitted to each of the three disease's

AUDPC and the total AUDPC values in order to provide information about the impact of key agronomic factors on disease severity. Disease difference was then calculated, as Treated AUDPC – Untreated AUDPC for each disease for each dataset. Disease difference was used to provide a more comparable summary of the impact of treatment on disease than disease severity, and to potentially provide useful information for the management of individual diseases. Disease difference factors were then used as response variates for stepwise regressions run for each disease (and Total AUDPC) for each dataset. Summaries of the models developed for each disease can be found below, as follows: Rhynchosporium – Table 3-7 ; mildew – Table 3-8; Ramularia – Table 3-9.

Table 3-7: Models developed testing Rhynchosporium AUDPC and Rhynchosporium disease difference

Dataset used	**1996 – 2014 dataset**		**2011 – 2014 plot level dataset**		**2011 – 2014 means level dataset**	
Model number	**Model 12**	**Model 13**	**Model 14**	**Model 15**	**Model 16**	**Model 17**
Model type	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression
Y variate	Rhynchosporium AUDPC	Rhynchosporium disease difference	Rhynchosporium AUDPC	Rhynchosporium disease difference	Rhynchosporium AUDPC	Rhynchosporium disease difference
X variates tested	Season rainfall	Season rainfall	Season rainfall	Season rainfall	Season rainfall	Season rainfall
	Season temperature	Season temperature	Season temperature	Season temperature	Season temperature	Season temperature
	Any Resistance	Any Resistance	Any Resistance	Any Resistance	Any Resistance	Any Resistance
	Sow Date	Sow Date	Sow Date	Sow Date	Sow Date	Sow Date
	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley
	Mildew AUDPC	Mildew disease difference	Mildew AUDPC	Mildew disease difference	Mildew AUDPC	Mildew disease difference
			Ramularia AUDPC	Ramularia disease difference	Ramularia AUDPC	Ramularia disease difference

Table 3-8: Models developed testing Mildew AUDPC and Mildew disease difference

Dataset used	**1996 – 2014 dataset**		**2011 – 2014 plot level dataset**		**2011 – 2014 means level dataset**	
Model number	**Model 18**	**Model 19**	**Model 20**	**Model 21**	**Model 22**	**Model 23**
Model type	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression
Y variate	Mildew AUDPC	Mildew disease difference	Mildew AUDPC	Mildew disease difference	Mildew AUDPC	Mildew disease difference
X variates tested	Season rainfall	Season rainfall	Season rainfall	Season rainfall	Season rainfall	Season rainfall
	Season temperature	Season temperature	Season temperature	Season temperature	Season temperature	Season temperature
	Any Resistance	Any Resistance	Any Resistance	Any Resistance	Any Resistance	Any Resistance
	Sow Date	Sow Date	Sow Date	Sow Date	Sow Date	Sow Date
	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley
	Rhynchosporium AUDPC	Rhynchosporium disease difference	Rhynchosporium AUDPC	Rhynchosporium disease difference	Rhynchosporium AUDPC	Rhynchosporium disease difference
			Ramularia AUDPC	Ramularia disease difference	Ramularia AUDPC	Ramularia disease difference

Table 3-9: Models developed testing Ramularia AUDPC and Ramularia disease difference

Dataset used	**2011 – 2014 plot level dataset**		**2011 – 2014 means level dataset**	
Model number	**Model 24**	**Model 25**	**Model 26**	**Model 27**
Model type	Stepwise regression	Stepwise regression	Stepwise regression	Stepwise regression
Y variate	Ramularia AUDPC	Ramularia disease difference	Ramularia AUDPC	Ramularia disease difference
X variates tested	Season rainfall	Season rainfall	Season rainfall	Season rainfall
	Season temperature	Season temperature	Season temperature	Season temperature
	Any Resistance	Any Resistance	Any Resistance	Any Resistance
	Sow Date	Sow Date	Sow Date	Sow Date
	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley	Non-continuous Barley
	Rhynchosporium AUDPC	Rhynchosporium disease difference	Rhynchosporium AUDPC	Rhynchosporium disease difference
	Mildew AUDPC	Mildew disease difference	Mildew AUDPC	Mildew disease difference

3.3 Results

3.3.1 Absolute Yield Difference

The mean absolute yield difference between treated and untreated across all trials in the 1996 – 2014 dataset was 0.74 t/ha.

3.3.2 Absolute Yield Difference Regressions

Full dataset (1996 – 2014) regressions

Individual disease severity regression – Model 1

The final stepwise model for the 1996 – 2014 data, testing individual disease severities, had an R^2 of 20.8%, based on Any Resistance and Rhynchosporium AUDPC, as seen in Table 3-10. As Any Resistance was coded as either 1 (variety had resistance rating of seven or above for at least one disease) or 0 (variety did not have resistance rating of seven or above for any of the three diseases), the negative direction of significance indicates that a variety being highly resistant to one or more diseases is linked to lower yield differences between treated and untreated. Both Any Resistance and Rhynchosporium AUDPC were also significant when tested in individual regressions. Season rainfall was significant when tested individually (dry seasons were linked with lower yield differences), but was not retained in the stepwise model. In no cases for any of the 27 models fitted in this chapter was it possible to analyse the interaction between season temperature and rainfall, or to include both individual and total disease severity, as these were aliased terms. The impact of removing each factor from the stepwise model on the R^2 was assessed, with Any Resistance explaining more variation than Rhynchosporium AUDPC. Any Resistance also has the largest coefficient (−0.512, standard error: 0.120) of the factors retained in the stepwise model as well as those in the individual regressions.

Table 3-10: Stepwise and individual regression results for 1996 – 2014 data, including individual disease severity*

	Model 1 – stepwise regression (1996 – 2014) including individual disease severity				Individual factor regressions (1996 – 2014) including individual disease severity			
	Significance	**Coefficient**	**Standard error of coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Standard error of coefficient**	**R^2 when tested in individual regression (%)**
Season rainfall					Dry: 0.007 Wet: 0.217	−0.372 0.167	0.172 0.134	12.5
Any Resistance	0.001	−0.521	0.120	−15.1	0.001	−0.380	0.120	9
Rhynchosporium AUDPC	0.001	0.000802	0.000197	−11.8	0.008	0.000529	0.000194	5.7
Model R^2	20.8%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only in individual regressions. Significance was tested at $p<0.05$.

Total AUDPC regression - Model 2

Testing Total AUDPC for the 1996 – 2014 data, the final stepwise regression contained three factors – season rainfall, any resistance, and Total AUDPC – and had an R^2 of 21.2% (see Table 3-11). All three factors were also significant when tested in individual regressions. In the stepwise regression model, wet seasons were significant in the positive direction, and thus were linked with higher yield differences. When tested individually, season rainfall was also significant, however here it was the dry seasons which were linked with lower yield differences than in average rainfall seasons. Season rainfall explained the most variation in the stepwise model, with an R^2 impact of −5.7% when removed from the final model, though Any Resistance was also important (−5.5% when removed). Any Resistance had the largest coefficient (−0.2817) of the factors retained in the stepwise model, and also the largest coefficient when each factor was tested individually (−0.380), though again, the differences between Any Resistance and Season rainfall were small (see Table 3-11).

Table 3-11: Stepwise and individual regression results for 1996 – 2014 data, including Total AUDPC*

	Model 2 – stepwise regression (1996 – 2014) including Total AUDPC				Individual factor regressions (1996 – 2014) including Total AUDPC			
	Significance	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Standard error of coefficient	R^2 when tested in individual regression (%)
Season rainfall	Wet: 0.017 Dry: 0.110	0.2187 −0.186	0.0910 0.116	−5.7	Dry: 0.007 Wet: 0.135	−0.372 0.1378	0.172 0.0919	12.5
Any Resistance	<0.001	−0.2817	0.0826	−5.5	0.001	−0.380	0.120	9
Total AUDPC	<0.001	0.000489	0.000122	−4.3	<0.001	0.000458	0.000129	5.2
Model R^2	21.2%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Significance was tested at $p<0.05$.

Comparison of Individual Disease and Total AUDPC regressions

The final stepwise regression model for the 1996 – 2014 dataset included Any Resistance, both when analysed using individual disease severity and using Total AUDPC (see Table 3-12). Disease severity was also included in both models; Rhynchosporium AUDPC in the Individual Disease severity model, and Total AUDPC in the other. Season rainfall was included in the final model testing Total AUDPC, but not in the final Individual Disease severity model. All three factors which were significant when tested individually were also significant in the Total AUDPC model, as compared to two out of the three for the individual disease model. The R^2 value for the Individual Disease severity model was 20.8%, only slightly less than the 21.2% R^2 for the Total AUDPC model.

Table 3-12: Comparison of final stepwise regression models for 1996 – 2014 dataset*

	Model 1 – stepwise regression (1996 – 2014) including individual disease severity				Model 2 – stepwise regression (1996 – 2014) including Total AUDPC			
	Significance	**Coefficient**	**Standard error of coefficient**	**Difference to R² when removed from model (%)**	**Significance**	**Coefficient**	**Standard error of coefficient**	**Difference to R² when removed from model (%)**
Season rainfall	Not significant				Wet: 0.017 Dry: 0.110	0.2187 −0.186	0.0910 0.116	−5.7
Any Resistance	0.001	−0.521	0.120	−15.1	<0.001	−0.2817	0.0826	−5.5
Rhynchosporium AUDPC	0.001	0.000802	0.000197	−11.8				
Total AUDPC					<0.001	0.000489	0.000122	−4.3
Model R^2	20.8%				21.2%			

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only in individual regressions. Significance was tested at p<0.05.

2011 – 2014 plot level dataset regressions

Individual disease severity regressions – Model 3

The stepwise regression model elaborated for the 2011 – 2014 plot level data testing individual disease severity included only two factors: Non-continuous barley, and mildew AUDPC, and had an R^2 of 13.7% (see Table 3-13). As Non-continuous barley was coded as 0 (previous crop barley) or 1 (previous crop not barley), the positive direction of significance indicates that sowing non-continuous barley is linked with higher yield differences between treated and untreated fields. Mildew AUDPC was the only factor which was significant when tested in the stepwise regression model and when tested in an individual factor regression. Non-continuous barley was significant in the stepwise regression but not as an individual factor, while Season rainfall, season temperature, and Rhynchosporium AUDPC were significant when tested in individual regressions but were not retained in the stepwise model. Mildew AUDPC explained most of the significance of the stepwise regression, with an impact on R^2 of −12.9% when removed. Non-continuous barley had the largest coefficient of the two factors in the stepwise model, at 0.316. Season rainfall, however, had the largest coefficient of the individual factor regressions (−0.631).

Table 3-13: Stepwise regression results for 2011 – 2014 plot level data, including individual disease severity*

	Model 3 – stepwise regression (2011 – 2014 plot level data) including individual disease severity				Individual factor regressions (2011 – 2014 plot level data) including individual disease severity			
	Significance	**Coefficient**	**Standard error of coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Standard error of coefficient**	**R^2 when tested in individual regression (%)**
Season rainfall					Dry: 0.003 Wet: 0.829	−0.631 −0.037	0.205 0.170	10.6
Season temperature					Hot: <0.001 Cold: N/A	0.448	0.121	8.9
Rhynchosporium AUDPC					<0.001	0.000547	0.000117	14.7
Non-continuous Barley	0.048	0.316	0.157	−2.8				
Mildew AUDPC	<0.001	0.001422	0.000400	−12.9	0.001	0.001245	0.000376	10.9
Model R^2	13.7%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only individually. Those highlighted in pink were significant in the stepwise regression model, but not in the individual regressions. Significance was tested at $p<0.05$.

Total AUDPC regressions – Model 4

The stepwise regression model testing Total AUDPC for the 2011 – 2014 plot level data included two factors, season temperature and Total AUDPC, and had an R^2 of 22.3% (see Table 3-14). Hot seasons were significant in the positive direction, indicating a link with higher yield differences as compared to seasons with average temperatures. Both season temperature and Total AUDPC were significant in both the stepwise and individual factor regressions. Season rainfall was significant when tested individually (with a link between dry seasons and lower yield differences), but not in the stepwise model. Of the factors in the stepwise regression model, Total AUDPC explained the most variation, with an impact on the R^2 of −13.4% when removed. Season temperature had a higher coefficient than Total AUDPC in the stepwise model: 0.291 as compared to 0.000574. In the individual factor regressions, however, season rainfall had the highest coefficient (−0.631).

Table 3-14: Stepwise and individual factor regressions for 2011 – 2014 plot level data, including Total AUDPC*

	Model 4 – stepwise regression (2011 – 2014 plot level data) including Total AUDPC				Individual factor regressions (2011 – 2014 plot level data) including Total AUDPC			
	Significance	**Coefficient**	**Standard error of coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Standard error of coefficient**	**R^2 when tested in individual regression (%)**
Season rainfall					Dry: 0.003 Wet: 0.829	−0.631 −0.037	0.205 0.170	10.6
Season temperature	Hot: 0.009 Cold: N/A	0.291	0.110	−3.8	Hot: <0.001 Cold: N/A	0.448	0.121	8.9
Total AUDPC	<0.001	0.000574	0.000117	−13.4	<0.001	0.000633	0.000117	18.5
Model R^2	22.3%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only individually. Significance was tested at $p<0.05$.

Comparison of Individual Disease severity and Total AUDPC regressions

The final stepwise models for the 2011 – 2014 plot level data varied considerably, with the only similarity being that disease severity was important in both; mildew AUDPC was included in the final Individual Disease severity model, while Total AUDPC was included in the other (see Table 3-15). Both factors included in the final stepwise model testing Total AUDPC were also significant in the individual factor regressions. In the stepwise model testing individual diseases, in contrast, only one of the two factors (mildew AUDPC) was significant when tested individually as well. The Total AUDPC model had an R^2 of 22.3%, accounting for considerably more variation than the 13.7% R^2 of the Individual Disease severity model.

Table 3-15: Comparison of the final stepwise models developed for the 2011 – 2014 plot level dataset

	Model 3 – stepwise regression (2011 – 2014 plot level data) including individual disease severity				Model 4 – stepwise regression (2011 – 2014 plot level data) including Total AUDPC			
	Significance*	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)
Season temperature					Hot: 0.009 Cold: N/A	0.291	0.110	−3.8
Total AUDPC					<0.001	0.000574	0.000117	−13.4
Non-continuous Barley	0.048	0.316	0.157	−2.8				
Mildew AUDPC	<0.001	0.001422	0.000400	−12.9				
Model R^2	13.7%				22.3%			

*Significance was tested at $p<0.05$

2011 – 2014 means level dataset regressions

Individual disease severity regression – Model 5

The final stepwise model testing individual disease severity for the 2011 – 2014 means data included season rainfall and season temperature, as well as mildew AUDPC, and had an R^2 of 47% (see Table 3-16). Dry years were linked with lower yield differences, as were hot years. Only one factor (season rainfall) was significant in both the stepwise model and individual factor regressions. Season temperature and mildew AUDPC were retained in the final stepwise model, but were not significant when tested individually. Rhynchosporium AUDPC, however, was significant when tested individually but was not part of the final stepwise model. Season rainfall also accounted for the majority of variation explained by the stepwise model, with a reduction in R^2 of 43.2% (of the total 47%), and had the largest coefficient (−1.618).

Table 3-16: Stepwise and individual factor regression results for 2011 – 2014 means data, including individual disease severity*

	Model 5: stepwise regression (2011 – 2014 means level data) including individual disease severity				Individual factor regressions (2011 – 2014 means level data) including individual disease severity			
	Significance	**Coefficient**	**Standard error of coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Standard error of coefficient**	**R^2 when tested in individual regression (%)**
Season rainfall	Dry: 0.002 Wet: 0.068	−1.618 −0.739	0.447 0.380	−43.2	Dry: 0.035 Wet: 0.915	−0.565 0.026	0.260 0.242	20.2
Season temperature	Hot: 0.036 Cold: N/A	−0.519	0.229	−11.6				
Rhynchosporium AUDPC					<0.001	0.000948	0.000192	39.3
Mildew AUDPC	0.017	0.001352	0.000516	−31				
Model R^2	47%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only individually. Those highlighted in pink were significant in the stepwise regression model, but not in the individual regressions. Significance was tested at $p<0.05$.

Total AUDPC regression – Model 6

The stepwise regression model testing Total AUDPC for the 2011 – 2014 means level data comprised season rainfall and Total AUDPC, with an R^2 of 52.6% (see Table 3-17). Again, dry seasons were linked with lower yield differences in trials as compared to average rainfall seasons. Both season rainfall and Total AUDPC were significant in individual factor regressions as well as in the stepwise model. Total AUDPC explains more variation than season rainfall in the stepwise model, with an impact on R^2 of −35.6% when removed. Season rainfall, however, has a larger coefficient in the model (see Table 3-17).

Table 3-17: Stepwise regression results for 2011 – 2014 means dataset, including Total AUDPC*

	Model 6: stepwise regression (2011 – 2014 means level data) including Total AUDPC				Individual factor regressions (2011 – 2014 means level data) including Total AUDPC			
	Significance	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Standard error of coefficient	R^2 when tested in individual regression (%)
Season rainfall	Dry: 0.008 Wet: 0.527	−0.656 −0.123	0.231 0.193	−13.3	Dry: 0.04 Wet: 0.915	−0.585 0.026	0.292 0.242	17
Total AUDPC	<0.001	0.000930	0.000166	−35.6	<0.001	0.000916	0.000186	39.3
Model R^2	52.6%							

*Factors in green were significant in both the stepwise regression model and the individual regressions. Significance was tested at $p<0.05$.

Comparison of Individual Disease and Total AUDPC regressions

Both the final stepwise regressions for the 2011 – 2014 means level data included season rainfall, with the same direction of significance showing a link between dry seasons and lower yield differences (see Table 3-18). Disease severity was also included in both regressions, with mildew AUDPC being retained in the Individual Disease severity model and Total AUDPC in the other. Season temperature was retained in the Individual Disease severity model only. Season temperature and mildew AUDPC were not significant in the individual factor regressions, while both season rainfall and Total AUDPC were.

Table 3-18: Comparison of final stepwise regression models for the 2011 – 2014 means level dataset*

	Model 5: stepwise regression (2011 – 2014 means level data) including individual disease severity				Model 6: stepwise regression (2011 – 2014 means level data) including Total AUDPC			
	Significance	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Standard error of coefficient	Difference to R^2 when removed from model (%)
Season rainfall	Dry: 0.002 Wet: 0.068	−1.618 −0.739	0.447 0.380	−43.2	Dry: 0.008 Wet: 0.527	−0.656 −0.123	0.231 0.193	−13.3
Season temperature	Hot: 0.036 Cold: N/A	−0.519	0.229	−11.6				
Total AUDPC					<0.001	0.000930	0.000166	−35.6
Mildew AUDPC	0.017	0.001352	0.000516	−31				
Model R^2	47%				52.6%			

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in pink were significant in the stepwise regression model, but not in the individual regressions. Significance was tested at $p<0.05$.

Fitting full dataset (1996 – 2014) models to 2011 – 2014 data

Individual disease severity regression – Models 7 & 8

When the final stepwise regression model developed for the 1996 – 2014 data testing individual disease severity is applied to the 1996 – 2014 dataset, and the fitted and actual values are compared, large amounts of vertical scatter are seen, particularly around 0.5 and 1 t/ha fitted values (see Figure 3-1). When this model is applied to the 2011 – 2014 plot level data, scatter continues to be pronounced, as seen in Figure 3-2. Applying this model to the 2011 – 2014 data, however, shows a better fit to the one-to-one line, with less scatter around the higher fitted values (see Figure 3-3).

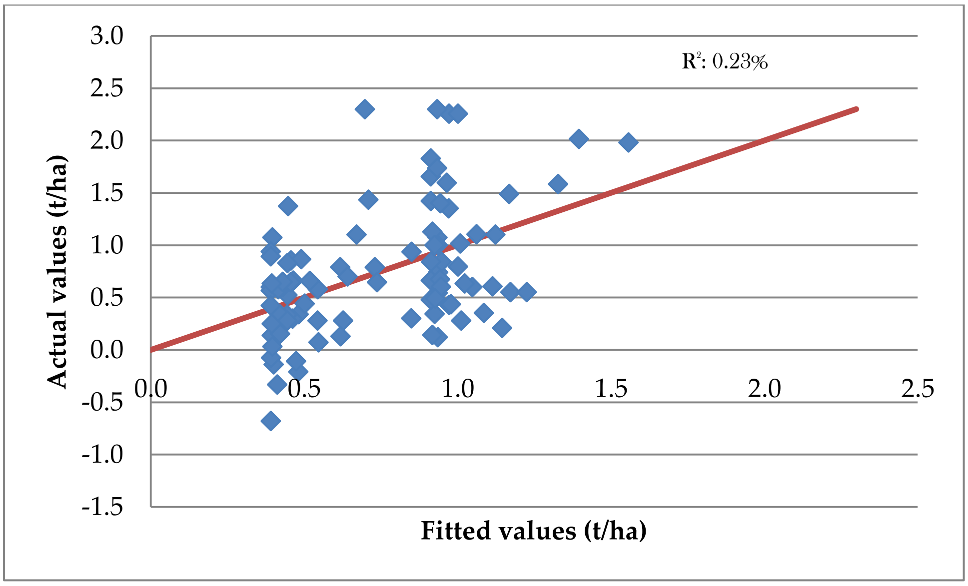


Figure 3-1: Fitted versus actual yield difference calculated using Individual Disease severity model developed for 1996 – 2014 dataset, run on the 1996 – 2014 dataset.*

*The red line is a one-to-one-line, for comparison.

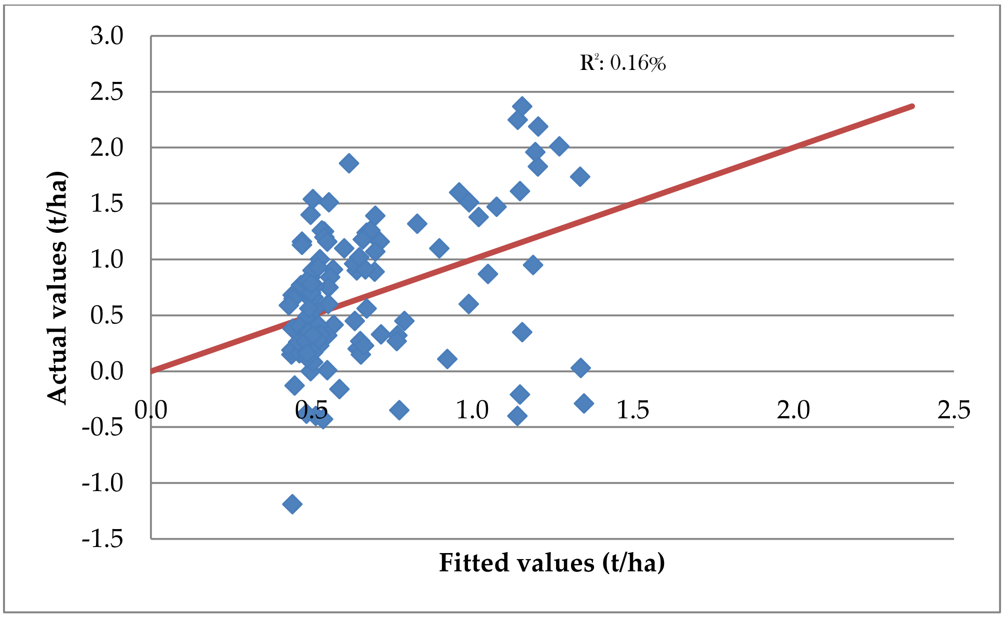


Figure 3-2: Fitted versus actual yield difference calculated using Individual Disease severity model developed for 1996 – 2014 dataset, run on the 2011 – 2014 plot level dataset.*

*The red line is a one-to-one-line, for comparison.

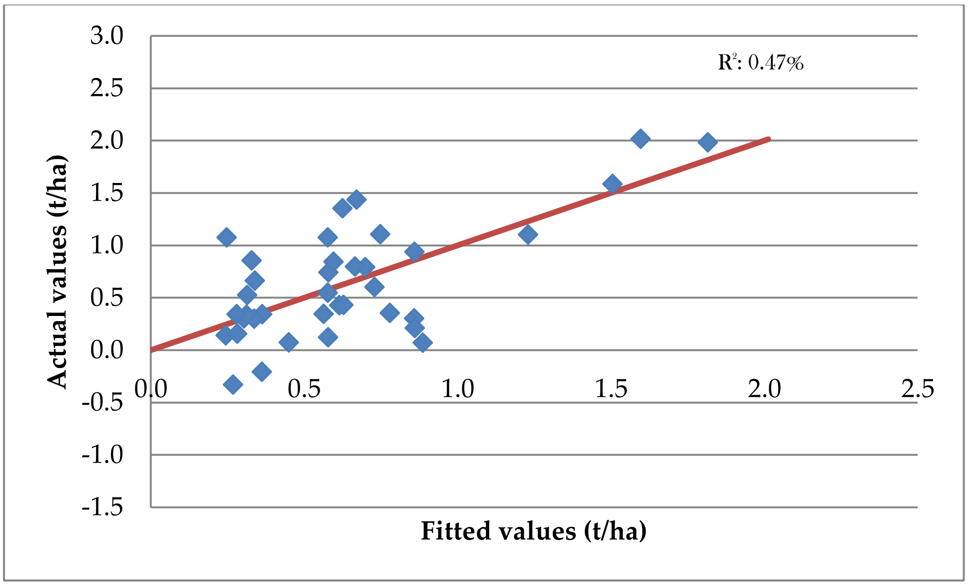


Figure 3-3: Fitted versus actual yield difference calculated using Individual Disease severity model developed for 1996 – 2014 dataset, run on the 2011 – 2014 means dataset.*

*The red line is a one-to-one-line, for comparison.

Total AUDPC regression – Models 9 & 10

When the final stepwise model for the 1996 – 2014 data assessing Total AUDPC was used to compare actual and predicted values, vertical scatter was clearly present for the 1996 – 2014 data, as seen in Figure 3-4. When applied to the 2011 – 2014 plot level data, scatter is particularly obvious in the higher region of fitted values (see Figure 3-5). The fitted and actual yields most closely fit the model when used for the 2011 – 2014 means level data (see Figure 3-6).

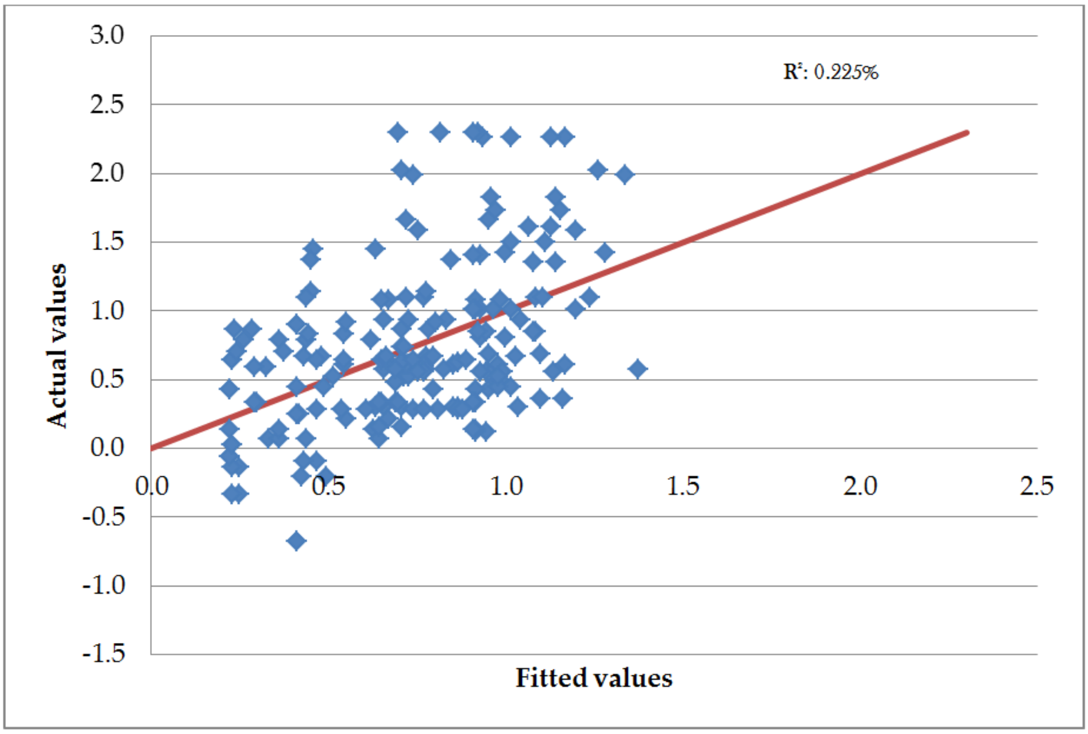


Figure 3-4: Fitted versus actual yield difference calculated using Total AUDPC model developed for 1996 – 2014 dataset, run on the 1996 – 2014 dataset.*

*The red line is a one-to-one-line, for comparison.

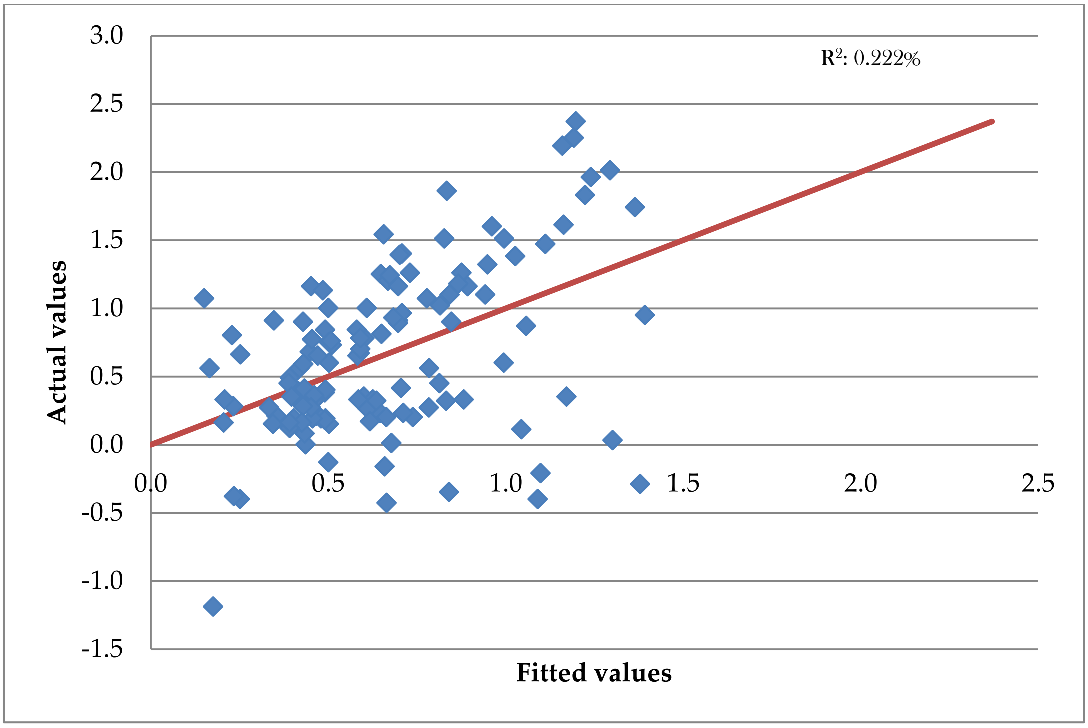


Figure 3-5: Fitted versus actual yield difference calculated using Total AUDPC model developed for 1996 – 2014 dataset, run on the 2011 – 2014 plot level dataset.*

*The red line is a one-to-one-line, for comparison.

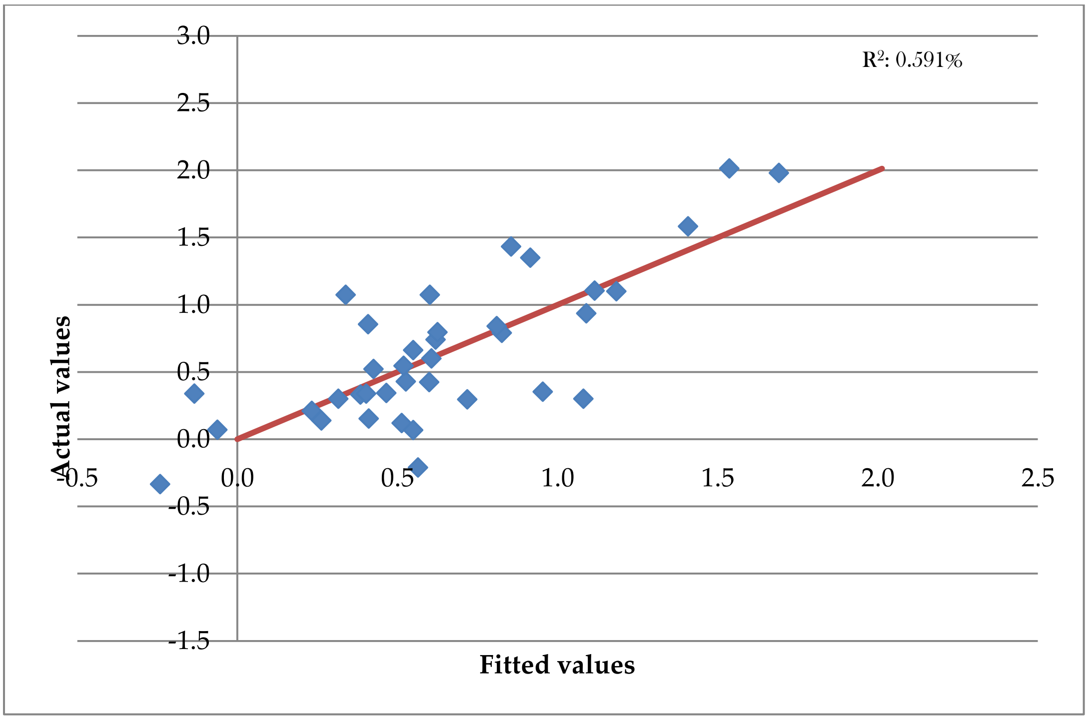


Figure 3-6: Fitted versus actual yield difference calculated using Total AUDPC model developed for 1996 – 2014 dataset, run on the 2011 – 2014 means level dataset

*The red line is a one-to-one line, for comparison.

Comparison of fit of full dataset models on 2011 – 2014 mean and plot level datasets

Both the full dataset models, developed testing Individual Disease severity or Total AUDPC showed vertical scatter when applied to the 1996 – 2014 dataset, though there was less scatter for the Total AUDPC model. In both cases, the model showed a limited fit to the 2011 – 2014 plot level data, with large amounts of vertical scatter, though again overall fit was better for the Total AUDPC model, which also had a higher R^2 value (0.222% vs 0.16%). The 2011 – 2014 means level data showed a better fit with both models than the plot level data, but again actual values were more closely reflected by the fitted values for the Total AUDPC model than the Individual Disease severity model.

Summary of stepwise regression models developed for Absolute Yield Difference

Stepwise regression models developed testing Individual Disease Severity

The final stepwise regression models varied in both which factors were significant, and the total R^2 accounted for, as summarised in Table 3-19. Most factors tested were found to be significant in one or more models, with the exceptions of Ramularia AUDPC and sow date. None of the stepwise models for Individual Disease severity perfectly matched the individual regressions, though only one factor was different between the two for the 1996 – 2014 dataset, as compared to three for the 2011 – 2014 means level dataset and four in the case of the 2011 – 2014 plot level dataset (see Table 3-19).

Stepwise regression models developed testing Total AUDPC

The final stepwise models for all three datasets included Total AUDPC, though other factors varied between the models (see Table 3-20). Only the 1996 – 2014 dataset included Any Resistance, for example, while season temperature was significant in only the 2011 – 2014 plot level data. For both the 1996 – 2014 means dataset and the 2011 – 2014 means dataset there was total agreement between the stepwise models and the individual factor regressions (see Table 3-19). The 2011 – 2014 plot level dataset had only one factor which was significant when tested individually, but which did not remain in the stepwise model: season rainfall. There is good agreement between the three datasets as to the importance of Total AUDPC (significant individually and in the stepwise regressions for each dataset) and season rainfall (significant individually in all three datasets, and in the stepwise regression of two of the datasets).

Comparison of Individual Disease and Total AUDPC regression models

The final stepwise regression models for the 1996 – 2014 dataset were similar, regardless of whether individual disease severity was tested or Total AUDPC. In both cases, trials with high levels of resistance to one or more diseases were linked with lower yield differences, and both models linked high disease severity (either Total AUDPC or Rhynchosporium, respectively) to high yield differences. Season rainfall was retained in the final model using Total AUDPC, though not in the Individual Disease severity model. The 2011 – 2014 means dataset analyses both included season rainfall and disease severity (either Total AUDPC or mildew) as significant, though season temperature was retained in the Individual Disease severity model but not for Total AUDPC. The 2011 – 2014 analyses were more divergent, with only disease severity being included in both models; each model identified one other factor, but these were not related. The stepwise regressions using Total AUDPC were also more similar across the three datasets, with each one including Total AUDPC, and two of the three including season rainfall (see Table 3-20). In the individual disease severity regressions, conversely, no factors were significant across all three datasets, though mildew AUDPC was found in two of the three (see Table 3-19).

The individual factor regressions gave more comparable results to those obtained through the stepwise regressions using Total AUDPC than Individual Disease severity. Each factor identified as significant through individual factor regressions was also retained in the relevant stepwise models using Total AUDPC, with the exception of season rainfall, which was not in the 2011 – 2014 plot level model (see Table 3-19). No factors were included in the stepwise models using Total AUDPC which were not also significant when tested individually. Conversely, five significant factors were identified through individual regression analysis which were not included in the stepwise models using Individual Disease severity, and three factors were included in the final Individual Disease stepwise models which were not significant when tested individually (see Table 3-20).

Table 3-19: Final stepwise regressions for each dataset, including individual disease severity*

	Model 1 – stepwise regression (1996 – 2014) including individual disease severity			Model 3 – stepwise regression (2011 – 2014 plot level data) including individual disease severity			Model 5: stepwise regression (2011 – 2014 means level data) including individual disease severity		
	Significance	**Coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Difference to R^2 when removed from model (%)**	**Significance**	**Coefficient**	**Difference to R^2 when removed from model (%)**
Season rainfall	Not significant	🟧	🟧	🟧	🟧	🟧	Dry: 0.002 Wet: 0.068	−1.618 −0.739	−43.2
Season temperature				🟧	🟧	🟧	Hot: 0.036 Cold: N/A	−0.519	−11.6
Any Resistance	0.001	−0.521	−15.1	🟩	🟩	🟩			
Rhynchosporium AUDPC	0.001	0.000802	−11.8	🟧	🟧	🟧	🟧	🟧	🟧
Non-continuous Barley				0.048	0.316	−2.8			
Mildew AUDPC				<0.001	0.001422	−12.9	0.017	0.001352	−31
Model R^2	20.8%			13.7%			47%		

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only individually. Those highlighted in pink were significant in the stepwise regression model, but not in the individual regressions. Significance was tested at $p<0.05$.

Table 3-20: Final stepwise regressions for each dataset, including Total AUDPC*

	Model 2 – stepwise regression (1996 – 2014) including Total AUDPC			Model 4 – stepwise regression (2011 – 2014 plot level data) including Total AUDPC			Model 6: stepwise regression (2011 – 2014 means level data) including Total AUDPC		
	Significance	Coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Difference to R^2 when removed from model (%)	Significance	Coefficient	Difference to R^2 when removed from model (%)
Season rainfall	Wet: 0.017 Dry: 0.110	0.2187 −0.186	−5.7				Dry: 0.008 Wet: 0.527	−0.656 −0.123	−13.3
Season temperature				Hot: 0.009 Cold: N/A	0.291	−3.8			
Any Resistance	<0.001	−0.2817	−5.5						
Total AUDPC	<0.001	0.000489	−4.3	<0.001	0.000574	−13.4	<0.001	0.000930	−35.6
Model R^2	21.2%			22.3%			52.6%		

*Factors in green were significant in both the stepwise regression model and the individual regressions. Those highlighted in orange were significant only individually. Significance was tested at $p<0.05$.

3.3.3 Overall most important factors for the full 1996 – 2014 dataset, based on individual and modelled R^2 values

Both the Individual Disease and Total AUDPC stepwise regressions developed for the 1996 – 2014 data, identified Any Resistance and disease severity as significant factors (see Table 3-21). The Total AUDPC model and individual factor regressions both also identified season rainfall as a key factor. Any Resistance explained a large amount of variation in the Individual Disease model (impact on R^2 when removed: 15.1%), and had the second highest impact on R^2 when removed in the Total AUDPC model (5.5%) and of the individually significant factors (9.5%). Season rainfall had the highest R^2 when tested individually (12.5%) and in the Total AUDPC model (5.7%). The key factors which influence yield difference in this dataset can therefore be determined, based on the R^2 values of the factors which were significant in each of 1996 – 2014 models: Any Resistance, season rainfall, and disease severity (both individual disease severity and Total AUDPC).

Table 3-21: Comparison of R^2 impact of significant factors in the 1996 – 2014 stepwise regressions and individual factor analyses

	R^2 in individual disease severity stepwise model (%)	R^2 in Total AUDPC stepwise model (%)	R^2 when tested individually (%)
	Model 1	Model 2	
Any Resistance	15.1	5.5	9.5
Season rainfall		5.7	12.5
Total AUDPC		4.3	5.2
Rhynchosporium AUDPC	11.8		5.7

3.3.4 Relative yield difference regressions – Model 11

The stepwise regression on relative yield difference, found similar results to the Absolute Yield Difference stepwise regression on the same data (in both cases, Any Resistance and Rhynchosporium AUDPC were the only factors retained in the model) and so is not described in further detail.

3.3.5 Disease severity and disease difference regressions – Models 12 – 27

Stepwise regressions for disease severity were run using each individual disease's AUDPC as the y variate for each dataset. Ramularia AUDPC was tested for both the 2011 – 2014 means and plot level datasets, and in each case stepwise regression continued until no factors were left in the model. A model was likewise unable to be fitted for Rhynchosporium or mildew AUDPC in any of the three datasets. Stepwise regressions using Disease Difference (Treated AUDPC – Untreated AUDPC) for each disease and each dataset were also unable to be satisfactorily fitted, and so are not reported further.

3.4 Discussion

3.4.1 Key points from Absolute Yield Difference regressions

The results shown in this chapter suggest that using season rainfall (perhaps via a model using within season weather forecasts to identify periods of high risk) as an indicator for likely need to spray fungicide in conjunction with varietal disease resistance has the potential to reduce the need for fungicide use while maintaining high yields. In all stepwise and individual factor regression models developed for Absolute Yield Difference, disease severity was identified as an important factor in terms of yield difference between treated and untreated trials. At least one disease (either Rhynchosporium or mildew) was included in final stepwise models where Individual Disease severities were tested, though which disease was retained varied between datasets. Lower mean disease severities in the untreated plots of trials where fungicide treatment did not have a significant impact on yield in the 2011 – 2014 Field Trials analysis also highlighted this trend (see Chapter 2). Where Total AUDPC was tested, this remained in the stepwise regressions and was significant in individual regressions for all three datasets. That the impact of one disease over another may vary between year, location, and weather, but aggregate measures of disease are important in a wider variety of circumstances has been previously reported in relation to foliar diseases of winter wheat in long-term field trials. Leaf blotch diseases as an aggregate explained the majority of yield increase due to fungicide treatment overall, while other specific diseases (including powdery mildew) were important in particular years (Wiik, 2009). However, this does not appear to have been previously reported in barley.

High levels of disease resistance to one or more of the three diseases was also important in both stepwise and individual factor regression models developed for the full 1996 – 2014 dataset. In all cases disease resistance was linked with lower yield differences between treated and untreated trials. This finding is consistent with the analysis presented in Chapter 2, of the 2011 – 2014 Field Trials dataset, where those trials with high levels of disease resistance also tended to be those with no significant impact of treatment on yield. That disease resistance buffers the effect of not spraying fungicide is well established in the field trial literature for wheat diseases (Berry et al., 2008; Cook & Thomas, 1990; Martens et al., 2014).

Season rainfall was significant when tested in individual factor regressions for all three datasets, and remained in both Individual Diseases and Total AUDPC stepwise regression models developed for the 2011 – 2014 means level data. Wet seasons were linked with larger yield differences between treated and untreated in the full 1996 – 2014 dataset regression for Total AUDPC, as compared to average seasons. Similarly, dry seasons were linked with smaller yield differences between treated and untreated in the 2011 – 2014 means level regressions and the plot level individual regressions. Wet weather in the 2011 – 2014 Field Trial analysis presented in Chapter 2 had also been linked with the impact of treatment on yield, as 86% of the trials with a significant impact of fungicide treatment on yield had occurred in wet years (see Chapter 2). Dry conditions have previously been seen to lower the impact of fungicide use on wheat yields in long-term experiments (Wiik & Ewaldz, 2009), and to be crucial to high yields in Scottish barley (Brown, 2013), while wet periods have been proposed as one of the risk factors for Ramularia (Havis et al., 2015) and Rhynchosporium (Ryan & Clare, 1975; Xue & Hall, 1992) to flourish, as has humidity for mildew development (Channon, 1981), conclusions which are supported by this analysis.

3.4.2 Comparison of Absolute Yield Difference regression models

Final stepwise regression models were related to individual factor regressions on each factor, following a similar method used to assess risk factors for sclerotinia in oilseed rape using logistic regressions (Yuen et al., 1996). For all three datasets, the Total AUDPC stepwise regressions better fitted the individual factor regression results, with 7 out of the 8 factors which were significant when tested individually also being retained in the relevant stepwise model. This is contrasted with the Individual Disease severity models, where only three of the seven factors which were significant when tested individually were also in the stepwise models, and another three factors were included in the stepwise models which were not significant when tested individually.

The Total AUDPC models provide a useful tool for assessing the overall impacts of factors on yield difference in the trials studied. However, for disease management purposes, it is also of interest to consider the Individual Disease severity models as these can be helpful for assessing the importance of a particular disease. For example, in the 2011 – 2014 models, mildew AUDPC was included in the final stepwise models, while for the full 1996 - 2014 dataset it is Rhynchosporium which was retained. Though the Individual Disease severity models developed for these data may not be as reliable due to the restricted number of trials/plots included in the analysis (as summarised in Table 3-4), it would be worth considering individual disease severity alongside Total AUDPC in future analysis, particularly if data can be retrieved or missing values verified to be true zeros. The full 1996 - 2014 dataset stepwise regressions provided a better fit to the 2011 – 2014 means level data than plot level data. Some variation within the dataset will have already been removed when converted to mean values, which may account for the comparably high R^2 values for these models.

3.4.3 Limitations of analysis

A number of limitations restrict the applicability of the regressions analysis presented in this chapter to a wider scope. Firstly, the small size of plots included in the Field Trials database (typically 20 x 2m), as compared to the size of a commercial barley field, combined with the fact that the single untreated plot in any given trial block is surrounded by treated plots, may reduce the yield difference between treated and untreated plots by buffering the plot from disease pressure. A lack of variation in sowing date and previous crop also makes it difficult to assess to what extent these factors may be important in the spring barley system. An attempt was made to include early season disease measurements (between GS 24 - 34) as a way of considering disease which provides farmers with a measure to act upon within season, as recommended in previous decision making tools (Burke & Dunne, 2008), however a lack of sufficient data prevented this from inclusion in the regressions analysis. Disease difference, likewise, was not successfully analysed, and could provide more information about the relationship between disease, yield, and treatment. Within the models themselves, being unable to include random terms, or interactions between terms such as rainfall and temperature which are unlikely to be fully independent also restricts the robustness of the results.

3.4.4 Dataset comparison

One of the aims of this chapter was to compare the outputs of stepwise regression models each of the three datasets. The 2011 – 2014 plot level data gave a high level of detail over a short period of time; this shortened period thus provided less factor variability to test, as there were necessarily a relatively small number of varieties, previous rotations, and weather conditions. Using the full dataset for 1996 – 2014 provided the opportunity to compare a larger number of factor levels, though with means rather than plot level data, and thus is useful for assessing a wider range of potential management situations. The final stepwise models for all three datasets using Total AUDPC were similar: each included Total AUDPC and one weather variable (season temperature for the 2011 – 2014 plot level data, and season rainfall for the other two datasets), however Any Resistance was only included in the full 1996 – 2014 dataset model. As the only stepwise model for Total AUDPC which contained a factor not significant when tested in an individual regression (season temperature) was that created for the 2011 – 2014 plot level data, it is not clear that plot level information provides a more accurate representation of the factors influencing yield difference than average trial information. In this instance, means level long-term data seems to provide more useful results for understanding the impact of management and weather factors on yield differences, due to the larger amounts of variation than are seen in the short term database. In future, comparing results from a long-term plot level database and its means counterpart could provide useful data about which is more important in modelling factor impacts on yield.

3.5 Conclusions: key factors impacting Absolute Yield Difference in the Field Trials database

Using the final stepwise regression model developed for the full dataset testing Total AUDPC and the individual regressions done, three factors appear to be crucial in determining the impact of fungicide treatment on yield in the Field Trials database: season rainfall, disease resistance, and Total AUDPC. Ranked by R^2, season rainfall explains the most variation in yield difference (12.5% when tested individually, and 5.7% in the stepwise model), followed by Any Resistance (9% and 5.5%, respectively), and Total AUDPC (5.7% and 4.3%, respectively). As fungicide use did not always result in increased yield, and the increases which did occur were often minimal, forecasting disease severity for the season and acting upon this, e.g. planning to spray when the season is forecast to be wet and reducing spraying when dry, may help to rationalise fungicide use. Similarly, sowing only spring barley varieties which are highly resistant to one or more key diseases may reduce the need for fungicides. The inclusion of Total AUDPC as a key factor highlights the fact that disease severity is important in yield dynamics; this may be managed within season through a combination of techniques, including fungicide applications. Other IPM measures, such as rotation and sowing date, may play a role in determining yield impacts of fungicides, but could not be fully assessed here, due to lack of variation. These models provide a useful tool for assessing the relative merits of different IPM tools on yield in Scottish spring barley and allow farmers and decision makers to prioritise acting on those which have a significant explanatory effect, such as sowing highly disease resistant varieties.

Chapter 4 Stakeholder surveying to assess current levels of uptake and willingness to use key IPM strategies

4.1 Introduction

Previous work on farmer attitudes towards and use of IPM

Several surveys of farmers have been carried out to gain understanding of IPM attitudes, uptake, and priorities in recent years. IPM use appears to be the norm both in the UK for wheat growers (Ilbery et al., 2012) and US for hop and mint growers (Sherman & Gent, 2014). However, the use of individual IPM techniques varies widely. Crop rotation, for example, is used by approximately 75% of UK farmers (Bailey et al., 2009; ADAS, 2002), as the use of "clean" land is seen as a key crop protection measure (Maye et al., 2012). Choosing disease resistant varieties was also frequently reported with 53% of arable farmers (Bailey et al., 2009), and 88% of cereal farmers (ADAS, 2002) using this technique. The use of disease resistance, however, may vary inversely with the availability of chemical alternatives. Wheat farmers in England, for example, have been found to choose varieties on the basis of agronomic traits such as grain quality rather than resistance levels because effective pesticides were widely available (Maye et al., 2012). Using forecasts for pests and diseases was used by only 36% of cereal farmers surveyed by ADAS (2002), and only 23% of those surveyed thought forecasts to be 'mainly effective'. Despite the generally high levels of self-reported uptake of IPM techniques such as crop rotation and varietal disease resistance, however, confusion remains amongst farmers over the exact definition of IPM in the UK (ADAS, 2002), suggesting a potential lack of information.

Sources of knowledge are a key factor in determining farm management decisions, with a majority of farmers relying on external experts when deciding a pest/disease management plan (Sherman & Gent, 2014; Maye et al., 2012; ADAS, 2002; Bailey et al., 2009), despite local knowledge (often acquired over multiple generations) being highly regarded (Ilbery et al., 2012; Sherman & Gent, 2014). Loss of traditional knowledge about diverse rotations due to increasing specialisation has also been pinpointed as an issue in Scotland (Feliciano et al., 2014). With outside information frequently coming for sources with potential bias, e.g. agronomists employed by chemical companies, industry bodies, academics, etc., farmers tend to rely on those individuals with whom they share a trusting relationship, and whom they feel understand the pressures of farm management, regardless of their potential bias (Sherman & Gent, 2014). Balancing these potentially biased viewpoints, farmers also report using multiple sources of information to make disease control decisions (Bailey et al., 2009). UK farmers have indicated that the information available about alternatives to pesticides was not impartial or easy to understand, and 86% agreed they would like to know more about them (ADAS, 2002). This lack of unbiased, easy to process knowledge may present a barrier for uptake of IPM – in the meantime, agronomists remain the most generally relied upon source of information for disease management decisions in the UK (Maye et al., 2012; Bailey et al., 2009; ADAS, 2002).

4.1.1 Rationale for the current work

Despite a growing body of literature, relatively little is currently known about farmer attitudes towards IPM uptake, still less that is relevant to Scottish spring barley. Research into IPM has thus far tended to be post-hoc and aimed at understanding general attitudes towards IPM, rather than assessing the potential of specific techniques. Two key exceptions to this – the work done by Bailey et al. (2009) and ADAS (2002) – provide useful background for UK agriculture as a whole. However, the former focuses on the impact of environmental policy on insecticide use, with relatively little information about fungal pathogens (Bailey et al., 2009), and, as both are concerned with UK agriculture as a whole, there is a lack of detailed information relevant to Scottish spring barley production. A number of key legislative changes have also occurred in the years since their publication, including the Sustainable Use Directive, requiring member states to support uptake of IPM and produce action plans for the sustainable use of pesticides (Defra, 2013), which makes revisiting the issues surrounding uptake, including levels of awareness and attitudinal aspects, and interest in light of these changes a useful exercise.

This project builds on previous work done to analyse risk, attitudes towards innovation, and information sources relating to IPM in the UK (e.g. ADAS, 2002; Bailey et al., 2009; Maye et al., 2012), with a focus on the key diseases affecting spring barley in Scotland. Outputs from this survey will be linked with analysis of the long-term experimental database in Chapter 2 and Chapter 3, as well as the Adopt-a-Crop data in Chapter 5 in order to provide a well-developed, cohesive analysis of the current state and potential for uptake of key IPM measures relevant to fungal disease and Scottish spring barley production.

Agronomists involved in the production of Scottish spring barley through providing advice to farmers were also included in the survey, due to the consensus in the literature that agronomist recommendations play a key role in farmer decision making (Ingram, 2008; Sherman & Gent, 2014; Maye et al., 2012). Surveying both farmers and agronomists allows for a direct comparison to be made of their opinions and perceptions, which may provide insight into persistent patterns or differences between the two groups.

4.1.2 **Bias in surveying and the utility of structured quantitative surveying methods to reduce this**

Surveying stakeholders can provide an insight into the complex realities within which IPM decisions are taken. However, this form of research can be influenced by bias from the sampled population not being representative of the true population, from bias in the survey itself, from interactions (or perceptions and personal judgements) between the researcher and the participant, from priming in the surrounding environment and daily life, and many other areas (Punch, 1998). It is not possible to control for all forms of bias in a survey sample, however, impacts of bias can be reduced with care; for example, by using pilot studies and careful editing to increase the probability of questions being understood as intended (Foddy, 1993). Understanding where bias comes from in a survey sample is crucial, so that the relative impact of this bias on results can be assessed, and accounted for; this can be done by including socio-demographic questions which allow for grouping of the survey population into categories which can then be compared to the wider population. This is particularly relevant when using a convenience sample – where a population is selected due to its availability, rather than a fully randomised sample of the entire population (Punch, 1998) – which, while not ideal, has been used in similar studies, e.g. Feliciano et al.'s (2014) work of stakeholder engagement due to the difficult and time consuming nature of obtaining a large, random sample. In this context, a structured quantitative approach to surveying carries several bias reduction benefits – questions and response categories are pre-established, with questions being received in the same way and order by all participants in a standardised manner (Punch, 1998). In addition, quantitative surveys provide clear answers in a pre-designed structure, which can be analysed according to scientific norms, and is therefore particularly useful in interdisciplinary work. This is especially relevant when the survey topic relates to motivation and attitudes, as these are essentially unquantifiable values; using a questionnaire approach can therefore give a proxy value in order to understand the issues at hand (Foddy, 1993).

4.1.3 Survey Aims

The goal of the survey carried out in this project was to understand the extent to which farmers would be open to taking up, or had already taken up, three IPM strategies identified as having potential to reduce the need for fungicide use in Scottish spring barley, namely: planned crop rotation, varietal disease resistance, and forecasting disease pressure. The primary target population identified was Scottish spring barley farmers and the secondary target population as agronomists involved in the production of Scottish spring barley, of which a purposive sample was taken.

4.2 Methods

4.2.1 Survey structure

The survey was divided into six major sections, each with a specific focus, which are summarised below. A copy of the questionnaire can be found in Appendix D – Farmer and agronomist survey.

Grouping questions

The first part of the survey contained questions designed to group the sample based on a number of relevant characteristics. Most were standard demographic questions, such as age, intended to provide an estimate of how representative the survey sample was of the general farming population, based on Scottish Government statistics, making it possible to identify bias in the sample population and go some way towards accounting for it. Other questions (such as farm size) were intended to pinpoint specific issues which have been shown in the literature to impact farmer decision making, risk aversion, and interest in novel management solutions.

Grouping questions were also included in the agronomist survey, but were focused on issues which might impact their advice; for example, which products form the majority of their expertise, and whether they are affiliated with any professional organisations.

Variety use on farm

The purpose of this section was to discover which varieties are in current or have been in recent use by the surveyed farmers, in order to provide a summary of resistance levels by linking this with previously gathered SRUC Cereals Recommended list data (SRUC & HGCA, 2013; SRUC & HGCA, 2014; SAC & HGCA, 2012; SAC & HGCA, 2011; SRUC & HGCA, 2015). Farmers were asked to list up to three varieties they had planted in each of the past five years (2011 – 2015), in order of hectarage planted. Farmers were also asked to identify key drivers in deciding which varieties to sow, and their perception of how frequently they sow disease resistant varieties. Agronomists were asked to comment on the varieties they have advised farmers to sow in the past five years, and their disease resistance ratings, as well as the factors which impact their decision to recommend these particular varieties.

Previous rotations

Here, participants ranked the reasons they use (or do not use) crop rotations on their farms, to provide information regarding current rotation practices, and specified how frequently they sow consecutive barley and cereals. Agronomists were posed the same questions regarding rotation, again in relation to their recommendations to farmers.

Fungicide use

Questions in this section related to farmer use and perception of fungicides. Frequency of application, factors influencing the decision to apply, and the perceived total increase in yield of the crop from fungicide use were queried.

Main diseases on farm

Farmers and agronomists were asked to rank the three diseases being studied in terms of how common they believe them to have been in the past five years and how much they feel they have impacted yield in the past five years for spring barley in Scotland, as well as how important they feel foliar diseases are to yield more generally.

Fungicide use in future

The focus of this section was determining which techniques are best suited to Scottish agriculture based on farmer willingness to implement these, and whether there are issues of practicality or cost which make some techniques less attractive than others to farmers.

The first half of this section focused on farmer perception of their fungicide use (or, in the agronomist survey, perceptions of their recommendations as well as farmers' fungicide use), and the impacts of fungicide on the environment, through a series of multiple choice questions. The key IPM methods being studied – sowing only disease resistant varieties, planned crop rotation, and forecasting disease pressure – were then proposed, and participants were asked to choose which they are most and least likely to use on their farm or recommend to their clients, as well as which they judged to be most/least practical.

The best-worst scaling questions were presented with separate boxes for the most and least likely options for each question. For each question participants were required to choose one management option they were most likely to implement, and one they were least likely to implement. Indicating "N/A (already use)" was also a possible choice for each practice, to provide a gauge of current uptake levels. Best-worst scaling questions were included as a way to 'force' participants to make a decision where they might prefer to indicate 'all of the above' or 'none of the above'. This can provide useful information about preferences for one type of technology over another, even in cases where the respondent might find multiple choices to be appealing.

4.2.2 Designing the survey

The survey was designed to be run at the annual agronomy events co-hosted by SRUC and AHDB in January of 2016 (more detail on running the survey and the events themselves in section 4.2.3, below). As the attendees at these events consisted of both farmers and agronomists, the survey was split into one section for the primary audience (farmers) and one for the secondary audience (agronomists).

To obtain the most relevant information possible, participants were instructed to respond about their majority practices in the survey, recognising that there may be variation at field level within the farm. All farmers at the events who grew spring barley in some capacity were invited to participate. The process of creating, running, and coding the survey is described below - for the final version of the survey, see Appendix D – Farmer and agronomist survey, and see Appendix E – Survey ethics procedure: Scottish Government approved proforma, Appendix F – survey ethics procedure: Ethics Assessment form for the University of Edinburgh's school of Biological Sciences, and Appendix G – survey ethics procedure: Self-Audit Checklist for Level 1 Ethical Review for the University of Edinburgh School of Social and Political Sciences, for the appropriate ethical requirements.

The questionnaire went through a number of iterations, with each draft being commented on by a different group of individuals in order to reduce bias and ensure the questions being asked were as clear and concise as possible. A pre-pilot group of seven PhD students from within the Crops and Soil Systems group at SRUC were asked to review and complete the questionnaire, and their participation was timed in order to gauge the length of the survey and ensure it could be completed within approximately ten minutes (see Appendix I – Summary of feedback from pre-pilot study for more detail). Following minor amendment based on pre-pilot responses, largely centring on word choice, a draft was piloted amongst a small group of farmers and agronomists. Five of each were contacted in the first instance and asked to arrange a time for a telephone interview; if this was not possible, an email exchange was offered instead. Of this, four agronomists agreed to telephone interviews, and one agreed to respond by email, while three farmers agreed to telephone interviews and one to respond by email. A standard introduction (see Appendix H – Protocol used for pilot survey) was given summarising the purpose of the survey, the pilot study protocol, and anonymity issues. Participants were asked to give general feedback about the wording of questions and their answers, as well as specific feedback for three questions highlighted in the pre-pilot study and follow-on discussions: length of time for which to request variety information; how to scale perceived yield increase from fungicide application; and the format of the best-worst scaling questions. Feedback from participants was collated into a single document for ease of review (see Appendix J – Summary of feedback from pilot study). As the length of time (five years) of varietal recall was felt to be appropriate by more than half of the participants, this question was left unchanged. A majority of participants preferred yield increase from fungicide application to be presented in terms of tonnes per hectare, rather than percent of yield. Some suggestions were also given to improve clarity of the best-worst scaling questions, including placing these in tables. A final draft was then made, taking into account these comments, and incorporating an additional question suggested by a farmer during the pilot study ("What proportion of your spring barley do you contract farm?").

4.2.3 **Running the survey**

The questionnaire was given out at the four Agronomy 2016 meetings (see Appendix K – Agronomy 2016 Agenda for an overview of these events) where a series of presentations by experts were given around the theme of risk, resilience, and reward at Carfraemill (Scottish Borders), Perth (Tayside), Inverurie (North East), and Inverness (Highlands) during January 2016. These four sites represent a useful geographical spread for data collection, as they are distributed across the main cereal production areas in Scotland (see Figure 4-1). Different farm structure, as assessed at regional level, is also captured by this sample; for example, two sites were located in regions with more large holdings (>200ha) than average (Tayside and Scottish Borders) and two with fewer than average (Highland and Grampian); two sites were in regions with lower than average levels of non-crofting tenancy (Highland and Tayside) and two with higher levels (Grampian and Scottish Borders) (ERSA, 2015). These meetings were selected as a large number of respondents could be reached at low cost, and a high response rate could be hoped for, as the importance of filling in the survey was specifically mentioned during the day by both the Chair and a key speaker. A total of 288 surveys were given out across the four locations (Carfraemill – 100; Perth – 81; Inverurie – 71; Inverness – 36).

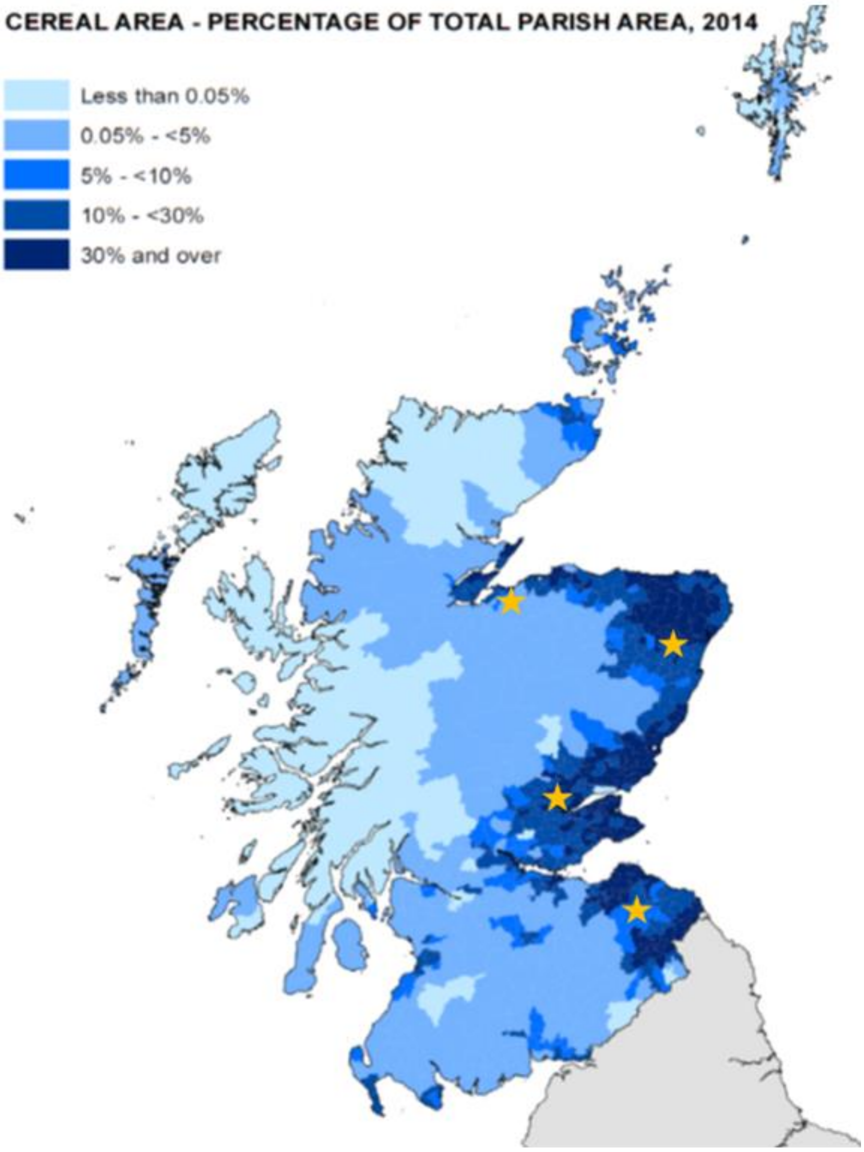


Figure 4-1: Concurrence of Scottish cereal production and survey locations. (Scottish Government, 2015a)

The similarity in topic between the focus of the events and the survey presented both an opportunity to increase participation and an area of potential bias. A number of presentations specifically mentioned IPM, and discussed fungicide use on cereals, thus priming participants to think about these issues, potentially in advance of completing the survey.

One presentation in particular – "Disease and fungicides: Lessons from 2015, messages for 2016" – could have influenced participants as trial results from SRUC work regarding key fungicides on spring barley, oilseed rape, and wheat from the past year were discussed. In order to reduce bias, no results were presented which specifically stated the impact of fungicide use on yields of spring barley, though the results shown regarding fungicide impact on disease level in spring barley may have influenced participant's perceptions of yield increases. This information was presented for both oilseed rape and wheat trials; however, the potential for bias may have been mitigated to some extent as the impacts of fungicide presented for these two crops were dissimilar (1.97 t/ha for wheat vs 0.58 t/ha for oilseed rape – see Appendix L – Key slides from the 2016 Agronomy presentation "Disease and fungicides: Lessons from 2015, messages for 2016"for a copy of all slides used in this presentation). In addition, the yields presented were based on UK-wide rather than Scottish results – in the past 16 years, average UK-wide and Scottish yields have been up to 0.9 t/ha, and 0.4 t/ha on average for wheat, and up to 0.7 t/ha with 0.3 t/ha on average for oilseed rape (UK Government, 2015). An upper and lower conceptual limit may have been suggested by this presentation, however, of approximately two tonnes and a half tonne per hectare respectively.

4.2.4 Coding the data

Responses to the questionnaire were coded anonymously, using a random number generator in Microsoft Excel to provide individual identity numbers for each survey response. The personal details of respondents (where given) were recorded alongside their individual identity number, and this was stored only on an external USB separate from all other work, in keeping with the survey ethics regulations. Raw data was kept in a locked drawer at all times when it was not in use.

Initially, all available data was coded, regardless of whether the survey was incomplete or not – a total of 17 farmer surveys and 10 agronomist surveys had at least one question not fully answered, in part due to participants failing to finish the entire survey and in part to some questions being skipped. The file was then cleaned to remove any ineligible participants (e.g. those who were not involved in Scottish spring barley production) and answers were checked to ensure instructions had been followed; all valid answers were coded as positives, with negative numbers reserved for invalid answers to preserve the information while discounting it from the analysis.

Where a given answer did not follow instructions, this response (and any linked response, if applicable) was coded as invalid. For example, ranking answers which used a number more than once, or best/worst answers which selected the same technique as both 'best' and 'worst', or where a technique was selected as 'best' but no technique selected as 'worst', were coded as invalid for the same reason – that these responses would not be comparable to those provided by other farmers. The questions most impacted by this were those relating to rotation in the farmer survey, as any responses from a farmer who answered both the question about motivation to use a rotation and the question motivation to not use a rotation were coded as negatives. As rotation practice is likely to vary within farms, participants were specifically asked to "complete the questionnaire based on what you consider to be your main practices". It is not possible to be sure why a farmer chose to answer both questions despite directions to the contrary (perhaps exactly half of his/her farm is under rotation and half not, the spring barley fields are under rotation but not others, he/she generally uses rotations but did not this year due to weather/market considerations, etc.), therefore these cannot be directly compared to answers from other farmers who may have had similar concerns but chose to respond based on main practices. A summary of the number of responses which were invalidated from farmers is provided in Table 4-1 and from agronomists in Table 4-2, below. In order to provide summaries of comments made on the surveys, these were gathered together, and grouped by theme. Survey analysis was then carried out using the cleaned data.

Table 4-1 – Summary of invalidated answers by survey location (Farmer Survey)

	Rotation use (ranking)	**Fungicide decisions (ranking)**	**Best/worst scaling**			
Question number(s)	17 &18	22	29	30	31	32
Scottish borders	4	4	0	0	0	1
Tayside	3	6	0	0	0	0
North East	1	0	0	0	1	2
Inverness	2	3	0	0	0	0
Total number	10	13	0	0	1	3

removed						
Total completed	26 (for Q17)	24	25	24	24	23

Table 4-2 – Summary of invalidated answers (Agronomist survey)

	Variety choice ranking	**Rotation use (ranking)**		**Fungicide use (ranking)**	**Best/worst scaling**	
Question number (s)	7	11	12	16	23	24
Total Number removed	3	1	2	5	7	8
Total Completed	33	33	13	34	34	30

4.2.5 **Analysis**

Given the non-probabilistic nature of the sampling method used in the questionnaire, a number of statistical methods were not applicable to the data collected, as an estimate of the likelihood that a given result was due to sampling error in relation to the target population (that of all Scottish spring barley farmers and agronomists) could not be calculated (de Vaus, 2002). However, as the purpose of the survey was to provide a basis for comparison with the Field Trials and Adopt-a-Crop databases, and to give a measure of practicality for the IPM methods studied, patterns and summary statistics of the survey results were adequate to address the research questions. The procedure used to analyse the survey is briefly described below.

Final results from the questionnaire were first analysed for sampling bias. Consistency across sites was verified for demographic questions (age and education), as well as one question from each survey section – most important factor when deciding which variety to sow; proportion sowing consecutive barley; estimation of yield increase from fungicides; disease impacting yield most; and practicality of implementing each IPM strategy. A summary of the sample population was then developed, and compared with the target population statistics available from the Scottish Government. The comparisons made with key documents are summarised below in Table 4-3.

Table 4-3: Summary of sources used to quantify sampling bias for farmer survey

	Demographic variable	Compared with:
Farmer survey	Age	June Agricultural Census (Scottish Government, 2015c)
	Educational attainment	Farm Structure Survey (Scottish Government, 2013)
	Farm size	Farm Accounts Survey for 2013 – 2014 (Scottish Government, 2015b)
	Farm region	Economic Report on Scottish Agriculture (Scottish Government, 2015a) for cereals, mixed holdings, and general cropping/forage
	Land Tenure	June Agricultural Census (Scottish Government, 2015c)

Using this information, a summary of the population sample and demographic bias for the farmers was created - for agronomists, no statistics were available for comparison, so the summary simply indicated where sampling bias might be expected to impact results (e.g. the main market type for which the agronomist is advising). Finally, to verify a lack of attendance bias between sites, several key questions were summarised based on location of survey completion and compared.

Summary statistics were generated for each question and inter-question comparisons. In general, percentages were used for comparison, as the number of respondents filling in a given question varied. For numerical ranking questions, the number of farmers responding to each choice has been indicated alongside average ranking, for the same reason. For questions relating to varietal resistance, comparisons were made using the Recommended Lists, based on both yearly and average resistance rating data for 2011 – 2015 (SAC & HGCA, 2011; SAC & HGCA, 2012; SRUC & HGCA, 2013; SRUC & HGCA, 2014). Where resistance data was not available (e.g. for Ramularia, where resistance information for all varieties only became available in 2012), this has been noted, and where varieties were never included on the Recommended Lists (6 of the 19 varieties listed; none of which were widely used by farmers, with none being listed more than 3 times) these varieties were not included in summary statistics.

4.3 Results

4.3.1 Survey demographic

Farmer survey

A total of 43 farmers and 36 agronomists responded to the survey, giving an overall response rate of 27%. The number of responses from each survey location was similar (between 9 and 13 farmers) and comparable results were obtained across sites for questions tested for bias, suggesting similar populations at each site. Farmers surveyed presented a young, highly educated population (data regarding formal qualifications were unavailable for comparison, thus agricultural qualifications statistics were used to provide a general index; note that these figures are therefore not directly comparable) with slightly larger farms than average (see Table 4-4).

Table 4-4: Comparison of Governmental and survey demographics[1]

	Percent with no qualifications	Age – under 35	Proportion of tenanted farms
Stakeholder Survey	4.8% (no formal qualifications)	12.2%	11.9%
Farm Structure Survey (2013)	59.1% (no agricultural qualifications)	2.6%	
June Agricultural Census (2015)			16.6%

[1]Data from the Scottish Government's Farm Structure Survey (2013) and June Agricultural Census (2015) relate to farm occupiers/managers only for arable and mixed farms. The proportion of tenanted farms does not include farms where some land is owned and some rented.

The spring barley producing regions of Scotland were well represented in the survey, with only two of the fourteen national sub-regions having a discrepancy of over 10% between the survey population and the Economic Report on Scottish Agriculture 2015 percentage of surveyed farms in each region: overrepresentation of the Highlands (15% difference); and underrepresentation of Tayside (18% difference). Distilling was the main spring barley market for more than three quarters of the surveyed farmers.

A large proportion (45.2%) of the farmers were affiliated with an environmental scheme or programme, as compared to the 28% of Scottish agricultural land reported to be under an agri-environmental scheme in 2014 (Defra, 2015). A direct comparison with the number of farmers taking up the Scottish Rural Development Programme (SRDP) is not possible, as number of unique individuals is not reported; however, in the most popular branch of the SRDP, 13371 unique applications were made as of its midterm assessment in 2010, accounting for approximately 26% of Scotland's farms in that year (Scottish Government, 2011). Despite the fact that 60.9% of the farms were mixed arable and livestock production, most farmers were growing large hectarages of spring barley in proportion to their total farm size. Farm ownership levels were high, with more than 80% of the farmers owning at least some of the land they farmed, and nearly 60% owning the entire farm. Contract growing was not universal, with just over half (51.2%) of farmers having no contract farmed spring barley whatsoever. There were no major trends in differences in farm size or barley hectarage by farm type, nor farm size or region by main market.

Agronomist survey

The regions in which agronomists advised farmers were similar to those represented in the farmer survey, though Tayside and the North East were both more strongly represented in the agronomist survey. The majority of agronomists (88.57%) primarily advised about spring barley which was intended for the distilling market. All agronomists indicated that they were experts in relation to spring barley. More than half of the agronomists surveyed (55.56%) were affiliated with trade/distribution.

4.3.2 Disease perception and varietal choice

Farmer survey – disease perception

Most farmers (94.59%) believed that foliar diseases of spring barley were important or very important in determining the yield. Rhynchosporium was indicated by the majority of farmers as being the most common of the three pathogens on spring barley in the past five years, as well as having had the greatest impact on yield (see Figure 4-2). Regional variation in the reported importance/commonness was minimal, except in the case of Ramularia, where 7 of the 11 farmers stating Ramularia impacted yields most were based in Eastern Scotland (encompassing Tayside, East Central, Fife, Lothians, and the Scottish Borders).

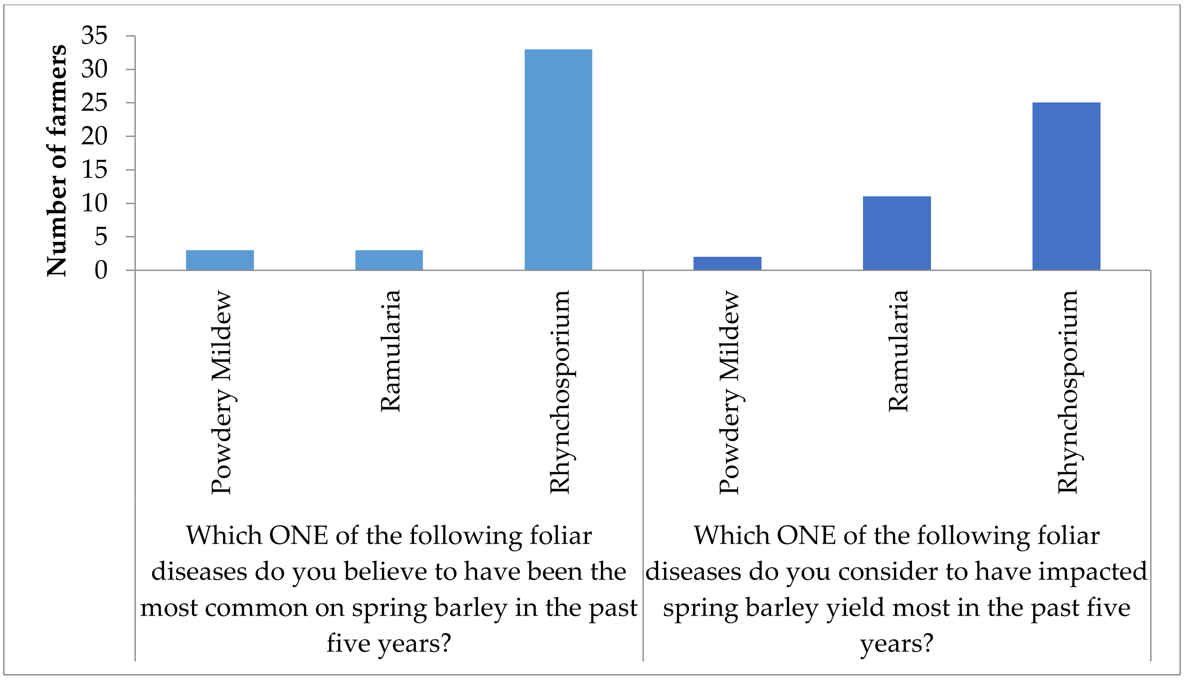


Figure 4-2: Farmer perceptions of disease commonness and impact on yield

Farmer survey - varieties

Most of the varieties sown by farmers, for which information is available in the 2011 – 2015 Recommended Lists, were distilling varieties – a number of crossovers existed, where farmers who had listed their main market as distilling also listed feed varieties, and vice versa. A majority of farmers (over 60%) stated that the varieties they sow are often or always highly resistant to each of the three diseases in question. The mean varietal disease resistance rating calculated for 2011 – 2015 using the Recommended Lists for each variety listed by farmers is summarised below in Table 4-5; 84.6% of varieties listed for which information is available were highly resistant to mildew, in contrast to 27.3% and 23.1% for Ramularia and Rhynchosporium, respectively.

Table 4-5: Mean disease resistance ratings of varieties listed by farmers[*]

Variety	Mildew	Ramularia	Rhynchosporium
Propino	7.6	6.3**	6.8
Concerto	8.2	6**	4.4
Odyssey	9**	5.8**	6.8**
RGT Planet	-	-	-
Waggon	9	7.3**	3.2
Sanette	9**	8**	6**
Belgravia	8.8	6.5**	7
Shada	8*	8**	4**
Momentum	-	-	-
Chronicle	8**	6.5**	6.5**
Optic	5	5.3**	5.3
Catriona	-	-	-
Golden Promise	1***	-	5***
Brioni	-	-	-
Westminster	9**	6.7**	7.5**
Oxbridge	7**	-	7**
Mintrel	-	-	-
Overture	8**	6.3**	6.7**
Braemar	-	-	-

[*]Means presented are based on years 2011 – 2015, except where marked by ** (based on less than five years of data within this period) or *** (based on data for 1990, the most recent year this variety was in the Recommended List). Variety/disease combinations for which no information is available in the Recommended List are marked with (-).

The variety ratings of all varieties listed by farmers in a given year are summarised in Table 4-6; more variation in resistance levels can be seen on an annual basis than in Table 4-5, however the overall trend of highly resistant varieties being the majority for mildew and minority for Rhynchosporium and Ramularia is the same. There are no years/diseases for which all farmers sowed the 'best choice' variety (e.g. the distilling variety with the highest mean disease resistance rating in that year) and in most years the majority of varieties had lower disease resistance ratings than the 'best choice' (see Table 4-6). As the 'best choice' was based only on fully recommended varieties, it is possible for a farmer to sow a provisionally ranked variety with a better rating than that year's 'best choice,' as was the case for Ramularia in 2015. Over 75% of the varieties listed by farmers who stated that they always/often sow highly resistant varieties to mildew were, in fact, highly resistant to mildew – by contrast, for Rhynchosporium and Ramularia, less than 25% of these were highly resistant according to the Recommended Lists (see Table 4-7). Farmers who stated a given disease was the most common/impacted yield most did not sow a higher proportion of varieties which were highly resistant to that disease for mildew or Ramularia, however, where farmers thought Rhynchosporium impacted yield most, a higher proportion of varieties they sowed were highly resistant (see Table 4-8). Despite farmer self-reporting that they often/always sow highly resistant varieties for all three diseases, this was not actual practice for Rhynchosporium or Ramularia in 2011-15. When considering which variety to sow, the two sources of information most frequently selected by farmers as being important/very important related to market demand (see Table 4-9).

Table 4-6: Annual percentage of varieties listed by farmers of each varietal disease rating*

	2015			2014			2013		
Rating	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium	Ramularia
3	-	3%	-	-	20%	-	-	17%	-
4	-	67%	10%	-	-	-	-	54%	-
5	3%	-	3%	10%	-	10%	10%	-	10%
6	8%	**30%**	**72%**	-	49%	68%	-	6%	67%
7	-	-	-	-	**31%**	**22%**	-	**23%**	**23%**
8	8%	-	15%	58%	-	-	65%	-	-
9	**80%**	-	-	**32%**	-	-	**25%**	-	-
Percent highly resistant[1]	88%	-	15%	90%	31%	22%	90%	23%	23%
Below best choice[2]	20%	70%	13%	68%	69%	78%	75%	77%	77%

	2012			2011	
Rating	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium
3	-	9%	-	-	8%
4	-	72%	-	-	65%
5	23%	-	5%	30%	-
6	-	-	**86%**	-	-
7	-	9%	9%	10%	28%
8	53%	**9%**	-	38%	**-**
9	**23%**	-	-	**23%**	-
Percent highly resistant[1]	76%	18%	9%	70%	28%
Below best choice[2]	76%	90%	5%	78%	100%

[1] Varieties with a resistance rating of 7 or more are rated as highly resistant throughout the thesis.

[2] Bold text indicates the ‘best choice’ variety; that with the highest disease resistance in a given year to a given disease (not including provisional ratings) for distilling/grain distilling varieties. Percentages do not include any varieties for which Recommended List information is not available for that year.

Table 4-7: Percent of varieties listed by farmers stating that they often/always sow highly resistant varieties for this disease which were highly resistant in the Recommended Lists

	2015	2014	2013	2012	2011	Mean
Mildew	91.7%	86.5%	87.1%	72.4%	56.5%	78.8%
Rhynchosporium	0.0%	38.2%	26.9%	18.2%	28.5%	22.4%
Ramularia	11.7%	21.1%	23.3%	11.1%	-	16.8%

Table 4-8: Variation in mean varietal resistance (2011 – 2015) of varieties listed by farmers in relation to perception of disease importance

	Total number of farmers in this category	Number stating often/always sow resistant varieties for this disease	Percent of varieties sown in past five years highly resistant to this disease	Total number of farmers in this category	Number stating always/often sow resistant varieties to this disease	Percent of varieties sown in past five years highly resistant to this disease
	Farmers who think this disease is most common			All other farmers		
Mildew	3	2	70.0%	36	24	82.2%
Ramularia	3	2	0.0%	36	22	10.5%
Rhynchosporium	33	20	14.5%	6	4	11.5%
	Farmers who think this disease effects yield most			All other farmers		
Mildew	2	2	100.0%	36	24	81.2%
Ramularia	11	9	8.9%	27	15	10.4%
Rhynchosporium	25	13	16.9%	13	10	8.4%

Table 4-9: Importance of sources of information to varietal selection

Source	Number of farmers choosing this source as important or very important	Percent of responses
Market demand for a particular variety	38	92.7%
Variety had malting/brewing certification	33	80.5%
Having prior experience with the variety on my farm	27	65.9%
Varietal disease resistance rating	27	65.9%
Agronomist selection	11	26.8%
Suggestion from/grown by another successful farmer in my area	9	22.5%

Agronomist survey

The varieties recommended by agronomists and those listed by farmers were broadly similar, with four of the five most commonly recommended also being the most commonly sown. The pattern of disease resistance for varieties recommended by agronomists was similar to that of the varieties sown by farmers – most varieties were highly resistant to mildew (84.62%) in clear contrast to Ramularia (11.11%) and Rhynchosporium (30.77%).

A majority of agronomists stated that they always or often recommended highly resistant varieties for each of the diseases, similar to farmer perception of sowing practices (see Table 4-10). A majority of agronomists also stated Rhynchosporium was the disease they believed to be most common and to have the greatest impact on yield, in a very similar pattern to the farmer results. The factor ranked as most important by agronomists when deciding which variety to recommend was 'other, please specify' – all but one comment related to the market or contract requirements. The second most important factor was 'variety had malting/brewing certification,' again, directly linked to the market – varietal disease resistance rating was the fourth most important of the five factors.

Table 4-10: Comparison of agronomist disease resistance sowing recommendations and farmer self-perception of disease resistance uptake

	Percentage of respondents recommending resistant varieties for this disease	Percentage of farmers sowing resistant varieties for this disease
Disease	**Often/always**	**Often/always**
Mildew	70.6%	66.7%
Ramularia	59.4%	61.5%
Rhynchosporium	71.9%	61.5%

4.3.3 Use of rotations

Farmer survey

All but five of the surveyed farmers used rotations, and the factor which ranked most highly in terms of influencing the decision to use this rotation was 'to spread risk of low yields/crop failure' with disease reduction being second (see Figure 4-3). Of the five farmers not using rotations, the need to fulfil contracts for main crop was the most highly ranked factor chosen by more than one of these farmers. The majority of farmers often or always sow barley and/or cereals consecutively – 66.7% and 82.0%, respectively (see Figure 4-4). No clear trend emerged regarding whether farmers who always/often sow consecutive barley sow consecutive cereals more often than others or vice versa. Farmers who chose disease reduction as one of their top two reasons for using a rotation were more likely to rarely/never sow consecutive barley/cereals than their counterparts, but consecutive sowing remained the norm in this group (see Figure 4-5).

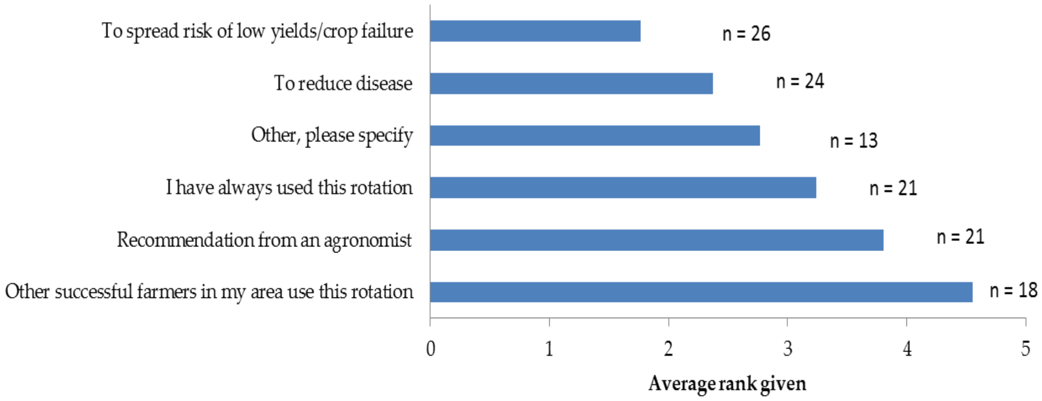


Figure 4-3:Average farmer ranking of factors influencing decision to use rotation[1]

[1] As with all average ranking figures, the closer the average ranking is to 1, the more important the factor; 'n' indicates the number of farmers who ranked this factor.

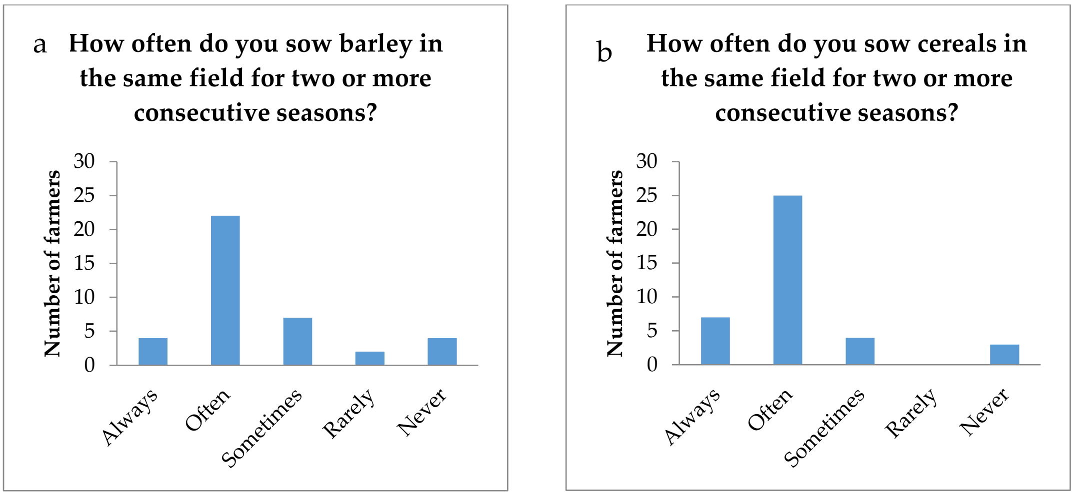


Figure 4-4: Self-reported frequency of use of consecutive (a) barley or (b)cereals

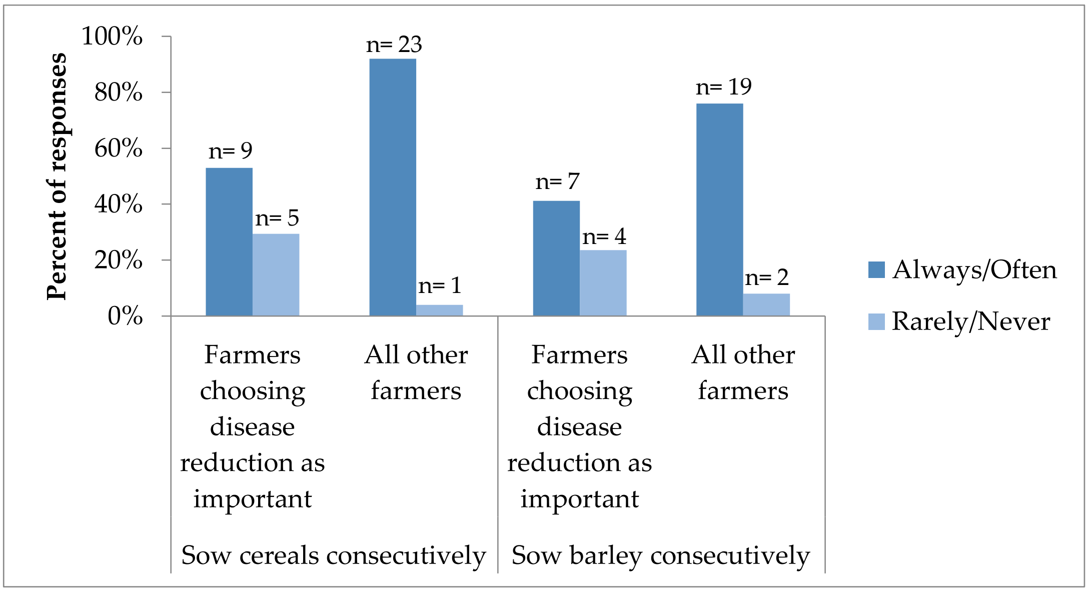


Figure 4-5: Relationship between ranking of disease reduction as a reason to use crop rotation and sowing cereals or barley consecutively

Agronomist survey

When recommending a rotation, the highest ranked factor involved in the decision was to reduce fungal disease, while the highest ranked factor when agronomists did not recommend a rotation was the need to fulfil contracts for the main crop. A majority of agronomists (60.61%) often/always recommended sowing consecutive cereals. Recommending sowing consecutive barley was less common, with just under half of the agronomists (48.48%) suggesting this often/always.

4.3.4 Fungicide use

Farmer and agronomist survey

Thirty-seven of 39 farmers surveyed stated that they applied fungicides to their spring barley crop every year. The most highly ranked factor impacting the decision to apply fungicides was in-field assessment of growth stage (see Figure 4-6). The impact of fungicide use on spring barley yields was thought to be an increase of 1-2 tonnes per hectare by most farmers (71.8%) and agronomists (75.0%) (see Table 4-11). The majority of agronomists recommended fungicide use to farmers for foliar diseases in spring barley every year to every client; the most highly ranked factor influencing the decision to recommend applying fungicides was on-farm assessment of growth stage, followed by weather forecasting and independent expert advice/information.

Comparison with Field Trials estimates of impact of fungicide use on yield

The impact of fungicide use on spring barley yields in the Field Trials data for 2011 – 2014 was, on average, 0.62 t/ha (see Chapter 2). Mean within-block absolute yield differences of the trials had a range of −0.3 to 2.0 t/ha, though the majority of yield differences were below 1.0 t/ha (see Figure 4-7). Over 70% of farmers believed fungicide use increased yields by 1 – 2 t/ha; however, only 17.5% of trials showed yield differences in this range (see Figure 4-8). That the impact of fungicide use on yields in the 2011 – 2014 database is generally less than one t/ha is confirmed by the differences between both mean and median yields for treated and untreated plots, as well as the frequency with which the mean absolute yield difference for a given trial was below this (80% of the time).

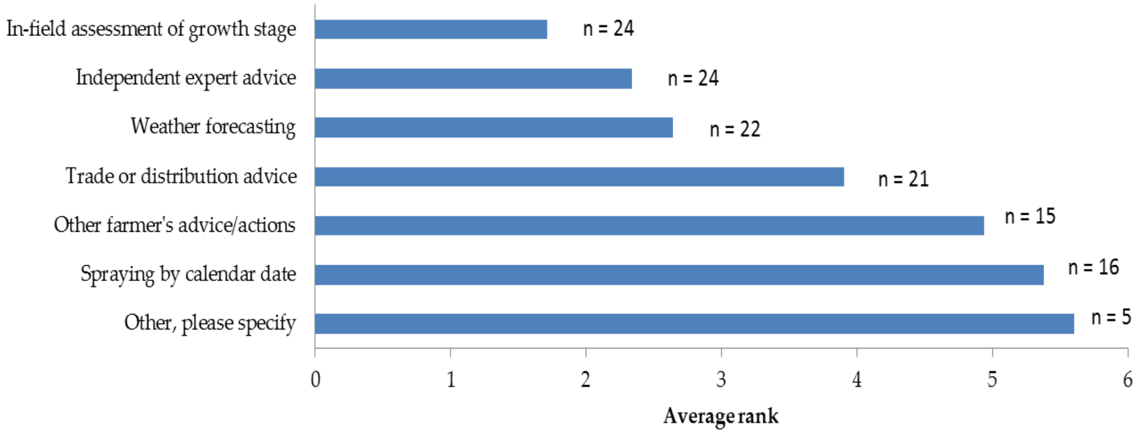


Figure 4-6: Average ranking of importance of factors to decision to apply fungicides

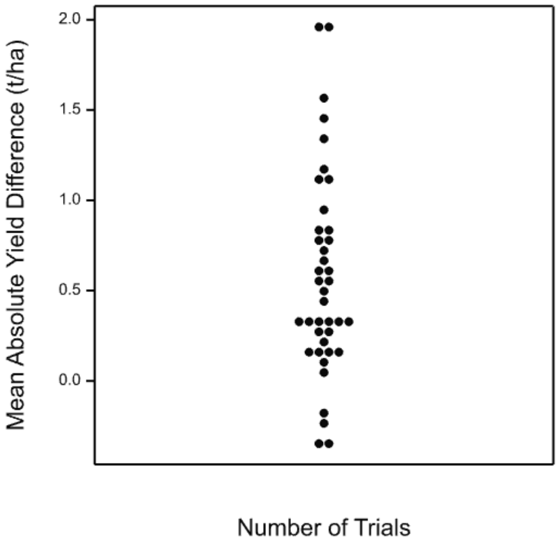


Figure 4-7: Spread of absolute yield differences at trial level

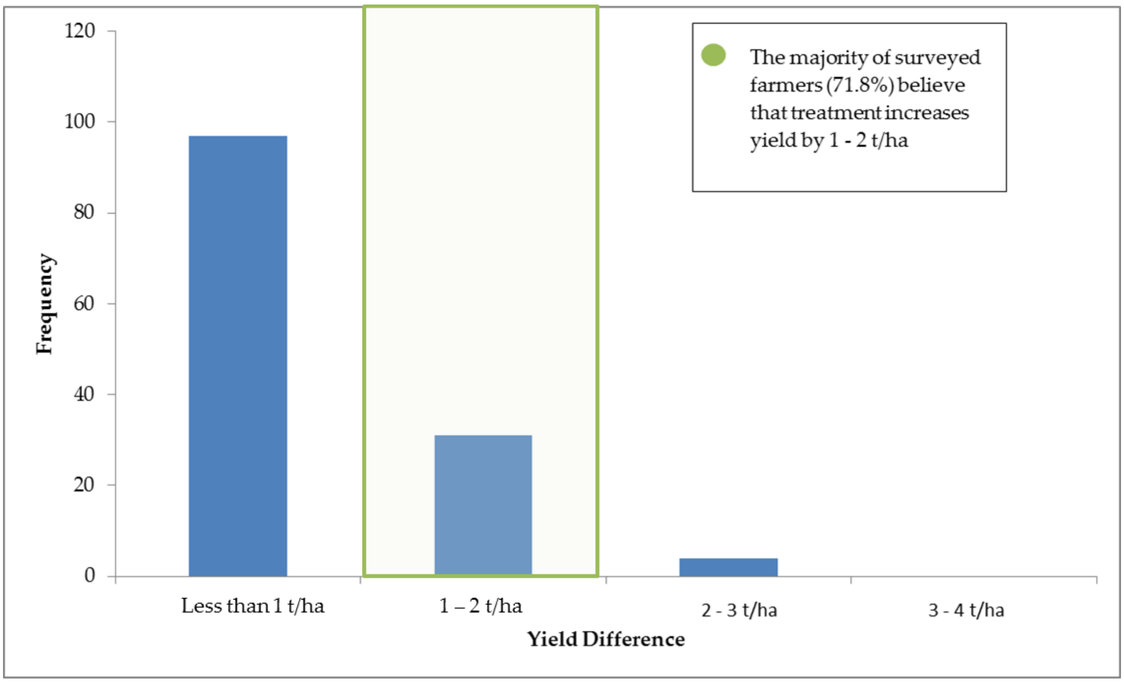


Figure 4-8: Comparison of observed absolute yield differences and farmer perception of fungicide impact on yields

Table 4-11: Farmer and Agronomist estimation of the increase in spring barley yields due to fungicide use

How much (in t/ha) do you think fungicide use increases spring barley yields by?

	Number of farmers	Percent of farmers	Number of agronomists	Percent of agronomists
Less than one tonne per hectare	5	12.8%	5	15.6%
1 - 2 tonnes per hectare	28	71.8%	24	75.0%
2 - 3 tonnes per hectare	5	12.8%	2	6.3%
3 - 4 tonnes per hectare	1	2.6%	1	3.1%
More than 4 tonnes per hectare	0	0.0%	0	0.0%

4.3.5 Perceptions of IPM strategies

Farmer survey

More than 80% of farmers were open to reducing their fungicide use if they could achieve the same yields and/or have fungicide reduction be cost-effective. A majority were also concerned about fungicide resistance, the amount of fungicides that they themselves used, and felt that finding methods to reduce fungicide use was important (see Figure 4-9). Note that in the survey, alternating positive (e.g. I think) and negative (e.g. I do not think) statements were used, in order to prevent bias. In Figure 4-9, the negative statements have been made positive, along with their results, to make comparison more straightforward. Farmers were asked to indicate which IPM technique they were most likely and which they were least likely to adopt as a cost effective alternative to fungicides – each technique had some farmers choosing it at the most/least likely, though forecasting disease pressure had the highest number of 'most likely' (see Figure 4-10). Farmers were then asked the same question in relation to which IPM technique they were most/least likely to adopt as a complementary technique alongside continued fungicide use – again, each technique had some farmers choosing it as best/worst, and again, forecasting disease pressure had the highest number of 'most likely' (see Figure 4-11). For each of these questions, farmers were also allowed to choose 'N/A – already use,' giving an indication of which of the IPM techniques are already common practice in the survey group. Again, all techniques are in use by some farmers, with planned crop rotation being the most commonly used.

A second series of best-worst scaling questions (which did not give an option for N/A – already in use) asked farmers first about the perceived practicality and second the perceived practicality in terms of cost of implementation of each IPM technique. Again, for both of these questions some farmers chose each technique as most/least practical; here it was sowing only disease resistant varieties which was most popular overall (see Figure 4-12 and Figure 4-13). Sowing only disease resistant varieties was most frequently chosen as being best both in terms of practicality and cost effectiveness, while forecasting disease pressure was most frequently chosen as being worst on both counts – this is displayed on a best-worst scale in Figure 4-14, below. The bubble plot (see Figure 4-14) represents the combinations of choices made by farmers for the two best-worst scaling questions relating to practicality.

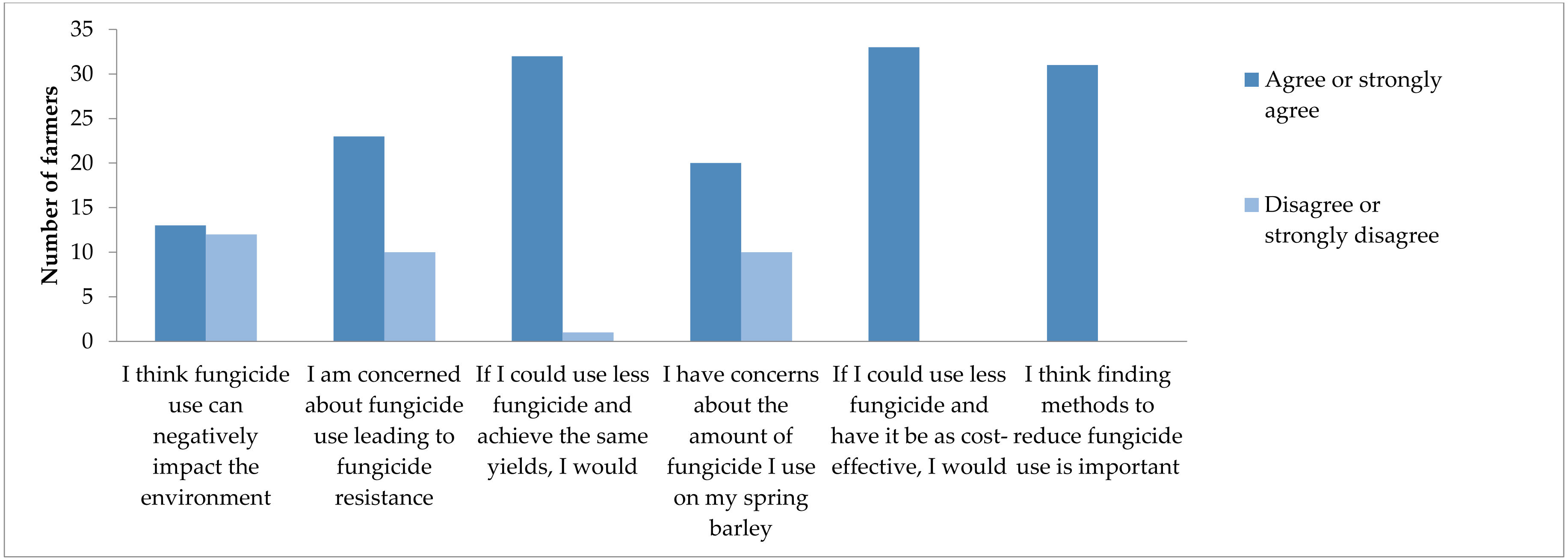


Figure 4-9: Summary of farmer's polarised attitudes towards fungicide use

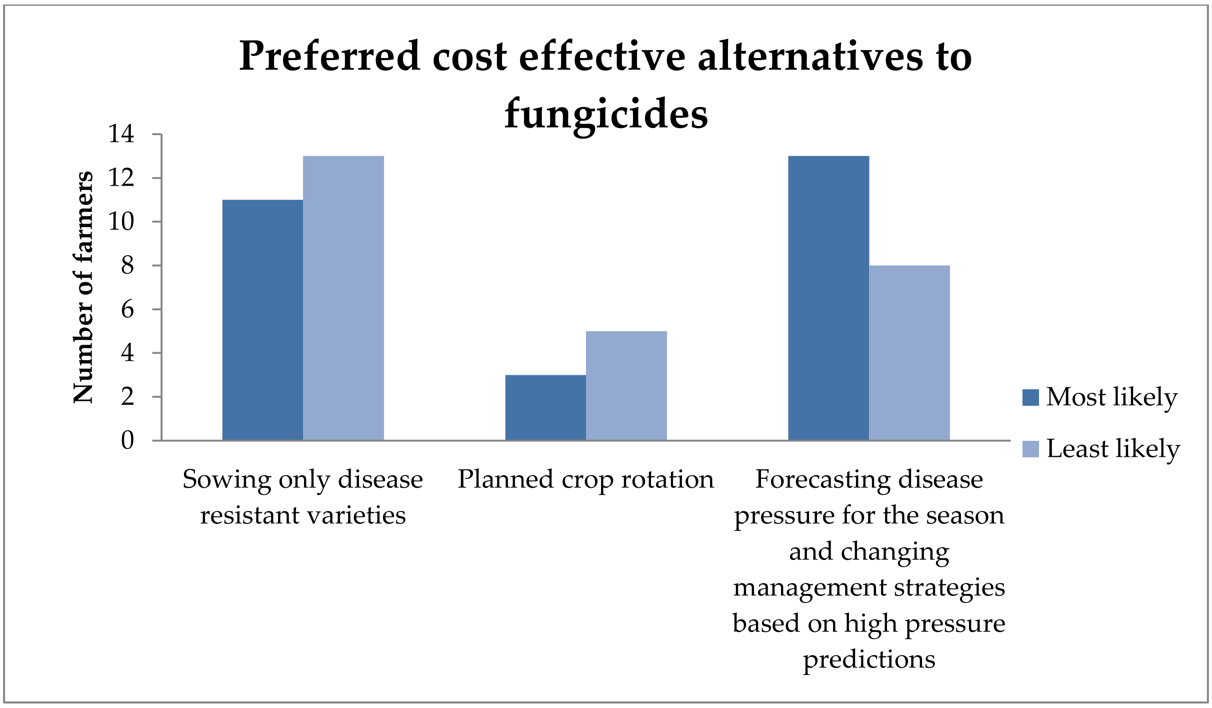


Figure 4-10: Farmer perception of IPM measures as cost effective alternatives to fungicides

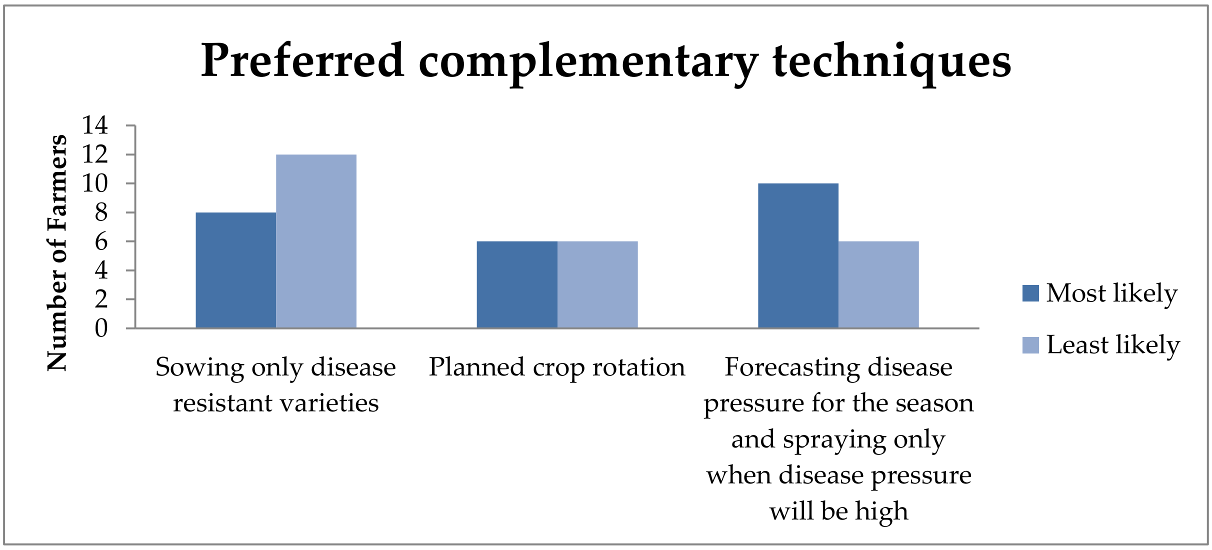


Figure 4-11: Farmer perception of IPM measures as complementary techniques to be used alongside fungicides

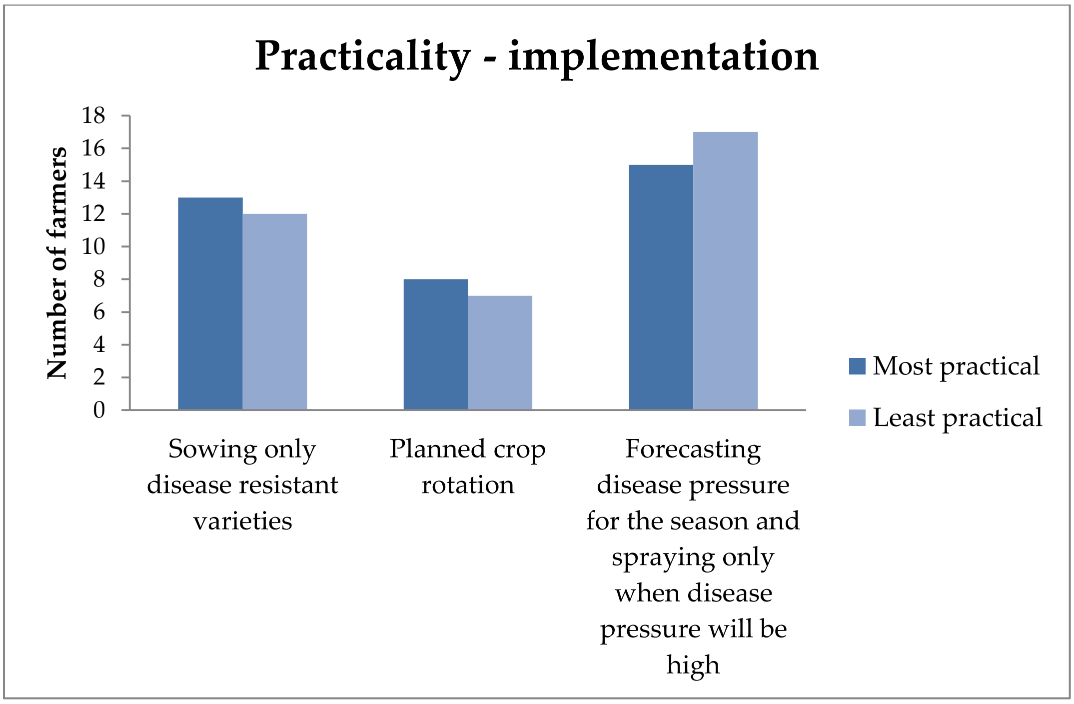


Figure 4-12: Farmer percetion of IPM techniques in terms of the practicality of implementation

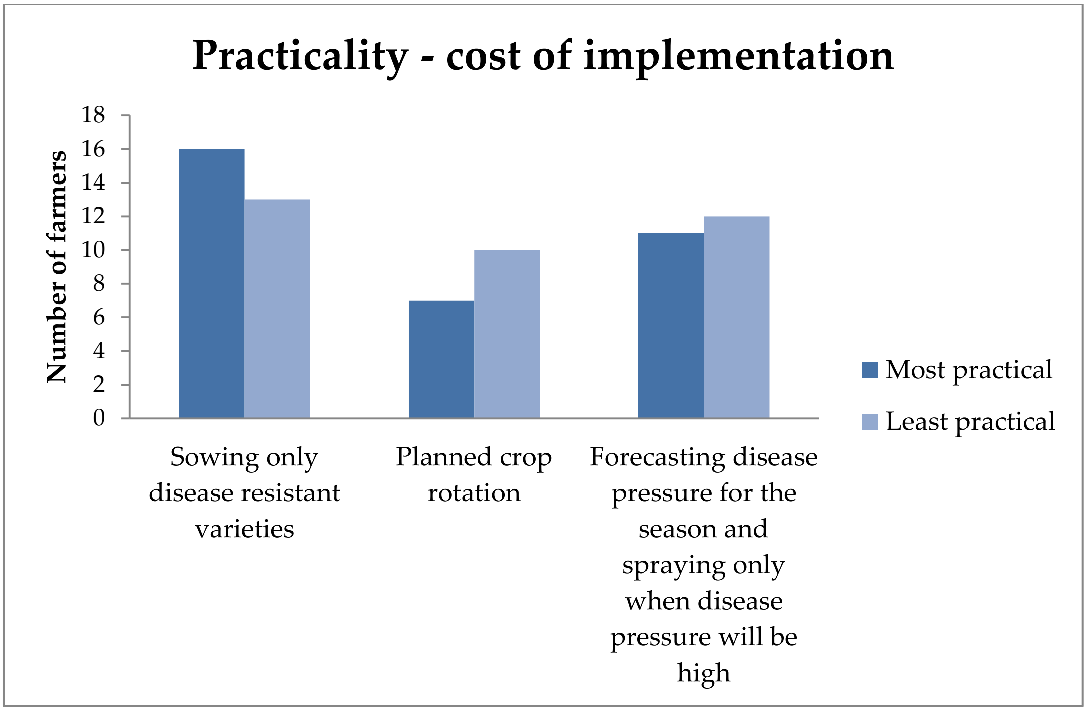


Figure 4-13: Farmer perception of IPM techniques in terms of the cost of implementation

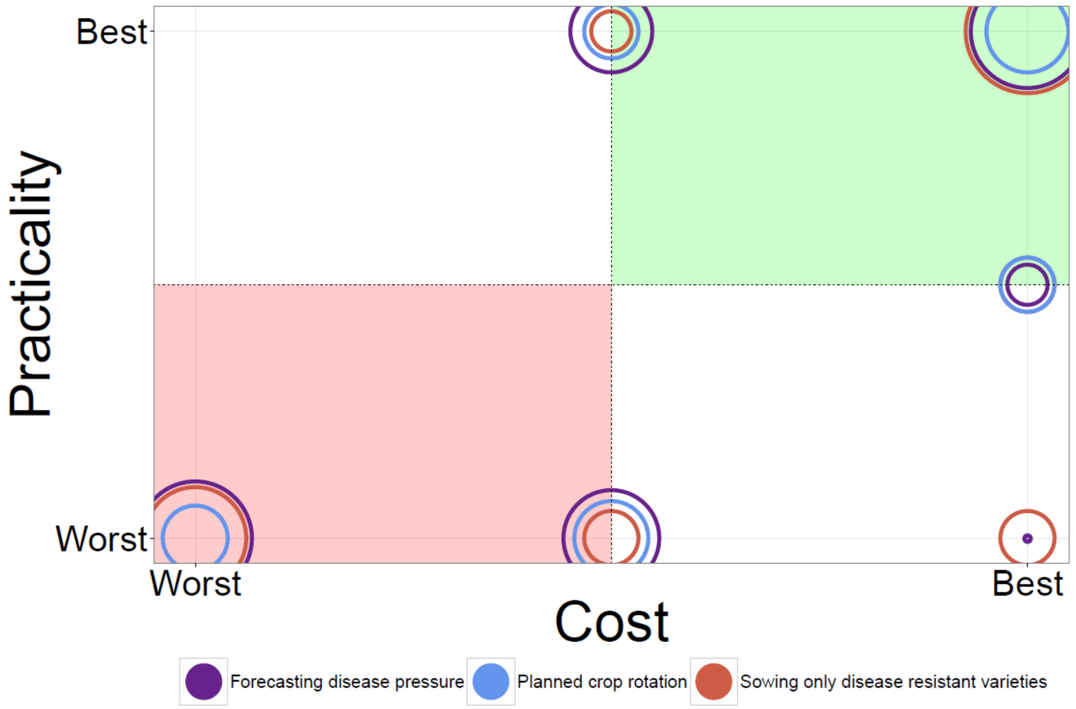


Figure 4-14: Best-Worst Scaling bubble plot of farmer perceptions of IPM techniques in terms of cost and practicality of implementation

The overall most preferred selections are in the top right hand corner of the graph – e.g. where a farmer has chosen a given technique as best both in terms of practicality and cost-effectiveness. By contrast, the overall least preferred will be in the bottom left hand corner of the graph – e.g. where a farmer has chosen a given technique as both worst in terms of practicality and cost effectiveness. As bubble size indicates the number of times a given combination was chosen, the outer colour of the bubble indicates the IPM technique which was most frequently chosen for this technique.

Agronomist survey

A majority of agronomists strongly agreed or agreed that if using less fungicides could achieve the same yields or be as cost-effective, they would recommend using less fungicide, were concerned about fungicide resistance and felt finding methods to reduce fungicide use was important. Each IPM technique was chosen as most/least likely by at least one agronomist in terms of being their preferred cost effective alternative to fungicides and preferred complementary techniques – unlike in the farmer survey, sowing only disease resistant varieties was most frequently chosen as most likely in both cases. All three IPM techniques were already being recommended by agronomists, with planned crop rotation being the most frequently chosen as being recommended, similar to farmer responses.

4.4 Discussion

4.4.1 Key messages

Farmers were generally positive about the IPM practices considered, with some farmers willing to take up each measure. A number of farmers also reported already using each IPM measure, and agronomists reported already recommending these. However, a mismatch was seen between farmer perception of their own IPM uptake and their self-reported practice, in regards to both varietal disease resistance and rotation use. Farmer openness to IPM, lack of actual uptake, and the fact that both farmers and agronomists considered fungicides to provide larger yield benefits in spring barley than shown in the database analysis provide a clear suggestion that IPM uptake can be improved. Market forces were an important factor in farmer decision making, and IPM plans should take end-market requirements into consideration in order to be successful.

4.4.2 Survey limitations and bias

One key area of bias which should be taken into account in an interpretation of the survey results is the similarity in topic between the focus of the cereal events themselves and the survey. Measures were taken to reduce the direct influence of the events on survey results as described above, such as removing direct mention of barley yields under different treatment types, and keeping the introduction to the survey itself general. However, the self-selection bias which is inherent in all voluntary surveys will here be magnified by the initial self-selection of attendance at events relating to disease management. As participants will have filled in the survey at various points throughout the day, the exact levels and types of bias will vary between survey responses – however, all participants will have been primed to think about IPM due to the programme of the day, and most will have been primed to think about the need to shift away from fungicide dependence and alter patterns of fungicide use by the presentations given during the event. While not all presentations focused on IPM, and some farmers may have attended solely to discover which fungicides would be best suited to their crops in 2016, the impact of the numerous mentions of IPM on participant mentality while completing the survey must be recognised. Survey results must therefore be interpreted in this light – farmers represented not only an early adopter of innovation group, based on age, farm size, and education characteristics (Diederen et al., 2003; Rogers, 1961), but also a group which was primed to consider IPM in a positive light. The survey results should be seen as a best case scenario, from the perspective of openness to IPM. If the primed, early innovator farmers whose opinions are presented here are unwilling to consider a certain aspect of IPM, it is unlikely that it will be more popular across the general farming population.

4.4.3 **Farmer attitudes towards IPM**

That farmers had concerns about fungicide use leading to resistance was evident, as was their willingness to reduce fungicide use if this could be cost-effective. Interest in using the three IPM strategies presented was more variable within the group. When farmers were asked to consider the strategies in terms of being cost-effective alternatives to fungicide or complementary strategies used alongside fungicide the preferred technique was forecasting disease pressure. However, when asked to review the same IPM techniques in terms of practicality and cost generally, sowing only disease resistant varieties was most frequently preferred. As each technique was preferred by several farmers in every question, however, the difference between these findings should not be overstated, as in neither case is the preferred option overwhelmingly more popular than the other two. Further, the initial question regarding cost-effective alternatives and complementary techniques allowed participants to indicate which techniques they already used on farm. This was included as a way to gauge the current uptake of each IPM technique. However, its inclusion may have complicated an already complex question design, and created confusion – several comments mentioned this pair of questions as being confusing or poorly designed. For this reason, the main conclusion that should be drawn regarding farmer perception of the IPM strategies is that all three strategies received some positive and some negative responses, and all were already being used by some farmers, with no single technique being preferred by all farmers.

4.4.4 Discrepancies between perception and practice

In spite of this generally positive attitude towards IPM and previous use of the techniques, a clear mismatch was seen between perceptions/intent and actual practice for both IPM techniques investigated in detail in the survey – varietal disease resistance and rotation – as well as the impact of fungicide use on yield. First, a disparity was seen between farmer perceptions of their use of highly resistant varieties and the reality of varietal disease resistance, based on their own lists of varieties sown in the past five years. While the majority of farmers stated that they sowed highly resistant varieties to all three diseases, the mean disease resistance ratings for the varieties listed by farmers for Ramularia and Rhynchosporium contradicted this. Indeed, when analysed on a yearly basis, the percentage of varieties listed by farmers which were highly resistant to Rhynchosporium in that year never exceeded 31%, despite two-thirds of farmers having stated they often/always sowed highly resistant varieties for this disease. This pattern of overestimating the extent to which they sowed highly resistant varieties persisted even when a farmer thought a given disease was most common, showing a clear gap between actual and perceived practice. Differences between perceived and actual behaviour have long been studied in the field of psychology, and recent work by Niles et al. (2016) have expanded this to include studies of farmers and climate change, showing that intended and actual adoption of climate change mitigating management strategies were dissimilar. In addition, work with

Dutch farmers about their farming styles indicates that farmers avoid identification with portraits that may be seen negatively, and may alter their responses accordingly (Vanclay et al., 2006). This contradiction between practice and perception does not, however, appear to have been reported in the context of IPM uptake before (for a copy of the paper submitted for publication based on this work, see Appendix N – Stetkiewicz et al., 2017. Perception vs practice: farmer attitudes towards and uptake of IPM in Scottish spring barley (journal article, submitted to Crop Protection)).

The fact that this gap was mirrored in the agronomist survey highlights how widespread the pattern is, and may, in fact, perpetuate the discrepancy. Recent work on relationships between farmers and agronomists has shown that, though there are a number of agronomist-farmer relationship types, agronomists are frequently seen as experts whose advice is crucial in decision making (Ingram, 2008; Sherman & Gent, 2014). If an expert called in for advice in varietal selection does not challenge or, indeed, does not notice the disparity, it could be reinforced.

A similar gap was seen in relation to rotation use in the survey. Nearly all farmers surveyed used rotations – those who did not primarily reported this was due to contract requirements – with disease reduction being the second most highly ranked reason for using a rotation, after spreading risk. Due to the nature of a rotation, it is not possible to be certain which crop disease(s) farmers are primarily using rotations in order to manage. Answering this would have required an additional question in the survey asking farmers to specify which crop/disease pair they used their rotations to counter, which may or may not have been fruitful, as it is likely to have encompassed multiple pairs which varied over time. However, the primary reason for using a rotation was spreading risk, not disease reduction so it is possible disease reduction is considered simply as an additional benefit where it arises and that the rotation is not specifically tailored to this end. However, given that reducing the build-up of relevant diseases in a field is one key way to reduce the risk of crop loss, it is likely the two objectives are synergistic. The fact that the majority of farmers often/always sowed both consecutive barley and cereals, despite disease reduction being a highly ranked reason for using rotation is therefore concerning, as consecutive sowing may undermine any disease reduction objectives farmers have. Again, expert-back up could be strengthening the idea that consecutive sowing within a rotation is compatible with the aim of reducing risk, as recommendations of consecutive sowing were only marginally less prevalent amongst the agronomist group.

Another discrepancy was seen between actual and perceived impact of fungicide use on yields. Both farmers and agronomists overestimated the impact of fungicide use on spring barley yields, as compared to the differences seen in the 2011 – 2014 Field Trials. The majority of trials studied had absolute yield differences below 1 t/ha, with an overall mean difference in yields of 0.62 t/ha. The majority of farmers and agronomists surveyed, however, believe fungicide treatment increases spring barley yields by 1 – 2 t/ha. Few studies have explicitly measured stakeholder perception of the impact of fungicide use on yields, and compared this with a measured yield difference; the one example which could be found in the literature also noted an overestimation of the impact of pests on yields of rice in China by approximately 35% (Huang et al., 2000). As discussed in Chapter 2, the impact of fungicide treatment on yield may be buffered by the Field Trials set up, as compared to a commercial field. However, based on the information available, it appears that the majority of farmers and agronomists surveyed overestimate the impact of fungicide use on spring barley. If so, this has wide-ranging implications for disease management practice in the sector; if farmers are anticipating a greater economic gain when applying fungicides than is delivered, the benefits to avoiding fungicide treatment may outweigh the yield loss.

These disparities between perception and reality have concerning implications for the uptake of IPM techniques. If farmers and agronomists believe that they are already using IPM to its fullest, e.g. sowing highly resistant varieties and using crop rotations, they are likely to dismiss these as options for further reducing disease burden, and instead opt to apply the fungicide which they perceive to be more effective than it is.

Market forces, which have been recognised as a key driver in the complexities of farm risk and innovation (Ghadim & Pannell, 1999; Marra et al., 2003), are likely to be influencing farmer uptake of IPM methods as well, because varietal choice is restricted to the varieties preferred by the market, and rotation plans may change in response to grain prices. This is particularly likely to be influencing varietal choice, as the two sources of information most frequently chosen as important/very important by farmers related back to market demand, surpassing varietal disease resistance rating. Resistance rating may therefore be used in decision making as a 'deal breaker' when choosing between two or more varieties of equal market value, rather than vice versa. Other IPM techniques may be seen in a similar manner – for example, farmers may generally use crop rotations, but alter this when market prices indicate it would be beneficial to do so. Clearly, this approach makes financial sense in the short-term, however as benefits from IPM are cumulative, breaks in IPM use reduce efficacy in the long-term. This, in turn, may cause stakeholders to question their effectiveness, and thus break the cycle again. It is crucial for farmers to both understand their actual practice on farm to ensure IPM perceptions are based on reality, as well as to be willing to continue using IPM in a longer term context in order to see full the full benefits.

4.5 Conclusions

Farmer attitudes towards the IPM measures of interest were broadly positive – each technique was thought to be most practical and cost effective by some farmers and can therefore be posited as feasible options in relation to IPM uptake in Scottish spring barley. However, the two IPM techniques which were investigated in further detail – planned crop rotation and sowing disease resistant varieties – showed a substantial gap between farmer perception and practice, such that where these techniques were being used by farmers they were not fully optimised. This has implications for overall uptake of IPM measures. If farmers believe themselves to be using an IPM technique to its fullest and yet not reaping any benefits, this could cause drop off in usage and/or dissuade them from taking up new IPM measures. This, in turn, could have a knock on effect on other farmers in the community through peer to peer exchange of faulty information, especially as agronomist perceptions were likewise skewed. The reasons behind this gap are not fully understood, but could include lack of trust in official sources of information (e.g. Cereal Recommended Lists) or an inaccurate reflection of practices on farm in the survey results, for example due to poor memory of varieties sown. Further research into the sources of information used, and the relative levels of trust placed in them by farmers as well as analysis of written farm records, could deepen understanding of this phenomenon, to avoid memory bias.

Chapter 5 Assessing the potential for improvement of commercial IPM practice via the Adopt-a-Crop database

5.1 Introduction

Field Trials analysis (see Chapter 2 and Chapter 3) suggests that sowing varieties with high levels of disease resistance and forecasting disease pressure based on weather may reduce the need for fungicide use in Scottish spring barley. The survey work presented in Chapter 4 indicates that the surveyed farmers are open to the three forms of IPM presented – sowing only disease resistant varieties, planned crop rotation, and forecasting disease pressure. In theory, therefore, it is possible to reduce fungicide use by implementing IPM strategies. However, there is a need to understand current commercial practice, with a larger sample of the Scottish farming population than was possible in the survey discussed in Chapter 4. This is required in order to assess how many farmers are actually using the IPM practices identified. This knowledge will ensure that the recommendations are practical and relevant. The Adopt-a-Crop (hereafter AAC) crop-monitoring database, collected by the SRUC, contains information about commercial farm practice which makes this assessment possible.

5.1.1 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 was collected for immediate, rather than long-term use, and this thesis 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, which is collected from across Scotland (data are available for 26 Scottish geographically distinct regions). Location, sowing date, variety planted, pesticides used, timing of pesticide application, and weekly growth stage and disease burden information collected 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. Thus, although certain farms have been included multiple times since 1983, farm inclusion varies from year to year. 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).

5.1.2 The AAC: linking experimental results with commercial realities

The AAC provides an opportunity to consider the experimental results presented in the chapters on the Field Trials database (2 and 3) and the survey (4), in order to determine whether there is scope for the IPM techniques identified as feasible (via the survey) and useful (via the Field Trials database) to be taken up in Scotland. The AAC data can be 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 Chapter 4, where the sample was necessarily limited in scope. Results from the AAC data and survey can be compared to understand how representative the farmers surveyed in Chapter 4 are in relation to the broader sector, and thus to what extent results from this survey can be used to gauge wider farmer attitudes. The AAC provides a link between field trials, survey work, and commercial data, allowing comparisons to be made and results considered across all three data sources – work that spans these data types is unusual in the field of IPM research. Considering these three sources of information together allows for insights into the potential for IPM uptake from several perspectives, producing a more unified picture of disease management.

Assessing the AAC is also informative, because, while previous work has assessed IPM uptake via survey methods e.g. the ADAS (2002) work on awareness and use of IPM and Bailey et al.'s (2009) IPM portfolio surveys, these were one-off questionnaires at a single time point. A multi-year database of actual practice such as the AAC allows management strategies to be tracked over a longer period, with a potentially larger sample size and geographical spread than would normally be achieved by a single survey experiment.

5.2 Methods

5.2.1 Data collection and preparation

Extensive cleaning and preparation of the AAC data was necessary for quality control purposes. Missing data was identified and collected from archives, and additional information (e.g. varietal disease resistance from the SAC/SRUC Cereal Recommended Lists) was incorporated for analysis. Originally, data running from 1983 – 2012 was prepared for study, and exploratory data analysis was conducted, culminating in a review of the impact of sowing dates (see Appendix M – Pesticide management in Scottish spring barley – insights from sowing dates (Conference Paper)) in order to understand the complexities of the spring barley system. Due to resource limitations, however, the entire AAC dataset could not be prepared adequately for comparison with the Field Trials and farmer survey data. Data from 2009 – 2015 was therefore sub-setted for analysis, as these years had been fully cleaned, and this provided a useful overlap with the farmer survey variety data, running from 2011 – 2015.

5.2.2 Data analysis

Varietal information from the AAC was analysed both to understand the resistance profiles of the fields included in the database, as well as to provide a comparison with the 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, mean disease resistance ratings, number of mixed-variety fields per year, and the percent of varieties sown which were listed as being suitable for a given market in the Recommended List (see Table 5-1 for a summary of each metric produced). A comparison was then made between the relevant datasets for each metric and correlations were used to determine the level of association between the varieties listed in the 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 per Chapter 4) based on the highest rated distilling variety in a given year was made, along with an overall measure of 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 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 survey results, Field Trial data, and Scottish Government farming statistics (Scottish Government, 2015a), 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 (2015a), and are shown in Figure 5-1.

Table 5-1: Summary of metrics produced assessing the AAC and the sources to which each was compared

AAC metric:	Compared with	Analysis notes	Data found in
Proportion of varieties sown which were Recommended List for that year	Farmer survey	Percentage	Page 164
Instances of mixed variety sowing		Number per year	Table 5-2
Most frequently listed varieties	Farmer survey	Top ten most commonly listed for each source; correlations test for association between the two sources	Table 5-3
Mean disease resistance rating for each disease	Farmer survey; Field Trials database	Unweighted means for each source, and weighted means for Field Trials; percentage highly resistant to one or more diseases; percentage highly resistant to two or more diseases	Table 5-4; Table 5-5
Mean disease resistance by market	Farmer survey	Mean resistance rating for each disease; proportion resistant to one or more diseases	Table 5-6

Table 5 -1 (continued)	Compared with	Analysis notes	Data found in
Resistance rating by year	Farmer survey	Percent of varieties with each disease resistance rating by year; percent highly resistant per year; percent below best choice per year	Table 5-7
Potential market	Farmer survey	Percent of varieties with the potential (assessed via Recommended Lists) to be used in each barley market	Figure 5-3
Previous crop	Farmer survey	Number of fields with each previous crop reported in AAC; percent of fields with continuous barley/cereals in each source	Table 5-8; Figure 5-4
Impact of previous crop on resistance rating	Farmer survey	Mean disease resistance rating for continuous and non-continuous barley	Table 5-9
Variation in sowing of continuous barley/cereals by year		Percent of fields in AAC with continuous barley/cereals each year	Figure 5-5
Geographical spread	Economic Report on Scottish Agriculture	Number and percent of farms in each sub-region of Scotland for each source	Table 5-10

Table 5 -1 (continued)

	Compared with	Analysis notes	Data found in
	; farmer survey; Field Trials database		
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	Table 5-11
Regional variation in main market		Percent of fields with varieties of each market type, by sub-region	Page 176

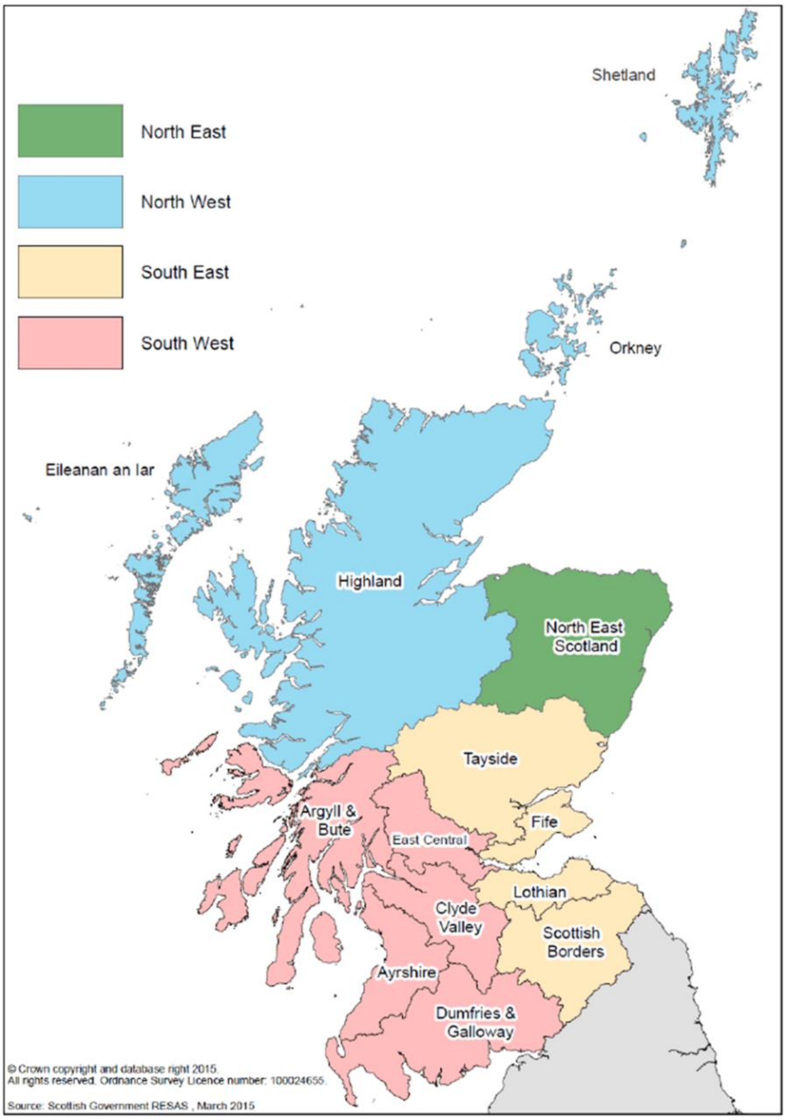


Figure 5-1: Regions and sub-regions of Scotland, taken from Scottish Government (2015)

5.3 Results

5.3.1 Varietal information

Frequently sown varieties

Of the varieties sown in the AAC, 22.1% were not found in the Recommended List for that year, while in the farmer survey only 4.6% of varieties were not in the Recommended List. Eight entries in the AAC listed mixed variety sowing. These entries were removed from all comparisons and proportions, as variety mixes cannot be directly compared to individual varieties. A mean disease resistance rating, for example, would not accurately reflect the impact of multiple varieties on disease severity, as the two varieties may have differing resistance types and thus provide a more difficult target for the pathogen. It is interesting to note, however, this presence of varietal mixing on commercial farms (see Table 5-2), which was not found in the farmer survey.

The ten most frequently listed varieties in the AAC and survey are shown below in Table 5-3. Three of the five most popular varieties were the same in both the AAC and 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 from the farmer survey were listed in the AAC, and seven of the top ten in the AAC were listed in the farmer survey – suggesting substantial overlap and comparability between the two. The varieties listed in the survey and AAC were strongly correlated with a coefficient of 0.81.

Table 5-2: Number of mixed variety fields sown in the AAC per year in 2009, 2010, 2012, and 2013

	2009	2010	2012	2013	Total
Concerto/Optic				1	1
Waggon/Westminster		1			1
Waggon/Oxbridge	6				6
Total number of fields in AAC	109	96	59	88	

Table 5-3 – 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 in farmer survey	Present in Field Trials database 2011 – 2014	Present in Field Trials database 1996 – 2014
Concerto	132	125	Yes	Yes
Optic	102	35	Yes	Yes
Waggon	79	23	Yes	Yes
Oxbridge	30	8		Yes
Propino	16	14		
Belgravia	15	28	Yes	Yes
Maresi	15			
Decanter	12			
Riviera	11			Yes
Westminster	11	Present	Yes	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.

Disease resistance

The mean disease resistance rating based on the Recommended List is reported for each source below, in Table 5-4. Though variation between sources is present, the rankings are broadly similar. The proportion of varieties which were highly resistant to each disease, as well as those highly resistant to two or more diseases is presented in Table 5-5 for further comparison. This showed fewer fields with highly resistant varieties to mildew in the AAC than the survey (although the figure was consistent with the Field Trials), but more fields with highly resistant varieties to Ramularia in the AAC than in the survey or Field Trials. The farmer survey had a higher percentage of varieties with high resistance to two or more diseases than the AAC or Field Trials. However, the proportion of varieties which were highly resistant to Ramularia, Rhynchosporium, or 'two or more diseases,' was below one third of the total in all cases. The proportion highly resistant to mildew, by contrast, was over half in every source. Differences in disease resistance between malting and feed barley were similar in both the survey and AAC, with more feed varieties being resistant to one or more diseases than distilling varieties, as shown in Table 5-6.

Though unweighted mean disease resistance ratings were also calculated for the Field Trials data, there was not enough data to make a valid comparison with the weighted means. 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 Rhynchosporium nearly 90% of varieties sown were below the best choice (see Figure 5-2 and Table 5-7).

Table 5-4: Mean disease resistance ratings for each data source*

	Ramularia	Rhynchosporium	Mildew
AAC	6.3	4.5	7.5
Survey (farmer)	6.1	4.9	7.9
Field Trials 2011 – 2014 (survey varieties only): **Weighted mean**	6	4.3	6.9
Field Trials 2011 – 2014 (survey varieties only): **Unweighted mean**	6.5	5.5	8
Field Trials 1996 – 2014 (all varieties): **Weighted mean**	5.9	4.5	6.7
Field Trials 1996 – 2014 (all varieties): **Unweighted mean**	6.2	5.5	7.4

*Disease resistance ratings run on a scale from 1 – 9, with 9 being the most highly resistant

Table 5-5: Proportion of varieties which were highly resistant to each disease*

	Ramularia (2012 onwards)	Rhynchosporium	Mildew	Two or more diseases	Any Resistance**
AAC	26.1% (69)	14.2% (77)	58.1% (316)	17.4% (95)	74.5% (316)
Survey (farmer)	17.8% (38)	19.3% (49)	84.3% (214)	28.7% (73)	84.3% (214)
Field Trials 2011 – 2014 Weighted	14.3% (28)	13.6% (36)	59% (156)	15.9% (42)	59.2% (157)
Field Trials 1996 – 2014 (all varieties) **Weighted**	5.3% (4)	15% (30)	59% (118)	12% (24)	63% (126)

*Proportion based on: total number of varieties for which varietal information is available (i.e. discounts varieties not in the Recommended Lists), also discounts variety mixtures. Ramularia proportions are based on the varieties in each dataset from 2012 onwards, when resistance ratings were first published. In this thesis, '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.

Table 5-6: Comparison of disease resistance in feed and malting varieties*

Database/source	AAC distilling/brewing mean	Survey distilling/brewing mean	AAC feed mean	Survey feed mean
Rhynchosporium	4.7	5.0	3.7	3.4
Mildew	7.1	7.8	8.9	9.0
Ramularia	5.9	6.0	7.1	7.3
Proportion resistant to one or more of the diseases	67%	82.5%	100%	100%

*Disease resistance ratings run on a scale from 1 – 9, with 9 being the most highly resistant

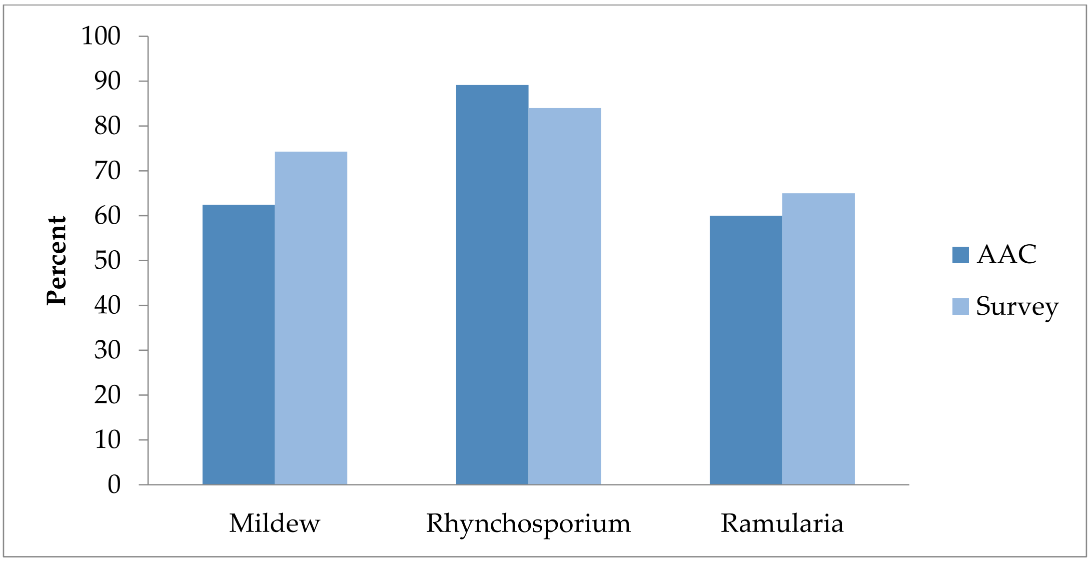


Figure 5-2: Percent of varieties in AAC and Survey which are below the best choice for that year (mean across all years) for the specified disease

Table 5-7: Best choice versus actual uptake of varieties in the AAC (expressed as a percentage of varieties recorded)*

		2015			2014	
Rating	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium	Ramularia
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%

Table 5 – 7 (continued)

	2013			2012			2011	
Rating	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium	Ramularia	Mildew	Rhynchosporium
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%

Table 5 – 7 (continued)

	2010		**2009**	
Rating	Mildew	Rhynchosporium	Mildew	Rhynchosporium
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)

Barley market

The potential market (as determined from the Recommended List) for AAC varieties is compared with the farmer survey data in Figure 5-5, below. The percentage of varieties which could be used in each market was comparable between the two sources, with a large majority having the potential to be sold for Distilling/Grain Distilling in both the AAC (73%) and the farmer survey (84%).

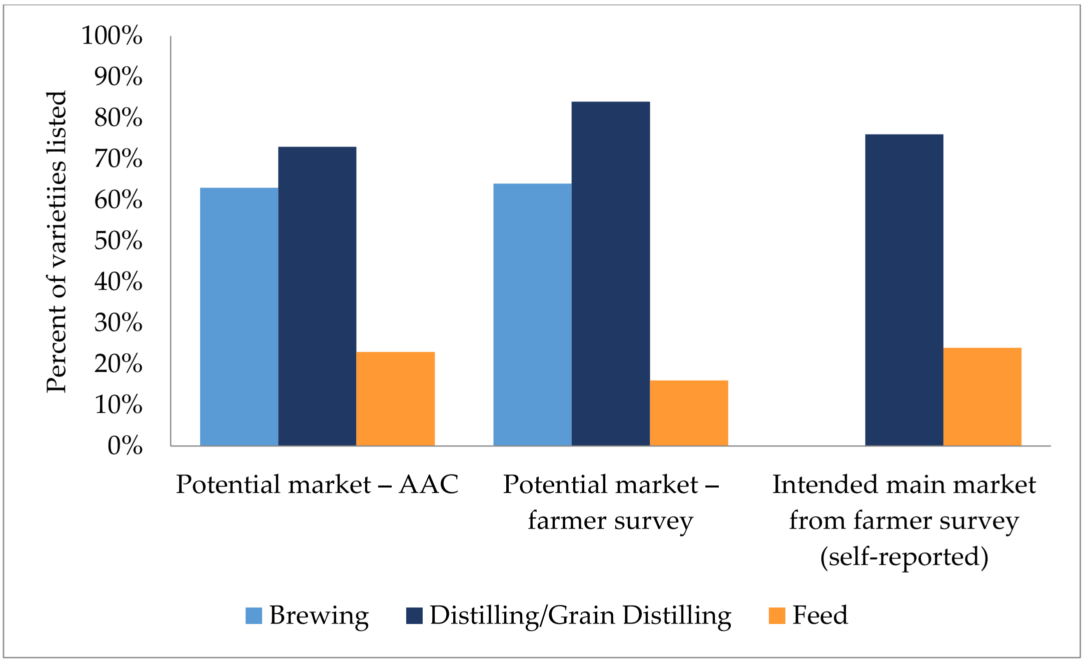


Figure 5-3: Comparison of the potential market(s) for each variety in the AAC and farmer survey, and the intended market in the farmer survey (number of crops reported: percent suited to market)

5.3.2 Rotation information

Despite a large amount of variation in previous crop, the majority of fields had been sown with either consecutive barley or consecutive cereals (see Table 5-8). This mirrored the farmer survey results (see Figure 5-4), 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 5-9). While the percent of fields with continuous barley or cereals varied across years, there was no clear trend showing any increase or decrease in this practice, with a majority of fields having continuous barley/cereals each year (see Figure 5-5).

Table 5-8: Previous rotation information from the AAC (out of a total of 552 fields)

Previous crop		Number of fields with this as previous crop
Bean		1
Beetroot		1
Fallow		1
Kale		1
Leek		1
Winter oilseed rape		1
Pea		2
Swede		2
Winter oats		2
Spring wheat		3
Spring oats		5
Winter barley		13
Potato		17
Grass		32
Winter wheat		71
Spring barley		326
	Total	479
Cereals (barley, oats, wheat)		420
Barley (winter and spring)		339

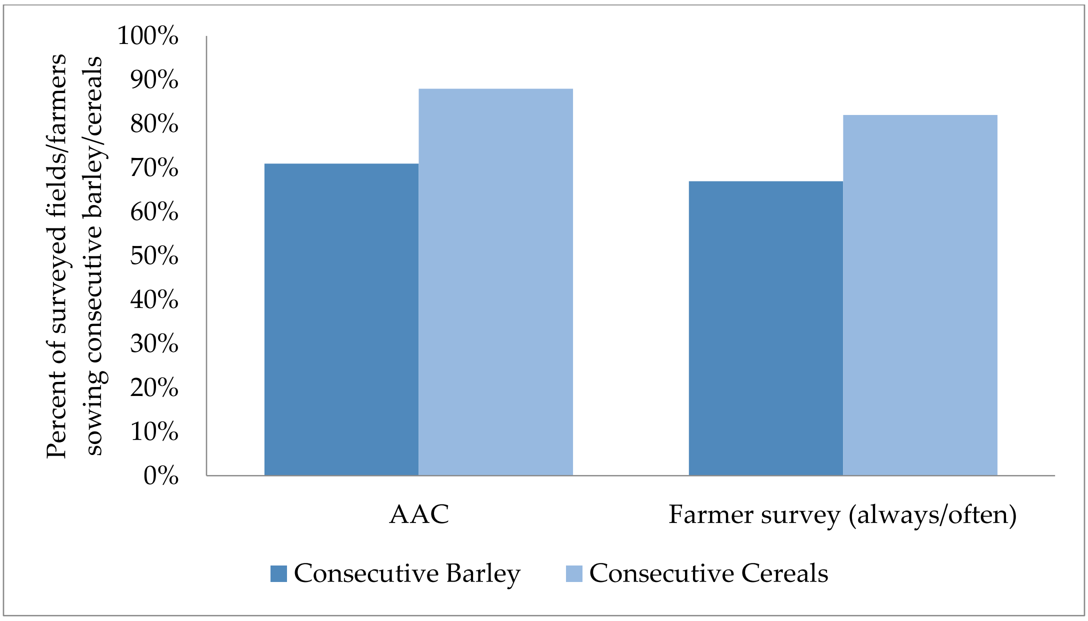


Figure 5-4: Comparison of percentage of AAC fields and farmer survey responses indicating consecutive barley/cereals

Table 5-9: 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)
Mildew	7.4	7.6	7.5	7.9
Rhynchosporium	4.5	4.6	4.4	4.6
Ramularia	6.2	6.3	6.2	6.1

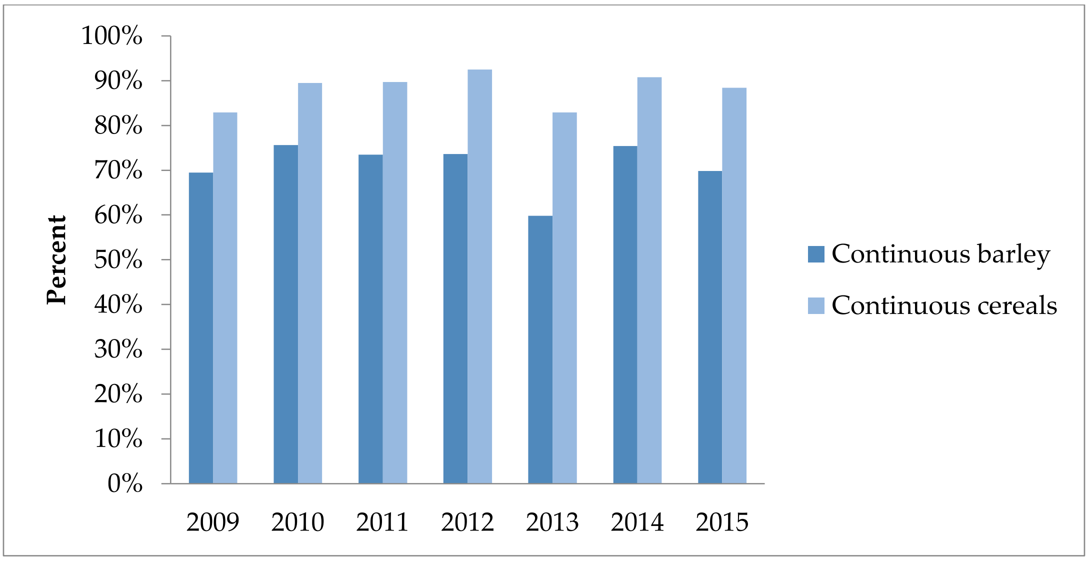


Figure 5-5: Variation in percent of AAC fields sowing continuous barley/cereals by year

5.3.3 Geographical information

The AAC data was 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 (ERSA) (see Table 5-10). Both exceptions, North East and Tayside, had a higher proportion of farms reported in the AAC than in the ERSA, but were within 20% of the ERSA figures. Geographical spread in the AAC also matched well with that reported in the farmer survey, with both showing higher proportions of farmers located in the North East than in ERSA figures; however variation between proportions for the Scottish Borders and Tayside were substantial (see Table 5-10). 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.

The variation in the proportion of highly resistant varieties or consecutive barley/cereal sowing across sub-regions is summarised in Table 5-11). Some differences in varietal resistance across regions were evident, with fluctuations from 0% of varieties being highly resistant to two or more diseases to 30% - however, this never exceeded one-third in any sub-region. Only one sub-region in the AAC had less than 50% of farmers sowing consecutive barley, suggesting that this is a common practice across the country, though differences in prevalence are visible. The minimum proportion of farmers sowing consecutive cereals in the AAC was 60%, 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%).

Table 5-10: Comparison of regional spread of data from AAC, farmer survey, and Field Trials database to Scottish Government statistics, expressed as a proportion of the number of fields/farms surveyed in each*

Sub-region	AAC		Percent farms included in Economic Report on Scottish Agriculture (2015)	Percent farms included in farmer survey	Percent farms in Field Trials database (1996 – 2014)
	Number of farms	Percent of farms			
Ayrshire	20	3.6%	4.8%	-	-
Clyde Valley	8	1.5%	5.6%	0.2%	10.7%
Dumfries & Galloway	19	3.4%	6.1%	0.2%	5.4%
East Central	14	2.5%	2.6%	2.3%	-
Fife	17	3.1%	3.6%	0.5%	4.5%
Highland	57	10.3%	19.9%	23.3%	-
Lothian	26	4.7%	3.4%	2.3%	46.4%
North East	210	38%	19.7%	34.9%	1.8%
Orkney	15	2.7%	3.6%	-	-
Scottish Borders	62	11.2%	4.7%	16.3%	14.3%
Tayside	104	18.8%	8.6%	1%	17%
Total	552				

*Shaded green if more than 10% of what is seen in ERSA, or orange if 10% less than ERSA figures

Table 5-11: Variation of farming practices across sub-regions in the AAC expressed as a proportion of AAC data

Sub-region	Percent of varieties highly resistant to two or more diseases	Percent of fields with consecutive barley	Percent of fields with consecutive cereals
Ayrshire	30.0%	50.0%	60.0%
Clyde Valley	12.5%	85.7%	100%
Dumfries & Galloway	15.8%	75.0%	100%
East Central	28.6%	75.0%	91.7%
Fife	0.0%	76.9%	100%
Highland	3.5%	88.9%	94.4%
Lothian	3.8%	55.0%	90.0%
North East	17.6%	81.1%	91.8%
Orkney	0.0%	66.7%	66.7%
Scottish Borders	11.3%	42.4%	83.1%
Tayside	6.4%	60.8%	82.3%

Table 5-12: Number of reports and proportion of varieties approved for each market reported in AAC drilled in each sub-region by market

Sub-region	Number of times feed varieties were reported	Number of times Distilling/Grain Distilling/Brewing varieties were reported	Total number of fields in the AAC
Ayrshire	11	9	20
Clyde Valley	7	1	8
Dumfries & Galloway	5	14	19
East Central	6	8	14
Fife	1	16	17
Highland	9	48	57
Lothian	3	23	26
North East	15	195	210
Orkney	9	6	15
Scottish Borders	19	43	62
Tayside	11	93	104
Total	96	456	552

5.3.4 Comparison of the AAC, farmer survey data, and Field Trials database

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 are therefore broadly comparable.

5.4 Discussion

5.4.1 Key opportunities to improve commercial practice

Considering current practice as recorded in the AAC, the potential for improving integrated pest management decisions regarding varietal choice and crop rotation seems appreciable. There is substantial scope for improving disease resistance in the varieties sown in the AAC, as less than one third of varieties were highly resistant to Ramularia, Rhynchosporium, or two or more diseases, and less than two thirds were highly resistant to mildew. This finding echoes research on wheat production in the UK, which found a majority of farmers chose to grow high yielding but low resistance varieties (Ilbery et al., 2013; Defra, 2003). The AAC data had a lower proportion of varieties in the Recommended List in a given year as compared to the farmer survey data, suggesting a possible difference between the AAC and survey groups. However, market possibilities, mean disease resistance ratings, and variety popularity had strong similarities between the two data sources.

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. The lack of diversity in rotations used was also 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 which does not rely on figures taken directly from farming records (such as that collected by ADAS, 2002 and Maye et al., 2012) may be less reliable than the data presented in the Scottish Government report, which underwent three levels of validation, as farmers have been found to alter answers to present more socially acceptable responses (Vanclay et al., 2006). There is no evidence in the AAC data that farmers are 'trading off' one IPM technique 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 pressure on farm.

5.4.2 Comparison of conclusions from Field Trials analysis, farmer survey work, and AAC

The AAC, as it covers a large number of farms and was not gathered at events where IPM was widely discussed, can provide a useful comparison of general farming practice in Scottish spring barley to the results found in the Field Trials analysis and survey work. The AAC does contain the same self-selection bias inherent in all voluntary recording schemes, and tends towards including farmers who make use of agronomist advice, as up to 50% of farmers are SAC clients. This is likely to encompass a particular sub-set, as small-scale farmers were more likely to be the main decision maker regarding pesticide practice than larger scale operations in ADAS's (2009) survey of pesticide practice in Scotland, and therefore less likely to make use of an independent agronomist. Geographical spread in the AAC and the farmer survey does not reflect the spread seen in the Scottish Government reports perfectly, so there are also potential regional biases at work.

The analysis undertaken in Chapter 2 and Chapter 3 of this thesis of the Field Trials database suggests that season rainfall and disease resistance are important factors when considering the impact of fungicide use on yields. Survey results from Chapter 4 indicate that some farmers are willing to take up disease resistant varieties, rotations, and forecasting disease pressure – there is therefore no inherent attitudinal problem which prevents farmers from using these IPM techniques. The AAC results add to this picture, by confirming that in a larger sample of farmers, rotation practices and varietal resistance usage could be substantially improved upon. Further analysis including forecasting of disease pressure would be useful in expanding this work linking commercial practice with farmer 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.

No other research projects were found in the literature which integrated Field Trials, stakeholder surveying, and commercial practice data. Rola and Pingali's (1993) review of rice production did incorporate these three sources, and suggested that rice farmers in the Phillipines overestimated the impacts of pesticides on rice yields, and that there was scope for increasing and improving rotation use; however, this was based on a number of previously published experiments, rather than being a single research project. This multi-source approach has proven particularly useful in the current work, as it allowed IPM, a fundamentally multi-faceted management approach, to be analysed through a number of lenses.

5.4.3 Future work

Similar crop monitoring platforms to the AAC exist in the UK, such as CropMonitor, which collects and disseminates information from monitoring sites across England about key pests and diseases of winter wheat, spring beans, and potatoes (Crop Health & Protection, 2017). CropMonitor data has been used to produce risk maps and tools, such as the Rothamsted phoma leaf spot and light leaf spot forecasts for oilseed rape (Rothamsted Research, 2017a; Rothamsted Research, 2017b) but its archives have not been analysed for wider research purposes to date. AHDB provides some disease and pest monitoring and forecasting services, but these are based on measurements at specific trial sites across England and Scotland, rather than collected from a wide range of commercial farms (AHDB, 2016a). A commercial software, GateKeeper, which provides crop recording and management services, provides data from their users for research purposes; in theory this information could be used to assess IPM uptake, though it has not yet been put to this use (Farmplan Gatekeeper, 2017). Future research could expand upon the analysis presented in this chapter, to link these other sources of commercial data to Field Trial and survey information, to provide a view of IPM uptake and potential across the whole UK, and for a range of other crops.

5.5 Conclusions

Similar to the results found in the farmer survey from Chapter 4, the AAC data highlights the gap between best IPM and current practices. Previous work has shown that cereal farmers use less than optimal varieties (Defra, 2003) and rotations (Scottish Government, 2012). However, the AAC presented a unique opportunity to review commercial practice specifically for spring barley across a large sample. The results from this analysis indicate that there is scope for IPM practices in Scottish spring barley to be improved, and thus that there is potential for rationalising fungicide use, reducing disease pressure and the negative environmental impacts of fungicide reliance.

Chapter 6 Discussion

6.1 Importance of IPM

Integrated Pest Management presents potential opportunities to aid in solving a major dilemma of our time: how can high crop yields be maintained while minimising the use of environmentally damaging inputs. Crop diseases have the potential to be a limiting factor to yield (Gaunt, 1995), while fungicide use can provide a number of benefits, such as reducing the spread of diseases to new areas (Cooper & Dobson, 2007). Their use can also have detrimental effects on the environment, including soil health (Walia et al., 2014), biodiversity (Geiger et al., 2010), and water pollution (FAO, 1996), thereby reducing sustainability over the long-term. Studies assessing IPM systems across a range of economic and environmental factors, such as resource use and biodiversity, have found these systems to be more environmentally sustainable than conventional farming, where standard programmes of pesticide use to control disease are relied upon, in several crops (Pelzer et al., 2012; Mouron et al., 2012). IPM can encompass a variety of techniques, each of which provides a different approach to managing disease and pest burdens. The three techniques explored in this thesis – planting highly disease resistant varieties, using diverse crop rotations, and forecasting disease pressure – are aimed at preventing a build-up of pathogens, thus reducing the need for fungicide interventions.

6.2 Possibilities for IPM in Scottish spring barley

Field Trials analysis has highlighted the fact that fungicide treatment did not significantly increase yields in the majority (65%) of trials from 2011 – 2014 (see Chapter 2). The mean impact of fungicide use on field trials was 0.62 t/ha in 2011 – 2014, well below the 1 – 2 t/ha impact that 70% of farmers estimated. For the full 1996 – 2014 dataset, the overall yield difference between treated and untreated plots was 0.74 t/ha (see 3.3.1 Absolute Yield Difference). Regressions analysis indicated that, for the full 1996 – 2011 dataset, yield differences between treated and untreated fields were significantly higher in wet seasons than under average rainfall conditions, and that yield differences were significantly lower where the variety sown was highly resistant to one or more diseases (see Chapter 3). The finding that fungicide treatment does not necessarily lead to higher yields in cereal crops has also previously been reported in several long-term experiments (Wiik & Ewaldz, 2009; Wiik, 2009; Cook & Thomas, 1990). Previous work has also demonstrated both the relationship between rainfall and increased yield impact from spraying (Wiik & Ewaldz, 2009; Regev et al., 1997), and that between disease resistance and reduced yield impact (Loyce et al., 2008; Mazzilli et al., 2016; Sundell, 1980 cited in Wiik & Rosenqvist, 2010). However these relationships have not hitherto been verified in the barley production system. Forecasting disease pressure by considering rainfall predictions within the season may therefore be of use in determining when fungicide application is likely to benefit yields, though a formal risk forecasting tool would need to be produced and validated to facilitate uptake of this technique. Previous assessments of the gap between actual yield impacts of spraying and farmer estimates were not found in the literature for cereal crops, and provides a useful insight into the likely motivations for widespread fungicide use in the industry.

The survey work presented in Chapter 4 also provided insight into the willingness of Scottish spring barley farmers to take up three IPM techniques; using only disease resistant varieties, implementing diverse crop rotations, and fungicide use based on forecasting disease pressure. All three techniques had some proponents who would be willing to adopt these measures on farm, at least in principle, with sowing only disease resistant varieties being slightly more favoured than the others overall. Similarly, both Bailey et al. (2009) and ADAS (2002) reported a large proportion of cereal farmers using resistant varieties (nearly 60% and 88%, respectively). A visible gap between farmer perception and actual practice, however, was highlighted by the fact that a majority of farmers surveyed in Chapter 4 (over 60%) stated they always/often sowed highly resistant varieties for all three diseases of concern, while less than a third of the varieties listed by these same farmers were, in fact, highly resistant to two of these diseases (Rhynchosporium and Ramularia). Similar gaps between farmer perception and practice have been noted before, e.g. where farmer stated agri-environmental practices or objectives were not associated with actual adoption (Niles et al., 2016; Guillem et al., 2012), or where social desirability bias affected farmer responses (Vanclay et al., 2006), though not in the context of IPM uptake.

Using the AAC data to further assess the scope for greater uptake of IPM practices across a larger sample of the farming population, once again, the potential for improving the uptake of better varietal disease resistance was evident, with well under one-third of varieties sown being highly resistant to Rhynchosporium and Ramularia, and under 60% to mildew (see Chapter 5). Market forces for malting barley are likely at play in this low level of resistance, yet even if farmers were to choose from only varieties with full malting and distilling approval, there is still scope to improve varietal resistance, as evidenced by the fact that 81% of varieties reported by farmers in the survey had lower disease resistance ratings for Rhynchosporium than the best choice malting approved variety for that year. Similar results have been reported from surveys in France, where only 56% of surveyed wheat farmers used a variety which was resistant to one or more diseases (Nave et al., 2013).

Lack of crop rotation was evident in both the AAC and survey data, with roughly 70% of farmers from both sources having planted consecutive spring barley. That the rotations used and varietal resistances are often less than ideal has been previously reported in UK cereal farming (Bailey et al., 2009; ADAS, 2002). Although the exact reasons why these IPM techniques are not more widely used probably vary, work on wheat in England suggests farmer perceptions regarding the impact of production risks on profit may play a key role (Ilbery et al., 2013). The actual relationship between input use and profit margin is not clear, however, with studies on wheat finding fungicide application to be cost effective in less than 50% (Wiik & Rosenqvist, 2010) or 70% (Cook & Thomas, 1990) of situations in long-term studies, and medium input systems to be more economically efficient than high or low input systems overall (Nave et al., 2013).

In an IPM context, then, there is potential for fungicide application to be coupled with alternative management solutions to reduce the need for high inputs and optimise both fungicide use and profitability. The preliminary economic analysis presented in Chapter 2, based on the Field Trials data for 2011 - 2014, however, suggests that farmers may be overestimating the economic benefits of spraying fungicide, as actual profit increases were estimated to be below 5% on average. The AAC indicated there is potential for improving IPM uptake, the survey indicated that farmers are open to taking up these IPM techniques, and the Field Trials analysis indicated that using disease resistant varieties and forecasting disease pressure could reduce the impact of fungicide use on yield. Increased IPM uptake could therefore feasibly reduce the need for fungicide use while maintaining high yields in Scottish spring barley. If appropriately planned, future policy interventions promoting or requiring IPM on farm could therefore be useful in reducing fungicide use without negatively impacting on production.

6.2.1 Wider benefits of and risks associated with IPM uptake

Pesticide application has, historically, been useful in reducing pest damage to crops. However, Integrated Pest Management, which may include the use of pesticides in certain situations, can provide several important benefits, apart from maintaining high yields by managing pathogen populations. Firstly, where fungicide levels are reduced and yields are maintained, greenhouse gas emissions intensities related to crop production may be cut back. Reduced impacts on human health may also be realised, as the types of fungicides used in the Scottish spring barley system pose potential direct health risks to humans. For example, epoxiconazole (a DMI) is classed as a probable human carcinogen (Pesticide Properties DataBase, 2017d), azoxystrobin (a strobilurin) has been noted as a liver toxicant, and eye and skin irritant (Pesticide Properties DataBase, 2017a), chlorothalonil, a broad-spectrum fungicide, is a known carcinogen (Pesticide

Properties DataBase, 2017c), and bixafen (a SDHI) may be a thyroid and liver toxicant (Pesticide Properties DataBase, 2017b). All four of these fungicide active ingredients are also toxic to birds, honeybees, earthworms and most aquatic organisms, though the level of toxicity varies (Pesticide Properties DataBase, 2017d; Pesticide Properties DataBase, 2017a; Pesticide Properties DataBase, 2017c; Pesticide Properties DataBase, 2017b). Reduced fungicide use may therefore also increase biodiversity and reduce negative impacts on potentially beneficial organisms to agriculture, such as earthworms and honeybees. Finally, reducing the quantity of fungicide applied to crops has been suggested as a way of reducing the speed at which pathogens develop resistance to fungicides (Brent & Hollomon, 2007), thus providing additional time to develop and test new chemical controls. This may be particularly beneficial, as there is moderate to high risk of fungicide resistance developing in mildew, Ramularia, and Rhynchosporium populations to several key fungicide groups, as discussed in Chapter 1 (Fungicide Resistance Action Group UK, 2015).

In contrast to the benefits of reduced fungicide use described above as part of IPM, such a shift might increase reliance on host plant resistance. This could raise the potential for pathogens to overcome varietal resistance, though this can be mitigated to some extent by the use of a number of host resistance strategies. One such strategy is stacking or pyramiding resistance genes, whereby a variety is bred to have multiple genes which confer resistance to a given pathogen, in order to make it more difficult for the pathogen to overcome the plants' resistance (Burdon et al., 2016). Additionally, working at the landscape scale to ensure a number of varieties with differing genetic resistance types are sown in a given area or region can help to prevent pathogen resistance development by reducing evolutionary pressure on the pathogen (Burdon et al., 2016). Using other IPM practices could also assist, but some, such as diverse crop rotations may also pose an economic risk, as farmers are unable to change crops based on the most profitable product in a given year. However, the long-term benefits of rotations which can include increased soil fertility and decreased disease build-up may be sufficient to compensate for any short-term economic losses, as a review of eight studies testing the use of break crops in wheat production in Northern Europe found an average yield increase of 24% (Kirkegaard et al., 2008). Forecasting disease pressure and altering spray programmes based on the likely incidence of disease carries the potential for mistaken predictions, with potentially devastating consequences for yield losses if unexpected epidemics occur. There may therefore be a need for disease risk forecasts for Scottish spring barley which not only pair local weather information with decision assessments, but which also allow for a range of risk attitudes to be accommodated, such that highly risk averse farmers can choose to spray at lower risk levels than others. Lower dose rates, or fewer applications of fungicide might be recommended for farmers willing to take larger risks, while risk averse farmers might be recommended to reduce fungicide use only when forecasts predict low disease pressure with a high level of certainty. Additionally, while research into a forecasting system for Ramularia is ongoing (Havis, 2017 – personal communication), an updated model for mildew building on Channon's (1981) work, and a model for Rhynchosporium would need to be developed prior to their being able to be used in a commercial setting. Given that the most highly ranked factor impacting the decision to apply fungicides was in-field assessment of growth stage in the farmer survey (see Chapter 4), many farmers are already comfortable with using key factors as triggers for management action. This may make uptake of forecasting technologies more straightforward, though it is unclear from the present study whether farmers consider these key growth stages to be indicators of disease pressure or risk. While the risks from IPM uptake can be minimised through careful management strategies and thoughtful decision making, there may also be a case for the increased use of crop insurance in Europe, as is common in the US, in order to temper the potential effects of particularly difficult seasons (Lefebvre et al., 2014). The use of a number of IPM strategies in concert, alongside fungicide where spraying is necessary to prevent epidemics, can prevent pressure on any given strategy to prevent disease outbreaks individually. IPM uptake, where appropriately implemented alongside risk reduction strategies, therefore offers the potential to reduce fungicide use and human health risks, deliver environmental benefits such as increased biodiversity, and maintain high yields.

6.2.2 Novelty of the research

This thesis draws on long-term field trials to produce stepwise regression models of management factors in Scottish spring barley, an output which was not found in previous literature. The stakeholder surveying in this project provides a useful addition to current knowledge regarding IPM from a social science perspective, as little has been published in this area thus far. The commercial data used to assess the potential for uptake of IPM in Scotland has not previously been analysed, and therefore provides new information regarding current practice. While interdisciplinary research has been recognised as being of particular use in optimising IPM (Birch et al., 2011), no studies could be found in the literature which used such a diverse range of data to assess IPM potential – 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.

6.2.3 Contribution to scientific knowledge

Though previous studies have reviewed key factors influencing yield in wheat (Wiik & Ewaldz, 2009; Wiik, 2009; Cook & Thomas, 1990) and oilseed rape (Yuen et al., 1996; Twenström et al., 1998), work on barley to date does not appear to have included long-term experiments assessing the impact of fungicide use on yields. The work presented in Chapter 3 represents the first models developed to consider the impacts of disease severity and integrated pest management strategies on yield differences between treated and untreated spring barley. Other studies comparing the results from long-term, short term, and high and low precision data as seen in Chapter 3 could not be found in the literature. Given the differences between the final models produced for the long and short term datasets, further research on this question would be of use in assessing the potential advantages and downsides of each type of data source. A previous assessment of the potential of

IPM uptake which combines information from long-term field trial datasets, stakeholder surveying, and a database of commercial practice in a single research project was also not found in the literature.

This work provides interdisciplinary insight into IPM in Scottish spring barley, and highlights a useful method for assessing IPM in other systems. While calls have been made for more integration of stakeholder engagement into agricultural and environmental research to improve research quality and relevance (Murray-Rust et al., 2014; Lefebvre et al., 2014; Gramberger et al., 2015; Phillipson et al., 2012; Lamichhane et al., 2016), there remain relatively few surveys of pest and disease control attitudes and methods amongst cereal farmers. Those few papers dealing with this topic do not attempt to link the outcomes to biological data, epidemiology, or crop models (Ingram, 2008; Ilbery et al., 2013; Maye et al., 2012; Ilbery et al., 2012; Bailey et al., 2009; ADAS, 2002). This thesis 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. Such a synthesis can be of use in encouraging farmers to take up IPM measures, as it provides information about a range of scenarios and across a number of farm conditions. In addition, this approach could provide policy recommendations with both modelling outputs assessing IPM efficacy over a prolonged period of time and farmer survey work which shows there is not only a willingness to take up these IPM measures but also a gap within which to improve upon current practice.

The findings of this project show that there are IPM measures which have the potential to reduce the need for fungicide use, and which are not currently widely taken up by farmers. Interventions, in the form of governmental policies and regulations, increasing farmer awareness of the efficacy of such techniques, and incentivising uptake could all potentially aid in increasing the use of these techniques. More stakeholder engagement during the development of new IPM techniques, policies, and barley varieties could also be beneficial, in order to understand what barriers to uptake exist for each, and how these can be overcome, and ensure that new measures are fit for purpose.

6.3 Limitations of the research

Using long-term information, such as the Field Trials data, creates both difficulties and opportunities for research. 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. Over the course of the SRUC Field Trials database's lifespan, experimental protocols and data management procedures have changed, leaving gaps and asymmetrical data availability (e.g. unbalanced and incomplete data sets). In particular, the lack of plot level data for 1996 – 2014, and the difficulty of obtaining field-specific weather data restricts the type of analysis which can be undertaken. However, assessing fields over nearly two decades allows a wide range of weather conditions, natural pathogen pressure variation, crop rotation patterns, and varieties to be considered.

One drawback to the use of the Field Trials database is the possible buffering effects of disease from using small fields, where untreated plots are close to treated ones (see Chapter 2 for an example field plan). It is possible that this Field Trial set up has led to a reduction in disease severity in the untreated plots as compared to what would be seen if a commercial field were left untreated, due to a lack of build-up of inoculum in nearby plots. Unfortunately, it is very difficult to assess the impact this may have had on disease levels and yields. Recent work on maize in the USA has found an impact of plot size on disease, whereby larger plots showed higher impacts of fungicide use on yields than smaller plots (Tedford et al., 2017), and other studies have shown an increase in disease severity in larger plots than small for septoria leaf blotch (caused by *Septoria tritici*) in wheat and net blotch (caused by *Pyrenophora teres*) in barley in Morocco (Burleigh & Loubane, 1984).

However, the implications for Scottish spring barley systems are not clear from this limited work. The fields and plot sizes used in the Field Trials database (between 20 – 40m^2) are within the recommendations from the efficacy evaluation of plant protection products testing standards (European and Mediterranean Plant Protection Organization, 2012), and fall within the common range for plant disease epidemiology studies. Barber et al. (2003) and Wegulo et al. (2012) relied on plots of approximately 9m^2 to assess fungicide effects, while Wiik (2009) used plots of 40m^2 and Cook and Thomas (1990) 40m^2 to 80m^2. Additionally, border effects, whereby plants at the edge of plots have greater access to key resources such as light and water (Hall & Wallace, 1975), can impact a larger proportion of plants in smaller plots, though random sampling can go some way towards addressing this issue. Gaining access to larger, commercial sized fields, while potentially useful, is simply impractical for many research projects due to resource constraints, and finding true replicate fields would be extremely difficult, due to the uniqueness of each field.

In this project, yield has been the sole metric of barley production to be analysed – other considerations, such as grain quality, have not been included in assessments of the impacts of fungicide use. This decision was taken in order to ensure a focus on what has often been the main aim of farmer-centric disease and fungicide use research (Dyke & Slope, 1978; Pinnschmidt & Jørgensen, 2009; Sutton & Steele, 1983; Cook & Thomas, 1990; Gaunt, 1995; Wegulo et al., 2012; Lim & Gaunt, 1986; Priestley & Bayles, 1982; Martens et al., 2014; Wiik & Ewaldz, 2009; Hysing et al., 2012), and one which aligns with a key concern of farmers – that yields are not negatively impacted by management changes (Ilbery et al., 2013; ADAS, 2002; Sherman & Gent, 2014). Including other factors, such as grain quality, which are also of concern to farmers (Ilbery et al., 2013) and decision makers (Lefebvre et al., 2014) could provide a useful additional dimension to further studies, though additional data would need to be sourced, for this, as the Field Trials database coverage of grain quality is sparse.

Combining the modelling work done on the Field Trials database with surveying of farmers adds to the relevance of the overall findings. However, it is important to bear in mind that the sample of farmers surveyed in Chapter 4 is likely biased by discussion of IPM as an artefact of the survey methods (which aimed to maximise response rate). 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 on 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. The farmer surveys are skewed towards larger cereal farms, and it is possible the AAC shares this bias, due to being made up in large proportion of farms which make use of agronomists (SAC consulting). While specialist cereal (more than two thirds of income coming from cereals and oilseeds) and general cropping (more than two thirds of income coming from all crops) farms in Scotland tend to be larger than other farm types – 62% of general cropping and 54% of cereal farms were 50 hectares or larger, as compared to mixed farms (where no enterprise contributes more than two thirds of income), where over 60% were under 10ha (Scottish Government, 2015a) – the results presented here may not be representative of smaller scale barley production. Expanding this snapshot picture of large scale Scottish spring barley farmer opinion in future work could give a broader understanding of IPM potential.

6.3.1 Future work in this area

Expanding the analysis done on spring barley to include the other crops and their respective diseases recorded in the Field Trials database, such as wheat, oilseed rape, or winter barley could provide useful information for other sectors. Spring barley production made up 45% of land devoted to arable crops in Scotland in 2016; expanding the analysis presented to include all barley, wheat, and oilseed rape would provide information about IPM potential for 80% of Scotland's arable land in 2016 (Scottish Government, 2016a). This could be particularly useful where multiple crops share the same pathogen, as may be the case for Ramularia, which has been reported in wheat and oats in addition to barley (Havis et al., 2015), as strategies for IPM control could be optimized by considering all hosts together to prevent inoculum build up. IPM recommendations could then be formulated for a whole range of crops and disease systems, optimizing fungicide use across arable farms in Scotland.

The work presented in Chapter 4 suggests that while farmers and agronomists are generally open to taking up IPM measures, there is a gap between self-reported perceived and actual practice. The reason behind this gap was not explored in the current research project, but could be key to understanding what barriers exist to IPM uptake, and could be explored in future in-depth surveys or interviews of farmers. Larger-scale farmer engagement could also provide useful inputs in future, building on the small survey conducted in this project. Current UK-Irish IPM work is being carried out by which will gather information about attitudes towards and uptake of IPM across a wide range of farmers, and should provide useful data for scaling up the work presented here (Creissen, 2017- personal communication).

The Field Trials analysis suggested that season rainfall is a key factor in determining whether or not applying fungicides will increase spring barley yields. Forecasting disease pressure could therefore be a useful IPM tool for farmers, though further work is needed to link within season weather forecasting with fungicide impacts, and to create a forecasting tool which is practical for on-farm use. That fungicide applications do not reduce risk to revenues in dry conditions has been reported before (Regev et al., 1997), and a number of risk forecasts and models for a range of arable crops include weather variables as key elements (Wiik &

Ewaldz, 2009; Wallwork, 2007; Twenström et al., 1998). However, despite their potential utility, there are currently no disease risk forecasts for Rhynchosporium or Ramularia which could be used by Scottish spring barley farmers. A forecasting system for mildew was developed for Scotland nearly forty years ago (Channon, 1981), but its accuracy may be reduced, given that the varieties sown and fungicides used have changed substantially in the intervening years. Previously, leaf wetness at stem extension alone was used to predict Ramularia development, but this was discontinued in 2016 as this simple, single predictor was not accurate in all seasons – a risk forecasting model for Ramularia is currently under development which will include leaf wetness along with other risk factors of importance (Havis, 2017- personal communication). No such models were found in the literature for Rhynchosporium, nor do any appear to be in progress. A risk forecasting model which encompassed multiple diseases, and which adapted its forecast based on varieties sown and weather variables would be a valuable tool for farmer decision making.

Finally, the gap between the 'best possible' and actual varieties sown by farmers in both the survey chapter 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. In the AAC, less than half the varieties sown by farmers were equal to the resistance ratings for the 'best choice' cultivar in that year, on average (see Chapter 5). Further research into what is preventing the widespread uptake of these varieties is needed to pinpoint the barriers to uptake. 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, feed buyers, and farmers themselves, to ensure that new varieties provide viable alternatives to current varieties, which match the needs of both farmers and industry. Discussions could, for example, take place through a steering committee, involving nominated representatives of the aforementioned stakeholders, and guided by surveys of larger groups of stakeholders. Recommendations could be given by this group as to key priorities for future breeding, as well as a revised Recommended List system, which better meets the needs of the producers, processors, and end-users. The UK Recommended List system, managed by AHDB, favours high yielding varieties, which can be automatically added to the Recommended List if their yield is more than 2% higher than control varieties – while minimum standards are in place to exclude varieties with very low disease resistance, there may be scope to value resistance ratings more highly in the Recommended Lists (AHDB, 2015). 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 & Brosnan, 2014). Using new varieties can therefore pose a risk to their production systems. Previous work (Vanloqueren & Baret, 2008) on the under-adoption of highly resistant varieties of wheat in Belgian systems has found twelve key factors which prevent uptake, including 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. An increase in IPM uptake in Scottish spring barley will require further research to assess the current constraints and develop solutions to provide farmers and decision makers with the tools they need to take action.

Greenhouse gas emissions resulting from fungicide use have not been considered in this thesis, though where inputs are being reduced without impacting yield it is reasonable to assume there will be a concurrent reduction in emissions intensity. Audsley et al. (2009) have estimated 254 MJ of energy input per hectare of spring barley for fungicide manufacture and use – with a factor of 0.069 kg CO_2 equivalent per MJ, this equates to 17.53 kg CO_2 equivalent per hectare of spring barley from fungicide in the UK. Greenhouse gas emissions from the application of fungicide to Scottish spring barley can therefore be roughly estimated to have been 5,070 tonnes CO_2 equivalent in 2014, based on the 289,222 hectares sown in that year (Scottish Government, 2014). This represents a small proportion of all emissions from agricultural activities, which reached approximately 10.7 million tonnes in Scotland in 2014 (Scottish Government, 2015d). Much of the emissions from the arable sector is accounted for by nitrogen fertilizer application, which is estimated at 879 kg CO_2 equivalent per hectare for spring barley with a fertilizer level of 110 kg N/ha by AgRE Calc (2014), including embedded emissions related to delivery to the farm, residues, and indirect emissions. Using these estimates, spring barley production could therefore have emitted approximately 25,400 tonnes of CO2 equivalent in 2014. However, where the benefit from fungicide application is minimal, fungicide use reductions could feed into the Scottish Government's targets for greenhouse gas emissions reductions of 42% of the 1990 baseline by 2020 (Scottish Parliament, 2009). Further work is needed to assess the extent to which fungicide optimisation could reduce emissions. Whether the application of fungicide to a crop increases or decreases the intensity of CO_2 emissions from production is, however, dependent upon the impact on crop yields. Where yields are increased by fungicide use, greenhouse gas emission intensities per tonne can be decreased, as seen in wheat production in the UK (Berry et al., 2008). However, in Berry et al.'s (2008) work, wheat yields were increased by an average of 1.78 t/ha. The work presented in this thesis found a mean increase in yield of only 0.74 t/ha in trials from 1996 – 2014, and, in the 2011 – 2014 data, where this could be assessed, that yield differences were not statistically significant in a majority of cases. Further work comparing the greenhouse gas emissions from treated and untreated plots in the Field Trials database for barley and other crops could provide useful information about the potential wider environmental impact of fungicide application. An assessment of the impact of disease severity on nitrogen uptake in the plant could provide useful information about the potential impacts of disease on emissions, regardless of yield impacts. Similarly, more detailed cost-benefit analysis could improve upon the estimate presented in Chapter 2. Risks from non-application of fungicide will vary widely from season to season, and farm to farm – while the initial estimates made in this thesis suggest low levels of financial loss from eschewing fungicide use (less than 5% of profits), more in-depth scenario analysis would provide more reliable measurements, which may be of more use for farmers and policy makers. Other benefits from reducing fungicide use may also accrue – including improved soil health (Chen et al., 2001), and increased biodiversity and ecosystem functioning in the surrounding waterways (McMahon et al., 2012) – which should be taken into account when assessing the relative merits and risks of IPM systems.

6.3.2 **IPM and regulation**

Following the EU CAP reform for 2014 – 2020, the Scottish and UK governments are required to promote IPM uptake (Lefebvre et al., 2014). The Scottish government has acted upon this by promoting an IPM planning tool for farmers (Scottish Government, 2016c), and has committed itself to reducing pesticide use in agriculture (Scottish Executive, 2006). Thus, despite the uncertainty about agricultural policies in the UK and Scotland following the probable exit of the United Kingdom from the European Union, it is likely that IPM will remain a focus of future agricultural policies. The AHDB's (2017b) recent report on the future of crop protection policy in the UK speculates that the reduction of pesticide use may even become more of a focus. Within this context, there are several mechanisms by which the research from this thesis could be used by government in order to reduce fungicide use and maintain high yields in Scottish spring barley. Minimum disease resistance standards could be developed for Scotland (and further afield), to ensure that only varieties with adequate resistance to key diseases are sown. This approach has been taken in Australia, as a method to reduce rust (caused by *Puccinia triticina*, *P. graminis*, and *P. striiformis*) levels in wheat, where minimum levels are set based on a number of risk factors at regional level – this programme has been met with widespread uptake and farmer enthusiasm (Wallwork, 2007). The use of highly resistant varieties is well suited as a long-term, wide-ranging strategy, as the

Australian programme acknowledges; resistance is useful within a given farm and a given year, as it reduces infection/disease levels, but it is most effective where it is used across farms and years, as it can reduce the levels of inoculum in the environment, thus reducing risk at the landscape scale (Wallwork, 2007; Loyce et al., 2008). Despite the fact that research has previously shown host resistance to be a profitable measure for controlling fungal disease (Sundell, 1980; Hysing et al., 2012), a large number of farmers in the AAC did not sow highly resistant varieties. Disease resistance was picked up on in the Field Trials regressions as being important in determining the impact of fungicide use on yields – intervention could therefore be highly effective on this issue. Providing an incentive to reduce fungicide use, such as a specific tax on pesticide use could also help to encourage a reduction in use. However, recent attempts in Denmark do not seem to have reduced pesticide use to the expected extent (10% reduction being the initially intended goal) (Pedersen et al., 2015; Böcker & Finger, 2016). Incentives or rewards for taking up IPM may therefore provide a useful approach, and one which has been suggested to be more effective in agri-environmental schemes, as behavioural changes in this sector are complex and multi-faceted (Barrett et al., 2016). Farmer Field Schools have been successfully used to encourage IPM uptake in developing countries (Feder et al., 2008), and could provide a useful alternative to the standard top-down approach of information delivery in Scottish systems as well, by allowing farmers to trial IPM methods on their own farms and share findings within the group. New EU policies may also contribute to uptake of IPM measures in the near future, though an obvious shift was not visible in the AAC data for 2015, as features such as the crop diversification rule, which requires farmers with over 30ha to grow at least three crops at any given time (European Commission, 2017), though as it is not specifically forbidden to grow the same three crops in the same fields for multiple years, crop rotation is not an automatic outcome. Governments could also promote the use of disease resistant cultivars and forecasting disease pressure through a number of less direct mechanisms – subsidising the development of resistant cultivars, educating farmers and other stakeholders involved in producing and using barley about the merits of IPM techniques, or funding research to produce accurate and user-friendly disease forecasting systems could all help to improve the outlook of IPM uptake.

6.3.3 Key Messages

Analysis of the Field Trials dataset highlighted the variability of treatment impact on yield (in the 2011 – 2014 data) and some key management and weather factors influencing yield difference (in the 1996 – 2014 data). Using long term data provided the opportunity to assess a range of different field conditions, with different combinations of varieties, weather, and disease pressure. This variation is useful in order to provide farmers and policy makers with information about the overall effects of a given management technique on yield differences. However, as the database was collected for other purposes, issues relating to the cleaning and preparation of the data arose, leading to a lack of plot-level information which would have allowed more detailed analysis of the trial results. Following standard operating procedures and forward planning are important to ensure that long running datasets are of maximum value for future research, as is a flexible approach when analysing long term information.

Stakeholders were aware of key disease risks in spring barley, however, in a majority of cases this did not lead to use of highly resistant varieties, or diverse crop rotations. Farmers also overestimated the impact of fungicide use on yield levels, as well as their own use of IPM techniques. Management decisions are therefore being taken in an environment of incorrect perceptions, the reasons for which are unclear. Further research is needed to understand why these misconceptions occur, and how they can be remedied, for example through further training and research dissemination, as improving uptake is likely to prove difficult while such gaps between perception and practice persist. Involving stakeholders in research, both in terms of understanding current barriers to uptake and co-producing new innovations, may benefit future research in IPM and increase the practicality of research outputs.

6.4 Conclusions

The work presented in this thesis indicates a gap between the willingness to take up IPM in surveyed farmers and the actual uptake of IPM measures both in surveyed and AAC farms. Additional research is needed to more fully understand the reasons for this gap, barriers to uptake of IPM, and the incentives needed to convert willingness into action. However, increasing the use of highly resistant varieties is a relatively straight-forward measure which could be encouraged by the Scottish Government, and taken up by farmers quickly, following dialogue with end-users, as suitable cultivars already exist. More varied crop rotations could be taken up by commercial spring barley farmers in Scotland, potentially reducing inoculum sources and disease pressure. The immediate utility of forecasting disease pressure is somewhat limited by the lack of formal disease risk forecasts for Rhynchosporium, mildew, and Ramularia. However, even without formalised disease forecasting technology, farmers and agronomists can use the information presented in this thesis – that wet seasons are linked to high yield differences between treated and untreated crops – to adjust spraying based on regional forecasts. Farmers and agronomists can also undertake their own surveillance of crops to tailor inputs to the diseases present, as well as making more use of sources of information such as the Adopt-a-Crop database, in order to stay informed about in-season risks and potentially reduce inputs on crops where fungicide is unlikely to give significant yield increases. The findings of this project therefore support the hypothesis that there is potential for IPM uptake to be improved in Scottish spring barley production, thereby reducing fungicide use without negatively effecting yield levels. In addition, the unusual and interdisciplinary approach taken in this work, combining field trials, stakeholder surveying, and commercial data provides a template which may be useful in assessing IPM in other contexts around the world.

Chapter 7 References

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Chapter 8　Appendices

8.1 Appendix A – Fungicide treatments used in the Field Trials database (1996 – 2014)

Year	Trial code	GS at first treatment	First treatment	GS at second treatment	Second treatment	GS at third treatment	Third treatment
2014	1863	32	Siltra Xpro 0.5*				
2014	1873	30-32	Siltra Xpro 0.4	39-49	Siltra Xpro 0.6		
2014	1877(1403)	25-30	Proline275 0.36 + Comet 0.5	53	Siltra Xpro 0.5		
2014	1877(1404)	25-30	Proline275 0.36 + Comet 0.5	53	Siltra Xpro 0.5		
2014	1878	31	Siltra Xpro 0.5	49	Proline275 0.175 + Bravo 1.0		
2014	1884	30-31	Siltra Xpro 0.6	39-45	Siltra Xpro 0.6		

2014	1885	30-31	Siltra Xpro 0.6	55-61	Siltra Xpro 0.6		
2014	1889	25-31	Siltra Xpro 0.4	45	Siltra Xpro 0.6		
2014	1906	31	Siltra Xpro 0.6	45	Siltra Xpro 0.6		
2014	1908	31	Siltra Xpro 0.6	39-45	Siltra Xpro 0.6		
2014	1909	45-49	Siltra Xpro 0.6				
2014	1919	30-31	Proline 0.4 + Flexity 0.24	59	Siltra Xpro 0.4 + Bravo 0.5		
2013	1746	25-30	Flexity 0.25 + Comet 0.5				
2013	1747	39-45	Siltra Xpro 0.5 + Bravo 1.0				
2013	1750	30-32	Siltra Xpro 0.5	39-49	SiltraXpro 0.5 +		

					MCW296 1.0
2013	1752	39-45	Adexar 1.0		
2013	1763	30-31	Siltra Xpro 0.6	39-45	Siltra Xpro 0.6 + Bravo 500 1.0
2013	1764	30-31	Siltra Xpro 0.6	55-59	Siltra Xpro 0.6
2013	1784	45-49	Siltra Xpro 1.0		
2013	1790	31	Siltra Xpro 0.5	59	Proline275 0.175 + Bravo 0.5
2013	1791	31	Siltra Xpro 0.5	49	Proline275 0.175 + Bravo 0.5
2013	1800	N/A**	Siltra Xpro 0.6	N/A	Fandango 0.8
2012	1585	25-30	Proline 275 0.36	49	Siltra Xpro 0.5

			+ Comet 0.5		
2012	1620	31	Siltra Xpro 0.5	39	Proline 275 0.175 + Bravo 0.5
2012	1625	31	Proline 0.35 + Bravo 1.0	45	Siltra 0.5 + Bravo 1.0
2012	1626	31	Adexar 0.75	39-49	Adexar 0.75
2012	1634	30-31	Siltra Xpro 0.6	39-45	Siltra Xpro 0.6 + CTL 1.0
2012	1659	25-30	Siltra Xpro 0.6	45-49	Siltra Xpro 0.6
2012	1664	25-30	Siltra Xpro 1.0	45-49	Siltra Xpro 1.0
2012	1665	N/A	Siltra Xpro 0.6 + Bravo 1.0	N/A	Siltra Xpro 0.6 + Bravo 1.0

2012	1675	31	Siltra Xpro 0.5	39-45	Siltra Xpro 0.5
2011	1517	31	Fandango 1.0	39-45	Siltra Xpro 0.5 + Bravo 1.0
2011	1519	25	Proline 275 0.35 + Bravo 1.0 + Flexity 0.25	49	Bontima 1.2 + Bravo 1.0
2011	1523	23-30	Proline 275 0.36 + Comet 200 0.625	39-45	Proline 275 0.36 + Comet 200 0.625
2011	1524	39 – 43	Siltra Xpro 0.6		
2011	1525	39 – 43	Siltra Xpro 0.6		
2011	1547	39	Siltra Xpro 1.0		

2011	1557	30-31	Siltra Xpro 0.5	45	Tracker 1.0 + Bravo 1.0		
2010	1422	25	Proline 275 0.36	49	Bravo		
2010	1423	25-30	Fandango 1.0 + Flexity 0.25	49	Proline 0.4 + Bravo 1	49	Prothioconazole250 0.4 + Bravo 1.0
2010	1424	25-30	Fandango 0.75	45-49	Fandango 0.75 + Bravo 1.0		
2009	1345	23-30	Fandango 0.75	39-45	Fandango 0.75		
2009	1331	No available data					
2008	1224	25-30	Proline 0.3 + Bravo 1.0	39-49	Fandango 0.75 +Bravo 1.0		
2007	1124	25-30	Proline 0.3 +	39 - 49	Fandango 0.75		

			Bravo 1.0		+Bravo 1.0
2007	1125	25	Proline 0.3 + Bravo 1.0	45-49	Fandango 0.75 +Bravo 1.0
2007	1127	25-30	Kayak 0.75 + Proline 0.3	39 - 49	Amistar Opti 0.75 + Proline 0.2
2007	1128	25 – 30	Proline 0.3 + Bravo 1.0	39 - 40	Fandango 0.75 +Bravo 1.0
2006	1037	25 – 30	Amistar opti + Unix	45 - 49	Amistar opti + Proline
2006	1038	25	Proline + Bravo	45-49	Fandango + Bravo
2005	938	N/A	Fandango 0.75 + Torch Extra	N/A	Fandango 0.75 +

			0.3		CTL 1.0	
2005	943	25 – 30	Proline 0.4 + Vivid 0.5	59	Bravo 1.0	
2004	843	N/A	JAU/HEC 0.65	N/A	JAU/HEC 0.65	
2004	844	N/A	Unix 0.4 + Acanto 0.4	N/A	Opus 0.4 + Amistar 0.4 + Bravo 1.0	
2004	845	N/A	Acanto 0.4 + Unix 0.4	N/A	HEC/JAU 1.0 + Bravo 1.0	
2004	846	N/A	HEC/JAU 0.75	N/A	HEC/JAU 0.75 + CTL 1.0	
2004	848	N/A	Jenton 1.0 + Unix 0.4	N/A	Vivid 0.5 + Opus 0.5 +	

					Bravo 1.0
2004	849	N/A	Jenton 1.0 + Opus 0.4	N/A	Opus 0.4 + Amistar 0.4 + Bravo 1.0
2004	860	N/A	Sanction 0.5 + Unix 0.4 + KQ926 0.1		
2004	882	N/A	Unix 0.4 + Acanto 0.4	N/A	Opus 0.4 + Amistar 0.4 + Bravo 1.0
2003	749	N/A	Unix 0.4 + Acanto 0.4	N/A	Amistar 0.4 + Opus 0.4
2003	750	N/A	Acanto 0.4 + Unix 0.4	N/A	Bravo

2003	751	N/A	Landmark 0.5	N/A	Landmark 0.5
2003	756	N/A	Landmark 0.5	N/A	Landmark 0.5
2002	487	25-30	Unix 0.5	45	Unix 0.5
2002	691	N/A	Unix 0.4 + Twist 0.8	N/A	Opus 0.4 + Twist 0.8
2001	605	25 – 30	Twist 125 EC 1.0 + Unix 0.4	39 - 49	Twist 125 EC 1.0 + Unix 0.4
2001	606	25 – 30	Punch C 0.47	49	Punch C 0.31
2000	489	25-30	Landmark 0.4	39-45	Landmark 0.4
2000	490	N/A	Unix 0.4 + Corbel 0.35	N/A	Unix 0.4 + Twist 1.0
2000	491	30	Unix 0.3+ Corbel	39-49	Sanction 0.2+

			0.3		Twist 0.8		
2000	516	31	Caramba 0.25	39	Caramba 0.25		
2000	523	21	Fortress 0.1				
1999	338	26-30	Punch C 0.4				
1999	340	26-30	Amistar 0.4 + Corbel 0.4	39-49	Opus 0.25 + Amistar 0.4		
1999	341	26 – 30	Amistar 0.4 + Corbel 0.4	39 - 49	Amistar 0.4 + Corbel 0.4		
1999	342	26 – 30	Amistar 0.6 + Corbel 0.5	39 - 49	Amistar 0.6 + Corbel 0.5		
1998	149	14-21	Tilt 0.125 + Corbel 0.25	26 - 30	Sanction 0.15 + Corbel 0.3	45 - 49	Sanction 0.15 + Corbel 0.5

1998	152	26 – 30	Sanction 0.15 + Corbel 0.3	45	Sanction 0.15 + Corbel 0.5
1998	156	24 – 30	Punch C 0.4		
1998	157	24 – 30	Sanction 0.3 + Corbel 0.5	52	Opus 0.5 + Corbel 0.5
1997	zensb1997	14 – 22	Alegro 0.75	45	Alegro 0.75
1996	sbhop1996	26 – 30	Opus 0.25 + Corbel 0.25	45 - 51	Opus 0.25 + Corbel 0.25
1996	sbrenny1996	15 – 22	Sanction 0.125 + Corbel 0.25	37	Sanction 0.125 + Corbel 0.25
1996	sbspot1996	N/A	Punch C 0.4		
1996	zensb1996	29	Sanction 0.2 +		

	Corbel 0.38

*Numbers next to the fungicide names indicates the application dose used for that fungicide

**N/A indicates that growth stage information was not available for these trials

8.2 Appendix B – Impact of treatment on yield and disease severity for all 2011 – 2014 trials

Trial	Year	Location	Yield	Mildew AUDPC	Ramularia AUDPC	Rhynchosporium AUDPC	Total AUDPC
1519 Belgravia	2011	BRY*	Not significant**	Not significant	Significant	Not significant	Significant
1519 Concerto	2011	BRY	Not significant	Not significant	Significant	Not significant	Significant
1058 (1105) Optic	2011	BRY	Significant	Significant	Significant	Significant	Significant
1523 Optic	2011	BLL	Significant	Not significant	Not significant	Not significant	Not significant
1519 Optic	2011	BRY	Significant	Significant	Significant	Not significant	Significant
1524 Optic	2011	DIN	Significant	Not significant	Significant	Significant	Significant
1557 Optic	2011	BIE	Not significant	No Disease	No Disease	Not significant	Not significant
1525 Optic	2011	BLL	Not significant	Not significant	Significant	Not significant	Not significant

Trial	Year	Location	Yield	Mildew AUDPC	Ramularia AUDPC	Rhynchosporium AUDPC	Total AUDPC
1547 Waggon	2011	BLL	Not significant	Significant	Significant	Significant	Significant
1659 Concerto	2012	BDE	Significant	Not significant	Not significant	Significant	Significant
1664 Concerto	2012	DIN	Not significant	No Disease	Not significant	Significant	Significant
1620 (1201) Concerto	2012	DIN	Not significant	No Disease	Significant	Not significant	Not significant
1665 Concerto	2012	CAU	Not significant	Not significant	Significant	Significant	Not significant
1625 Optic	2012	CAU	Significant	Not significant	Significant	Significant	Significant
1659 Optic	2012	BDE	Significant	Significant	Significant	Significant	Not significant
1675 Optic	2012	BIE	Not significant	No Disease	Not significant	Not significant	Not significant
1620 (1201) Optic	2012	DIN	Not significant	No Disease	Significant	Significant	Significant

Trial	Year	Location	Yield	Mildew AUDPC	Ramularia AUDPC	Rhynchosporium AUDPC	Total AUDPC
1634 Optic	2012	BLL	Not significant	No Disease	No Disease	Significant	Significant
1585 (1203) Optic	2012	CAU	Not significant	Significant	No Disease	Not significant	Not significant
1626 Waggon	2012	BLL	Significant	Not significant	Not significant	Not significant	Not significant
1659 Westminster	2012	BDE	Not significant	No Disease	Significant	Significant	Significant
1791 Belgravia	2013	BLL	Not significant	Not significant	No Disease	Not significant	Not significant
1790 Concerto	2013	DIN	Not significant	No Disease	Not significant	Not significant	Not significant
1750 Concerto	2013	DIN	Not significant	No Disease	Not significant	Not significant	Not significant
1763 Concerto	2013	BLL	Not significant	No Disease	No Disease	No Disease	No Disease
1800 Concerto	2013	CAU	Not significant	No Disease	No Disease	No Disease	No Disease

Trial	Year	Location	Yield	Mildew AUDPC	Ramularia AUDPC	Rhynchosporium AUDPC	Total AUDPC
1764 Optic	2013	DIN	Not significant	No Disease	Not significant	Not significant	Not significant
1790 Optic	2013	DIN	Not significant	No Disease	Not significant	Significant	Significant
1884 Concerto	2014	DIN	Significant	No Disease	Not significant	Significant	Significant
1873 Concerto	2014	DIN	Not significant	Not significant	No Disease	Not significant	Not significant
1919 Concerto	2014	BLL	Significant	No Disease	No Disease	Significant	Significant
1906 Concerto	2014	BDE	Not significant	Not significant	Not significant	Not significant	Not significant
1885 Concerto	2014	BLL	Significant	No Disease	Significant	Significant	Significant
1889 Concerto	2014	BLL	Significant	No Disease	Not significant	Significant	Significant
1908 Concerto	2014	CAU	Significant	No Disease	No Disease	Not significant	Not significant

Trial	Year	Location	Yield	Mildew AUDPC	Ramularia AUDPC	Rhynchosporium AUDPC	Total AUDPC
1877(1404) Optic	2014	DIN	Significant	No Disease	No Disease	Not significant	Not significant
1877(1403) Optic	2014	CAU	Not significant	Significant	No Disease	Not significant	Significant
1877(1404) Overture	2014	DIN	Not significant	No Disease	No Disease	Significant	Significant
1878 Overture	2014	DIN	Not significant	No Disease	Significant	Not significant	Not significant
1877(1403) Overture	2014	CAU	Not significant	No Disease	No Disease	No Disease	No Disease
Number not significant			26	12	12	20	18
Percent not significant			65%	30%	30%	50%	45%

* Farm locations are coded as follows: Burnside – BDE, Balruddery – BRY, Balgonie – BIE, Boghall – BLL, Cauldshiel – CAU, Drumalbin - DIN

**Significance of difference between treated and untreated values was tested at $p<0.05$ using ANOVA.

8.3 Appendix C – Most frequently used fungicides in the Field Trials database (1996 – 2014)

	Most common fungicide(s) and their active ingredients*		Second most common fungicide(s) and their active ingredients
2014	Siltra Xpro		Proline
	Bixafen, prothiconazole		Prothioconazole
2013	Siltra Xpro		Bravo
	Bixafen, prothiconazole		Chlorothalonil
2012	Siltra Xpro		Bravo
	Bixafen, prothiconazole		Chlorothalonil
2011	Siltra Xpro		Bravo
	Bixafen, prothiconazole		Chlorothalonil
2010	Bravo	Fandango	Opus
	Chlorothalonil	Prothioconazole, fluoxastrobin	Fenpropimorph, epoxiconazole

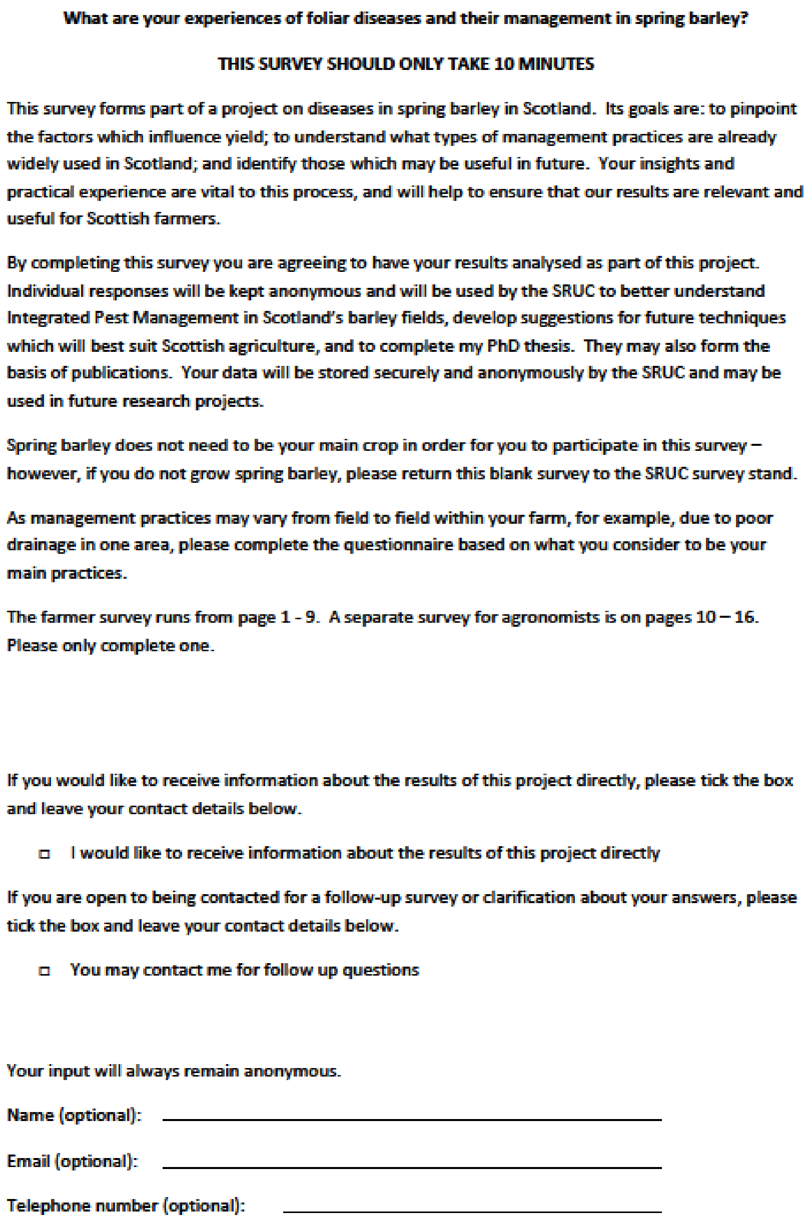
2009	Fandango			
	Prothioconazole, fluoxastrobin			
2008	Bravo			
	Chlorothalonil			
2007	Bravo			Proline
	Chlorothalonil			Prothioconazole
2006	Amistar	Bravo	Proline	
	Azoxystrobin	Chlorothalonil	Prothioconazole	
2005	Fandango			
	Prothioconazole, fluoxastrobin			
2004	Opus			Unix
	Fenpropimorph, epoxiconazole			Siprodinil

2003	Landmark			Acanto	Unix	
	Epoxiconazole, kresoxim-methyl			Cyprodinil, picoxystrobin	Siprodinil	
2002	Unix			Twist		
	Siprodinil			Trifloxystrobin		
2001	Unix			Twist	Punch	
	Siprodinil			Trifloxystrobin	Flusilazole, carbendazim	
2000	Unix			Corbel	Landmark	Twist
	Siprodinil			Fenpropimorph	Epoxiconazole, kresoxim-methyl	Trifloxystrobin
1999	Amistar			Corbel		
	Azoxystrobin			Fenpropimorph		

1998	Corbel	Sanction
	Fenpropimorph	Flusilazole
1997	Alegro	
	Epoxiconazole, Kresoxim-methyl, fenpropimorph	
1996	Corbel	Sanction
	Fenpropimorph	Flusilazole

*Active ingredients are listed below the fungicide name. Single occurrence fungicides are not included in this table. Where multiple fungicides are listed as ‘most common’ or ‘second most common’ in a given year, this indicates that they occurred the same number of times in the database.

8.4 Appendix D – Farmer and agronomist survey



What are your experiences of foliar diseases and their management in spring barley?

THIS SURVEY SHOULD ONLY TAKE 10 MINUTES

This survey forms part of a project on diseases in spring barley in Scotland. Its goals are: to pinpoint the factors which influence yield; to understand what types of management practices are already widely used in Scotland; and identify those which may be useful in future. Your insights and practical experience are vital to this process, and will help to ensure that our results are relevant and useful for Scottish farmers.

By completing this survey you are agreeing to have your results analysed as part of this project. Individual responses will be kept anonymous and will be used by the SRUC to better understand Integrated Pest Management in Scotland's barley fields, develop suggestions for future techniques which will best suit Scottish agriculture, and to complete my PhD thesis. They may also form the basis of publications. Your data will be stored securely and anonymously by the SRUC and may be used in future research projects.

Spring barley does not need to be your main crop in order for you to participate in this survey – however, if you do not grow spring barley, please return this blank survey to the SRUC survey stand.

As management practices may vary from field to field within your farm, for example, due to poor drainage in one area, please complete the questionnaire based on what you consider to be your main practices.

The farmer survey runs from page 1 - 9. A separate survey for agronomists is on pages 10 – 16. Please only complete one.

If you would like to receive information about the results of this project directly, please tick the box and leave your contact details below.

- ☐ I would like to receive information about the results of this project directly

If you are open to being contacted for a follow-up survey or clarification about your answers, please tick the box and leave your contact details below.

- ☐ You may contact me for follow up questions

Your input will always remain anonymous.

Name (optional): ______________________________

Email (optional): ______________________________

Telephone number (optional): ________________________

Section 1: Demographic Questions

1. **What is your profession?**
    - ☐ Farmer
    - ☐ Agronomist (please skip to page 10)
    - ☐ Other – at this time we are only looking for responses from farmers or agronomists
2. **Age**

☐ 16 – 24 ☐ 25 – 34 ☐ 35 – 44 ☐ 45 – 59 ☐ 60 – 74 ☐ 75+

3. **Education (tick highest applicable)**
    - ☐ Degree (BSc, BA, MSc, MA, PhD or equivalent)
    - ☐ Further education at college (HND, HNC, etc.)
    - ☐ Higher, A level, or equivalent
    - ☐ Standard grade, GSCE or equivalent
    - ☐ Vocational qualification
    - ☐ No qualifications
4. **Is your farm mixed animal and arable, or solely arable?**
    - ☐ Mixed
    - ☐ Arable
    - ☐ Animal only – at this time we are only looking for responses from arable and mixed farmers
5. **What size is your farm in total (including rented land)?**
    - ☐ 0 – less than 20 ha
    - ☐ 20 – less than 50 ha
    - ☐ 50 – less than 100 ha
    - ☐ 100 – less than 200 ha
    - ☐ 200 – less than 500 ha
    - ☐ 500 – less than 1000 ha
    - ☐ More than 1000 ha
6. **On average, how many hectares are devoted to spring barley in a given year?**
    - ☐ 0 – less than 20 ha
    - ☐ 20 – less than 50 ha
    - ☐ 50 – less than 100 ha
    - ☐ 100 – less than 200 ha
    - ☐ 200 – less than 500 ha
    - ☐ 500 – less than 1000 ha
    - ☐ More than 1000 ha
7. **What region is your farm located in?**
    - ☐ Eileanan an Iar
    - ☐ Highlands
    - ☐ Orkney
    - ☐ Shetland
    - ☐ Argyll and Bute
    - ☐ North East Scotland
    - ☐ Tayside
    - ☐ East Central
    - ☐ Fife
    - ☐ Lothians
    - ☐ Clyde Valley
    - ☐ Ayrshire
    - ☐ Dumfries & Galloway
    - ☐ Scottish Borders
    - ☐ Other, please specify: ____________________

8. Which ONE of the following markets do you grow the majority of your spring barley for?

☐ Brewing
☐ Distilling/Malting
☐ Animal Feed
☐ Human consumption

9. Does your farm have any specific certifications/organisation affiliation or are you a member of any specific agri-environmental schemes (please indicate all that apply, even if this is not applicable to the entire farm)

- Organic
- LEAF
- Agri-Environmental Scheme
- Other, please specify: ________________

10. Do you own or rent your farm?

☐ Own
☐ Rent
☐ Own ___hectares, rent ____ hectares
☐ Other, please specify: _______________

11. What proportion of your spring barley is contract farmed?

☐ All ☐ Most ☐ Some ☐ A little ☐ None

Section 2: Varieties

12. What spring barley varieties have you sown in the past 5 years? Please list as many as you can remember – if you have sown multiple varieties in a given year, please order based on the number of hectares devoted to each, such that 1 has the largest acreage.

- 2015
  1.
  2.
  3.
- 2014
  1.
  2.
  3.
- 2013
  1.
  2.
  3.
- 2012
  1.
  2.
  3.
- 2011
  1.
  2.
  3.

13. **How important are the following to your decision about which variety(ies) of spring barley you plant?**

a. Agronomist suggestion

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

b. Suggestion from/grown by another successful farmer in my area

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

c. Market demand for a particular variety

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

d. Having prior experience with the variety on my farm

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

e. Varietal disease resistance rating

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

f. Variety had malting/brewing certification

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

For the purposes of questions 14 – 16, a disease resistant variety is defined as one with a minimum ranking of 7 out of 9 in the Scottish Cereals Recommended List for that year.

14. **In relation to Mildew, please indicate which ONE of the following statements best describes the spring barley varieties you sow:**
    - ☐ Only sow disease resistant varieties
    - ☐ Often sow disease resistant varieties
    - ☐ Sometimes sow disease resistant varieties
    - ☐ Rarely sow disease resistant varieties
    - ☐ Never sow disease resistant varieties
    - ☐ Unsure
15. **In relation to Ramularia, please indicate which ONE of the following statements best describes the spring barley varieties you sow:**
    - ☐ Only sow disease resistant varieties
    - ☐ Often sow disease resistant varieties
    - ☐ Sometimes sow disease resistant varieties
    - ☐ Rarely sow disease resistant varieties
    - ☐ Never sow disease resistant varieties
    - ☐ Unsure

16. In relation to Rhynchosporium, please indicate which ONE of the following statements best describes the spring barley varieties you sow:

☐ Only sow disease resistant varieties
☐ Often sow disease resistant varieties
☐ Sometimes sow disease resistant varieties
☐ Rarely sow disease resistant varieties
☐ Never sow disease resistant varieties
☐ Unsure

Section 3: Previous Rotations

17. Rank the following factors in order of their influence on your decision to use a general crop rotation, with 1 being the most important and 6 the least important. (If you do not use a rotation, please skip to the next question)

___ To reduce disease
___ I have always used this rotation
___ To spread risk of low yields/crop failure
___ Recommendation from an agronomist
___ Other successful farmers in my area use this rotation
___ Other, please specify: _______________

18. If you do not use a rotation, please rank the following reasons in terms of how large a part they play in your decision not to use a rotation, with 1 being the most important and 5 being the least important: (if you use rotations, please skip onto the next question)

___ Lack of necessary equipment
___ Need to fulfil contracts for main crop
___ Do not think rotations are beneficial in terms of yield
___ Do not think rotations are beneficial in terms of disease
___ Other, please specify: _______________

19. Regardless of whether or not you use a rotation, how often do you sow barley in the same field for two or more consecutive seasons (e.g. spring barley followed by spring barley?)

☐ Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never

20. How often do you sow cereals in the same field for two or more consecutive seasons (e.g. winter wheat followed by winter barley?)

☐ Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never

Section 4: Fungicide use

21. How often do you apply fungicides to your spring barley crops?

☐ Every year ☐ Most years ☐ Some years ☐ Rarely ☐ Never

22. Rank the following in in terms of their influence on your decision to apply fungicides to your spring barley crop, with 1 being the most important and 7 the least important:

___ Weather forecasting

___ Independent expert advice (i.e. agronomist from SRUC, ADAS, AHDB, etc.)

___ Trade or distribution advice (i.e. representative from seed or pesticide company)

___In-field assessment of growth stage

___Other farmer's advice/actions

___ Spraying by calendar date

___ Other, please specify: _______________

23. How much (in t/ha) do you think fungicide use increases spring barley yields by?

☐ Less than one tonne per hectare
☐ 1 - 2 tonnes per hectare
☐ 2 - 3 tonnes per hectare
☐ 3 - 4 tonnes per hectare
☐ More than 4 tonnes per hectare

Section 5: Main Diseases on Farm

26. How important to yield do you believe foliar diseases of spring barley to be?

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

27. Which ONE of the following foliar diseases do you believe has been the most common on spring barley in the past five years?

☐ Powdery Mildew
☐ Ramularia
☐ Rhynchosporium

28. Which ONE of the following foliar diseases do you consider to have impacted spring barley yield most in the past five years?

☐ Powdery Mildew
☐ Ramularia
☐ Rhynchosporium

Section 6: Fungicide Use in Future

28. Please indicate how strongly you agree/disagree with each of the following statements in relation to spring barley:

a. I think fungicide use can negatively impact the environment

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

b. I am not concerned about fungicide use leading to fungicide resistance

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

c. If I could use less fungicide and achieve the same yields, I would

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

d. I have no concerns about the amount of fungicide I use on my spring barley

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

e. If I could use less fungicide and have it be as cost-effective, I would

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

f. I think finding methods to reduce fungicide use is important

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

29. If the following measures were all cost-effective *alternatives* to using fungicides on spring barley:

a. Which would you be MOST likely to use on your farm?

	Choose ONE	
Sowing only disease resistant varieties	☐ Most likely	☐ N/A (already use)
Planned crop rotation	☐ Most likely	☐ N/A (already use)
Forecasting disease pressure for the season and changing management strategies based on these predictions	☐ Most likely	☐ N/A (already use)

b. Which would you be LEAST likely to use on your farm?

	Choose ONE	
Sowing only disease resistant varieties	☐ Least likely	☐ N/A (already use)
Planned crop rotation	☐ Least likely	☐ N/A (already use)
Forecasting disease pressure for the season and changing management strategies based on these predictions	☐ Least likely	☐ N/A (already use)

30. If the following measures were all cost-effective *complementary* techniques used alongside fungicides on spring barley:

a. Which would you be MOST likely to use on your farm?

	Choose ONE	
Sowing only disease resistant varieties	☐ Most likely	☐ N/A (already use)
Planned crop rotation	☐ Most likely	☐ N/A (already use)
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Most likely	☐ N/A (already use)

b. Which would you be LEAST likely to use on your farm?

	Choose ONE	
Sowing only disease resistant varieties	☐ Least likely	☐ N/A (already use)
Planned crop rotation	☐ Least likely	☐ N/A (already use)
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Least likely	☐ N/A (already use)

31. In terms of implementation for spring barley:

a. Which of the following measures do you think is MOST practical?

	Choose ONE
Sowing only disease resistant varieties	☐ Most practical
Planned crop rotation	☐ Most practical
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Most practical

b.Which of the following measures do you think is LEAST practical?

	Choose ONE
Sowing only disease resistant varieties	☐ Least practical
Planned crop rotation	☐ Least practical
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Least practical

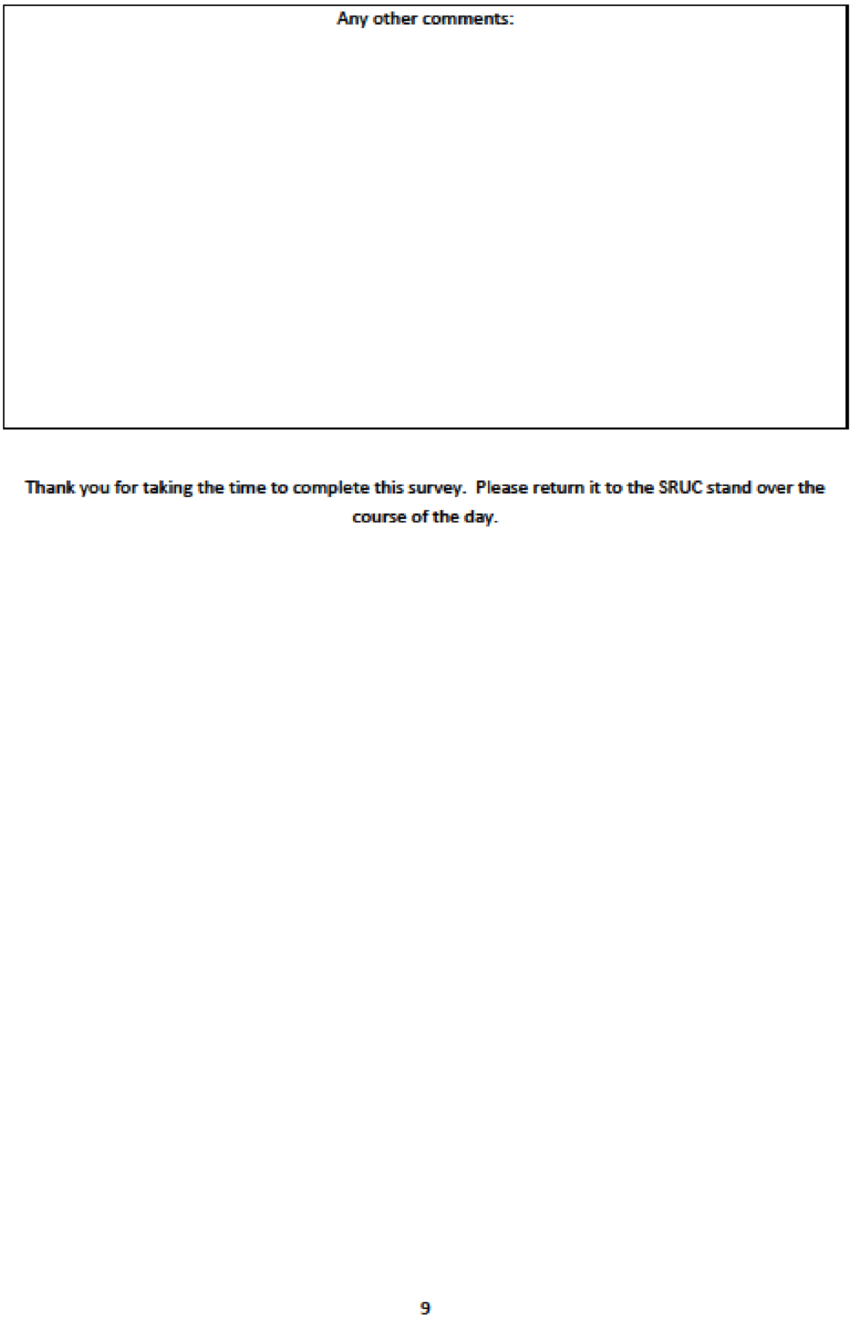
32. In terms of cost of implementation for spring barley:

a. Which of the following measures do you think is MOST practical?

	Choose ONE
Sowing only disease resistant varieties	☐ Most practical
Planned crop rotation	☐ Most practical
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Most practical

b. Which of the following measures do you think is LEAST practical?

	Choose ONE
Sowing only disease resistant varieties	☐ Least practical
Planned crop rotation	☐ Least practical
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Least practical



Any other comments:

Thank you for taking the time to complete this survey. Please return it to the SRUC stand over the course of the day.

Agronomist Survey

Section 1: General Questions

1. **In what region(s) do you mostly advise farmers (tick all that apply)?**

   ☐ Eileanan an Iar
   ☐ Highlands
   ☐ Orkney
   ☐ Shetland
   ☐ Argyll and Bute
   ☐ North East Scotland
   ☐ Tayside
   ☐ East Central
   ☐ Fife
   ☐ Lothians
   ☐ Clyde Valley
   ☐ Ayrshire
   ☐ Dumfries & Galloway
   ☐ Scottish Borders
   ☐ Other, please specify (for anyone outside Scotland)

2. **What products form the majority of your expertise (tick all that apply)?**

   ☐ Wheat
   ☐ Winter Barley
   ☐ Spring Barley
   ☐ Oats
   ☐ Oilseed Rape
   ☐ Triticale
   ☐ Vegetables
   ☐ Potatoes
   ☐ Peas/beans
   ☐ Fruits
   ☐ Animals/animal products
   ☐ Other, please specify: ____________

3. **For which ONE market is the majority of spring barley you discuss destined?**

   ☐ Brewing
   ☐ Distilling
   ☐ Animal Feed
   ☐ Human consumption

4. **Do you work on mixed farms, or solely arable?**

   ☐ Mixed farms only
   ☐ Some mixed farms, some arable farms
   ☐ Arable farms only

5. **Are you affiliated with/a member of any professional organisations?**

   ☐ Scottish Agronomy
   ☐ Association of Independent Crop Consultants
   ☐ SAC consulting
   ☐ Trade/distribution
   ☐ Other, please specify: ____________________

Section 2: Varieties

6. **What spring barley varieties have you advised farmers to sow in the past 5 years?** Please list as many as you can remember – if you have advised multiple varieties in a given year, please order based on the most commonly suggested, such that 1 was the variety you suggested to most farmers that year.
   - 2015
     1.
     2.
     3.
   - 2014
     1.
     2.
     3.
   - 2013
     1.
     2.
     3.
   - 2012
     1.
     2.
     3.
   - 2011
     1.
     2.
     3.

7. **Please rank the following in terms of their importance to your decision about which variety(ies) of spring barley you recommend, with 1 being the most important and 5 being the least important:**

   ___ Suggestion from/grown by another successful farmer in the area

   ___ Having prior experience with the variety on client farms

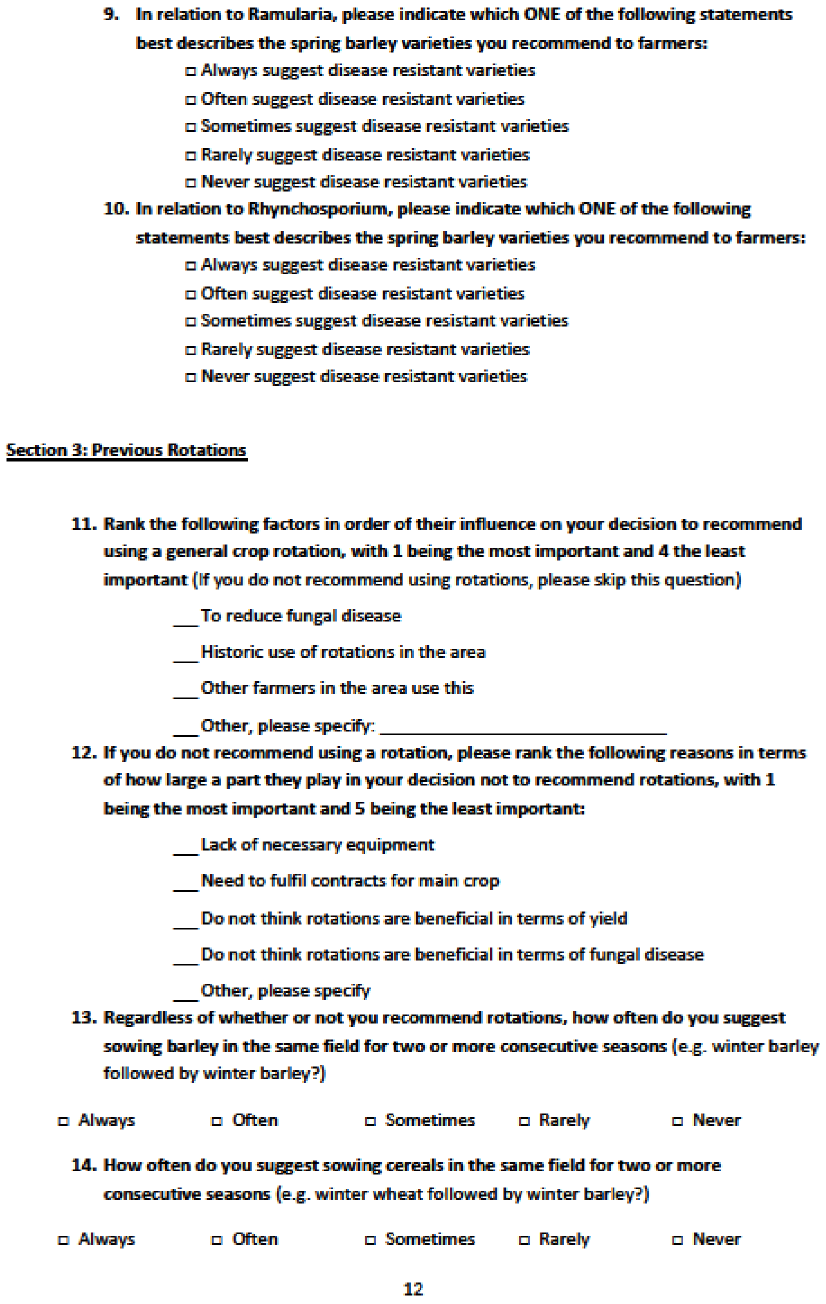
   ___ Varietal disease resistance rating

   ___ Variety had malting/brewing certification

   ___ Other, please specify: _____________________________

For the purposes of questions 8 – 10, a disease resistant variety is defined as one with a minimum ranking of 7 out of 9 in the Scottish Cereals Recommended List for that year.

8. **In relation to Mildew, please indicate which ONE of the following statements best describes the spring barley varieties you recommend to farmers:**
   ☐ Always suggest disease resistant varieties
   ☐ Often suggest disease resistant varieties
   ☐ Sometimes suggest disease resistant varieties
   ☐ Rarely suggest disease resistant varieties
   ☐ Never suggest disease resistant varieties



9. **In relation to Ramularia, please indicate which ONE of the following statements best describes the spring barley varieties you recommend to farmers:**
    - ☐ Always suggest disease resistant varieties
    - ☐ Often suggest disease resistant varieties
    - ☐ Sometimes suggest disease resistant varieties
    - ☐ Rarely suggest disease resistant varieties
    - ☐ Never suggest disease resistant varieties
10. **In relation to Rhynchosporium, please indicate which ONE of the following statements best describes the spring barley varieties you recommend to farmers:**
    - ☐ Always suggest disease resistant varieties
    - ☐ Often suggest disease resistant varieties
    - ☐ Sometimes suggest disease resistant varieties
    - ☐ Rarely suggest disease resistant varieties
    - ☐ Never suggest disease resistant varieties

Section 3: Previous Rotations

11. **Rank the following factors in order of their influence on your decision to recommend using a general crop rotation, with 1 being the most important and 4 the least important** (If you do not recommend using rotations, please skip this question)

    ___To reduce fungal disease

    ___Historic use of rotations in the area

    ___Other farmers in the area use this

    ___Other, please specify: ______________________________
12. **If you do not recommend using a rotation, please rank the following reasons in terms of how large a part they play in your decision not to recommend rotations, with 1 being the most important and 5 being the least important:**

    ___Lack of necessary equipment

    ___Need to fulfil contracts for main crop

    ___Do not think rotations are beneficial in terms of yield

    ___Do not think rotations are beneficial in terms of fungal disease

    ___Other, please specify
13. **Regardless of whether or not you recommend rotations, how often do you suggest sowing barley in the same field for two or more consecutive seasons** (e.g. winter barley followed by winter barley?)

☐ Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never

14. **How often do you suggest sowing cereals in the same field for two or more consecutive seasons** (e.g. winter wheat followed by winter barley?)

☐ Always ☐ Often ☐ Sometimes ☐ Rarely ☐ Never

Section 4: Fungicide use

15. Which ONE of the following statements best describes how often you recommend fungicide use for foliar diseases in spring barley?

Every year to:	**Most years to:**	**Some years to:**	**Rare years to:**	☐ **Never**
☐ Every client	☐ Every client	☐ Every client	☐ Every client	
☐ Most clients	☐ Most clients	☐ Most clients	☐ Most clients	
☐ Some clients	☐ Some clients	☐ Some clients	☐ Some clients	
☐ Rare clients	☐ Rare clients	☐ Rare clients	☐ Rare clients	

16. Rank the following in in terms of their influence on your decision to recommend applying fungicides to spring barley, with 1 being the most important and 6 the least important:

___ Weather forecasting

___ Independent expert advice/information (i.e. SRUC, ADAS, AHDB, etc.)

___ On-farm assessment of crop growth stage

___ Trade or distribution advice/information (i.e. seed or pesticide company)

___ Spraying by calendar date

___ Other successful farmer's actions in the area

17. How much (in t/ha) do you think fungicide use for foliar diseases increases spring barley yields by?

☐ Less than one tonne per hectare
☐ 1 - 2 tonnes per hectare
☐ 2 - 3 tonnes per hectare
☐ 3 - 4 tonnes per hectare
☐ More than 4 tonnes per hectare

Section 5: Main Diseases on Farm

19. How important to yield do you believe foliar diseases of spring barley to be?

☐ Very important ☐ Important ☐ Moderately important ☐ Of little importance ☐ Unimportant

20. Which ONE of the following foliar diseases do you believe to have been the most common on spring barley in Scotland in the past five years?

☐ Powdery Mildew
☐ Ramularia
☐ Rhynchosporium

21. **Which ONE of the following foliar diseases do you consider to have impacted spring barley yield most in Scotland in the past five years?**
    - ☐ Powdery Mildew
    - ☐ Ramularia
    - ☐ Rhynchosporium

Section 6: Fungicide Use in Future

22. **Please rank the following according to how strongly you agree/disagree in relation to spring barley:**
    - **a. I think fungicide use can negatively impact the environment**

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

b. I am not concerned about fungicide use leading to fungicide resistance

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

c. If using less fungicide could achieve the same yields, I would recommend using less fungicide to farmers

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

d. I have no concerns about the amount of fungicides farmers use on spring barley

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

e. If using less fungicide was as cost-effective, I would recommend using less fungicide to farmers

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

f. I think finding methods to reduce fungicide use is important

☐ Strongly agree ☐ Agree ☐ Neither agree nor disagree ☐ Disagree ☐ Strongly disagree

23. If the following measures were all cost-effective *alternatives* to using fungicides on spring barley:

a. Which would you be MOST likely to recommend to farmers?

	Choose ONE	
Sowing only disease resistant varieties	☐ Most likely	☐ N/A (already recommend)
Planned crop rotation	☐ Most likely	☐ N/A (already recommend)
Forecasting disease pressure for the season and changing management strategies based on these predictions	☐ Most likely	☐ N/A (already recommend)

b. Which would you be LEAST likely to recommend to farmers?

	Choose ONE	
Sowing only disease resistant varieties	☐ Least likely	☐ N/A (already recommend)
Planned crop rotation	☐ Least likely	☐ N/A (already recommend)
Forecasting disease pressure for the season and changing management strategies based on these predictions	☐ Least likely	☐ N/A (already recommend)

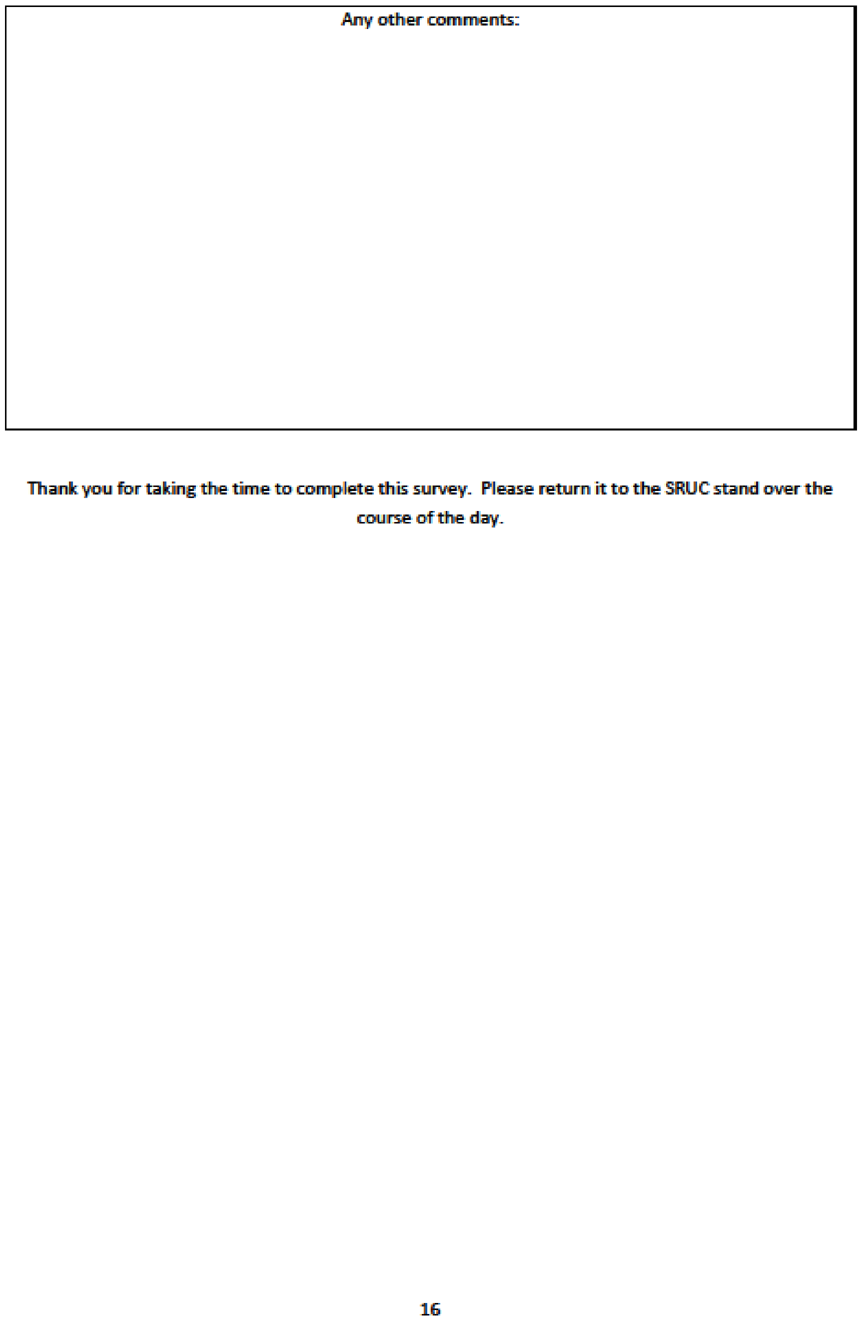
24. If the following measures were all cost-effective *complementary* techniques used alongside fungicides on spring barley

a. Which would you be MOST likely to recommend to farmers?

	Choose ONE	
Sowing only disease resistant varieties	☐ Most likely	☐ N/A (already recommend)
Planned crop rotation	☐ Most likely	☐ N/A (already recommend)
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Most likely	☐ N/A (already recommend)

b. Which would you be LEAST likely to recommend to farmers?

	Choose ONE	
Sowing only disease resistant varieties	☐ Least likely	☐ N/A (already recommend)
Planned crop rotation	☐ Least likely	☐ N/A (already recommend)
Forecasting disease pressure for the season and spraying only when disease pressure will be high	☐ Least likely	☐ N/A (already recommend)

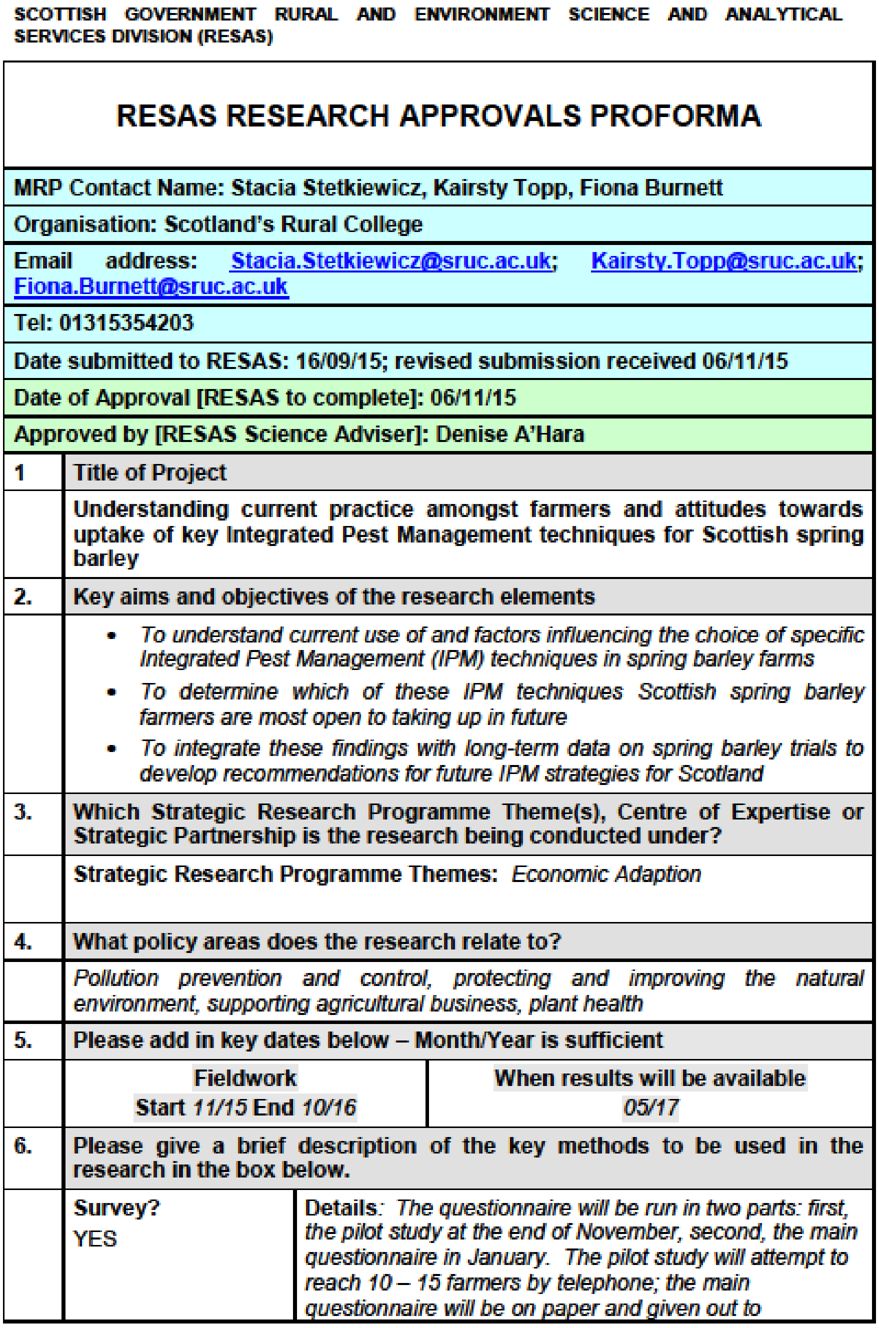


Any other comments:

Thank you for taking the time to complete this survey. Please return it to the SRUC stand over the course of the day.

16

8.5 Appendix E – Survey ethics procedure: Scottish Government approved proforma



SCOTTISH GOVERNMENT RURAL AND ENVIRONMENT SCIENCE AND ANALYTICAL SERVICES DIVISION (RESAS)

RESAS RESEARCH APPROVALS PROFORMA

MRP Contact Name: Stacia Stetkiewicz, Kairsty Topp, Fiona Burnett

Organisation: Scotland's Rural College

Email address: Stacia.Stetkiewicz@sruc.ac.uk; Kairsty.Topp@sruc.ac.uk; Fiona.Burnett@sruc.ac.uk

Tel: 01315354203

Date submitted to RESAS: 16/09/15; revised submission received 06/11/15

Date of Approval [RESAS to complete]: 06/11/15

Approved by [RESAS Science Adviser]: Denise A'Hara

1	**Title of Project**	
	Understanding current practice amongst farmers and attitudes towards uptake of key Integrated Pest Management techniques for Scottish spring barley	
2.	**Key aims and objectives of the research elements**	
	• *To understand current use of and factors influencing the choice of specific Integrated Pest Management (IPM) techniques in spring barley farms* • *To determine which of these IPM techniques Scottish spring barley farmers are most open to taking up in future* • *To integrate these findings with long-term data on spring barley trials to develop recommendations for future IPM strategies for Scotland*	
3.	**Which Strategic Research Programme Theme(s), Centre of Expertise or Strategic Partnership is the research being conducted under?**	
	Strategic Research Programme Themes: *Economic Adaption*	
4.	**What policy areas does the research relate to?**	
	Pollution prevention and control, protecting and improving the natural environment, supporting agricultural business, plant health	
5.	**Please add in key dates below – Month/Year is sufficient**	
	Fieldwork **Start** *11/15* **End** *10/16*	**When results will be available** *05/17*
6.	**Please give a brief description of the key methods to be used in the research in the box below.**	
	Survey? YES	**Details**: *The questionnaire will be run in two parts: first, the pilot study at the end of November, second, the main questionnaire in January. The pilot study will attempt to reach 10 – 15 farmers by telephone; the main questionnaire will be on paper and given out to*

		approximately 130 attendants over three HGCA/SRUC Cereals and Oilseed events. These events are likely to be spread across the country, with one each in the North East, Central, and South East of Scotland. Participants will have one day to complete the questionnaire during the event. *In addition to demographic questions, the survey will include sections on: varieties of spring barley the participant has grown in the past five years and how they chose these, use of crop rotation strategies on farm and how these were determined upon, fungicide use on farm and what yield impact they ascribe to this, main foliar diseases they encounter on farm and which they believe to impact yield most, and which of a short-list of IPM techniques they would consider using on their farm in the future.* *The questionnaire will consist of a combination of open-ended questions where respondents provide answers in their own words, and closed questions where participants chose from a predefined set of answers (including multiple choice, ranking, and best-worst scaling). Participants will also have the option to leave further open-ended feedback in the form of short comments throughout the survey. Respondents will be able to skip or leave blank any questions they feel uncomfortable with or do not know the answer to.* *The participants' demographic information and answers will be stored securely and anonymously so that answers cannot be linked to individuals – a unique survey ID number will be allocated to each survey for this purpose.*
	Qualitative Interviews? Possibly, yes	**Details**: *We may want to carry out individual interviews with farmers during the second phase of surveying, at the SRUC Cereal Trials Open Days across Scotland in the summer of 2016, in order to get more in-depth information about physical and financial barriers to uptake on farm of specific IPM techniques. This will be decided based on results from the initial questionnaire, as well as the analysis of long-term field trial data from the SRUC.* *If interviews were conducted, a socio-demographic section would be included, as in the original questionnaire. A section for each of the following would be envisioned: knowledge about specific short-listed IPM techniques, willingness to use these techniques on farm,*

		physical barriers to uptake, financial barriers to uptake, ranking the utility of incentives/aid for uptake. *Information would also be given regarding the results of the long-term trials analysis, in order to make a before-after comparison of participant interest in uptake. Again, all information collected would be stored securely and anonymously as for the main questionnaire.* *The interviews would be restricted to an hour or less, the target being to conduct between ten and twenty interviews over the course of the summer.*
	Focus groups? YES	**Details**: *Focus groups would be carried out in the second phase of surveying at SRUC Cereal Trials Open Days across Scotland in the summer of 2016. Focus groups would be limited in size to a maximum of ten, to facilitate discussion, with an aim of conducting between three and six focus groups.* *The focus group would begin with initial knowledge of/interest in implementing the specific IPM techniques for discussion. Information would be given regarding the results from the analysis of the long-term trial data, and discussion around these techniques would include physical and financial barriers to uptake, willingness to use these techniques on farm, and the utility of incentives/aid for uptake.* *Interest in implementation following the session would be used to make a before-after comparison of interest in uptake, to understand if this additional information could impact farmer opinion. Again, all information collected would be stored securely and anonymously.* *Focus group discussions would be limited to one hour.* *In addition, one or more passive surveying activities are envisioned to run simultaneously with the focus groups. For example, posters describing the IPM techniques and their advantages and disadvantages could have boxes for anonymous voting about which technique is preferred. These would be used to collect additional information from participants to the Open Days who do not participate in the focus groups – this participation would be voluntary and completely anonymous.*
7.	**Is the survey/interview/focus group work one-off or will it involve repeat**	

	contact with respondents? *If repeat contact is required, please give more information.*
	The work will be largely one-off, and repeat contact will not be required. If participants are open to being contacted with follow up questions, they will have the option to leave contact details on the paper questionnaire – participants could then be contacted to clarify statements they have made or ask pertinent questions which would help to put the survey responses in context. *However, due to the structure of the surveys, it is possible that farmers may attend events where both the initial questionnaire is presented in January, as well as events where focus groups/interviews are taking place in the summer. In this case, farmers are welcome to participate in both the questionnaire and focus groups, but there is no requirement to do so.*
8.	**Have you discussed the idea of the research, and the specific survey/focus groups/interviews, with the relevant Scottish Government policy teams?** • *If yes, please give details in the box below, including names of people you have contacted and whether they support the research.* • *if no, please specify reasons and/or note plans for contact.*
	Plans for this work will be presented during regular RESAS Theme 4.2 Capacity Building progress meetings. *In addition, contact has been made with Richard Murray from Scottish Government, and feedback from him regarding this work has been incorporated into this submission. Further discussion of the survey plan is envisaged as needed.*
9.	**Please set out the likely benefits of these research activities to the following:**

	A) *The respondent/participant: getting to be involved in research which may influence policy which will affect them; getting to focus research efforts in IPM, so that their opinions will be taken into account when further research is being planned; learning cutting edge research findings about techniques which may be useful for their business plans.* B) *The wider research project: these surveys are part of a larger project which is aiming to determine which of several IPM techniques could be useful in spring barley in Scotland. These surveys will provide information about which techniques farmers are able and willing to use on farm, which will be considered alongside which techniques seem to be the best fits for Scotland's farms based on the analysis of long-term field trials, in order to pinpoint the techniques which are both likely to be effective and likely to be taken up on farm. The surveys may also raise practical issues and solutions which are not visible from the long-term datasets, based on farmer knowledge, which could be incorporated into the project's conclusions.* C) *The Scottish Government: This research could help to provide valuable insight into current attitudes and opinions about pesticide use and IPM strategies, which can help Scottish Government to achieve its goals of promoting environmentally friendly farming. Responses about incentives/aids which would increase farmer likelihood of uptake could also be useful for Scottish Government recommendations and proposals for IPM uptake in line with the* 2020 Challenge *goals of promoting IPM and controlling pollution.* *In addition, this work will complement the IPM plan in work package 2.1 of the 2016-21 RESAS programme, by providing an in-depth analysis of IPM in one of Scotland's major crops and its key fungal diseases. Results from this work could be used to feed into the IPM plan's design and analysis, and comparing results from the two may highlight important patterns or areas of discrepancy between spring barley production and other crops.* *Information from the survey will also be used to inform the early design and structure of the IPM co-construction workshops planned at the beginning of the next program. Data from this work will also be used to structure survey questions planned in 2.3.12 where any barriers to uptake are suggested.*
10.	**Have these specific research elements been subject to a process of ethical approval?** *Please give further information on your answer, below.*
	An ethical review of the project was undertaken for the School of Biological Sciences at the University of Edinburgh on 16 September 2015, and a second ethical review will be undertaken for the School of Social and Political Sciences prior to any survey work beginning.
11.	**Have other information sources been considered as an alternative to carrying out primary research? Please give details.**
	No relevant information is available for Scotland, or for barley growers in the UK,

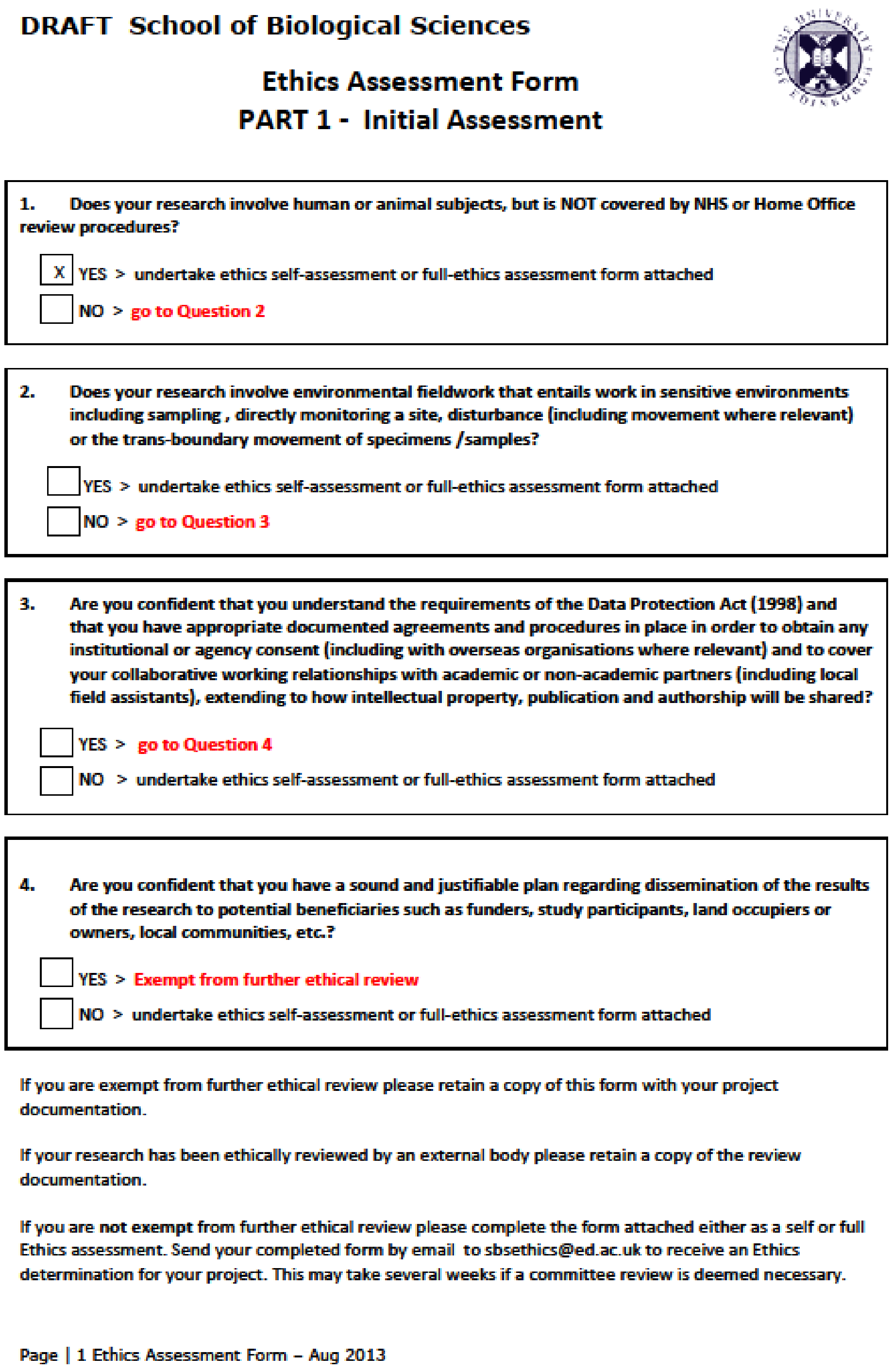
	more generally.
12.	**What steps are being taken to minimise the burden on respondents?**
	The survey and interviews will take place during scheduled events which commonly attract farmers, to minimise disruption of participant's schedules. No cost or time lost will therefore be associated with participating in the research.
13.	**Will you require access to any SG datasets in order to conduct the research? If YES, please give details.**
	NO

Please return this form by e-mail or post to:

Chris Rich
Scottish Government
Rural and Environment Science and Analytical Services Division (RESAS)
1-C (South)
Victoria Quay
Edinburgh EH6 6QQ

E-mail: chris.rich@scotland.gsi.gov.uk

8.6 Appendix F – survey ethics procedure: Ethics Assessment form for the University of Edinburgh’s school of Biological Sciences



DRAFT School of Biological Sciences

Ethics Assessment Form

PART 1 - Initial Assessment

1. Does your research involve human or animal subjects, but is NOT covered by NHS or Home Office review procedures?

☒ YES > undertake ethics self-assessment or full-ethics assessment form attached

☐ NO > go to Question 2

2. Does your research involve environmental fieldwork that entails work in sensitive environments including sampling , directly monitoring a site, disturbance (including movement where relevant) or the trans-boundary movement of specimens /samples?

☐ YES > undertake ethics self-assessment or full-ethics assessment form attached

☐ NO > go to Question 3

3. Are you confident that you understand the requirements of the Data Protection Act (1998) and that you have appropriate documented agreements and procedures in place in order to obtain any institutional or agency consent (including with overseas organisations where relevant) and to cover your collaborative working relationships with academic or non-academic partners (including local field assistants), extending to how intellectual property, publication and authorship will be shared?

☐ YES > go to Question 4

☐ NO > undertake ethics self-assessment or full-ethics assessment form attached

4. Are you confident that you have a sound and justifiable plan regarding dissemination of the results of the research to potential beneficiaries such as funders, study participants, land occupiers or owners, local communities, etc.?

☐ YES > Exempt from further ethical review

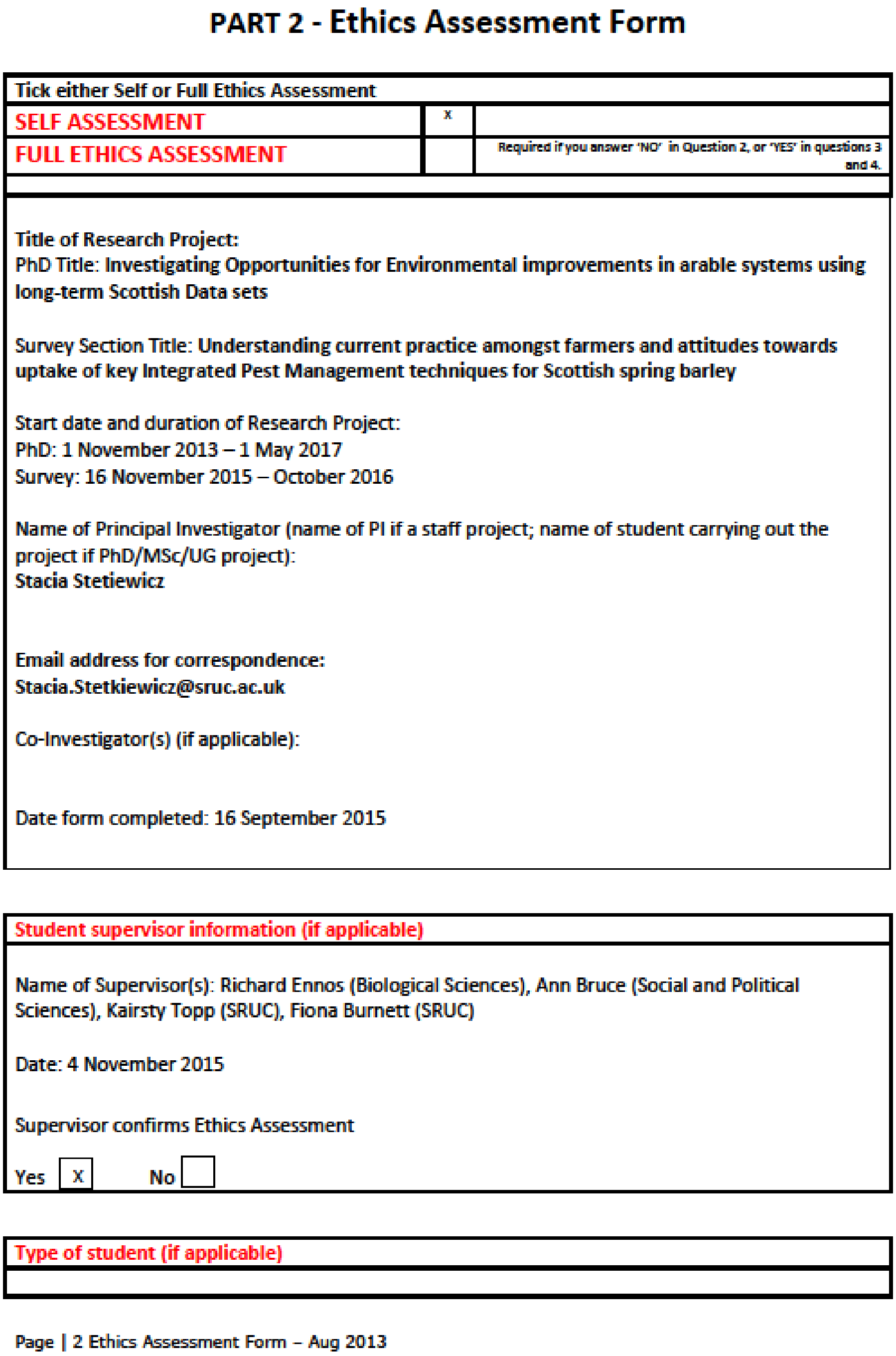
☐ NO > undertake ethics self-assessment or full-ethics assessment form attached

If you are exempt from further ethical review please retain a copy of this form with your project documentation.

If your research has been ethically reviewed by an external body please retain a copy of the review documentation.

If you are **not exempt** from further ethical review please complete the form attached either as a self or full Ethics assessment. Send your completed form by email to sbsethics@ed.ac.uk to receive an Ethics determination for your project. This may take several weeks if a committee review is deemed necessary.

Page | 1 Ethics Assessment Form – Aug 2013



PART 2 - Ethics Assessment Form

Tick either Self or Full Ethics Assessment		
SELF ASSESSMENT	x	
FULL ETHICS ASSESSMENT		Required if you answer 'NO' in Question 2, or 'YES' in questions 3 and 4.

Title of Research Project:
PhD Title: Investigating Opportunities for Environmental improvements in arable systems using long-term Scottish Data sets

Survey Section Title: Understanding current practice amongst farmers and attitudes towards uptake of key Integrated Pest Management techniques for Scottish spring barley

Start date and duration of Research Project:
PhD: 1 November 2013 – 1 May 2017
Survey: 16 November 2015 – October 2016

Name of Principal Investigator (name of PI if a staff project; name of student carrying out the project if PhD/MSc/UG project):
Stacia Stetiewicz

Email address for correspondence:
Stacia.Stetkiewicz@sruc.ac.uk

Co-Investigator(s) (if applicable):

Date form completed: 16 September 2015

Student supervisor information (if applicable)

Name of Supervisor(s): Richard Ennos (Biological Sciences), Ann Bruce (Social and Political Sciences), Kairsty Topp (SRUC), Fiona Burnett (SRUC)

Date: 4 November 2015

Supervisor confirms Ethics Assessment

Yes ☒ No ☐

Type of student (if applicable)

Page | 2 Ethics Assessment Form – Aug 2013

Masters by Research	☐
Taught Masters	☐
Undergrad Honours	☐
PhD	☒

Research Project Assessment

Research Abstract / Summary

Please include a 250-500 word research abstract / summary. The statement should include a summary of research methods and techniques.

This PhD will include a farmer/agronomist survey, which aims to understand current practice and opinion towards integrated pest management techniques in Scottish barley production.

The survey will be run in two sections: first, a paper survey conducted in January 2016, second, a series of interviews/focus groups to be held in the summer of 2016. Participants would be free to participate in both surveys if desired, but would not be required to do so.

First survey:

First, a pilot study will be conducted at the end of November, followed by the main questionnaire in January. The pilot study will attempt to reach 10 – 15 farmers by telephone; the main questionnaire will be on paper and given out to approximately 130 attendants over three HGCA/SRUC Cereals and Oilseed events.
In addition to demographic questions, the survey will include sections on: varieties of spring barley the participant has grown in the past five years and how they chose these, use of crop rotation strategies on farm and how these were determined upon, fungicide use on farm and what yield impact they ascribe to this, main foliar diseases they encounter on farm and which they believe to impact yield most, and which of a short-list of IPM techniques they would consider using on their farm in the future.

Participants will have the option to leave further open-ended feedback in the form of short comments throughout the survey. Respondents will be able to skip or leave blank any questions they feel uncomfortable with or do not know the answer to.

Second survey:

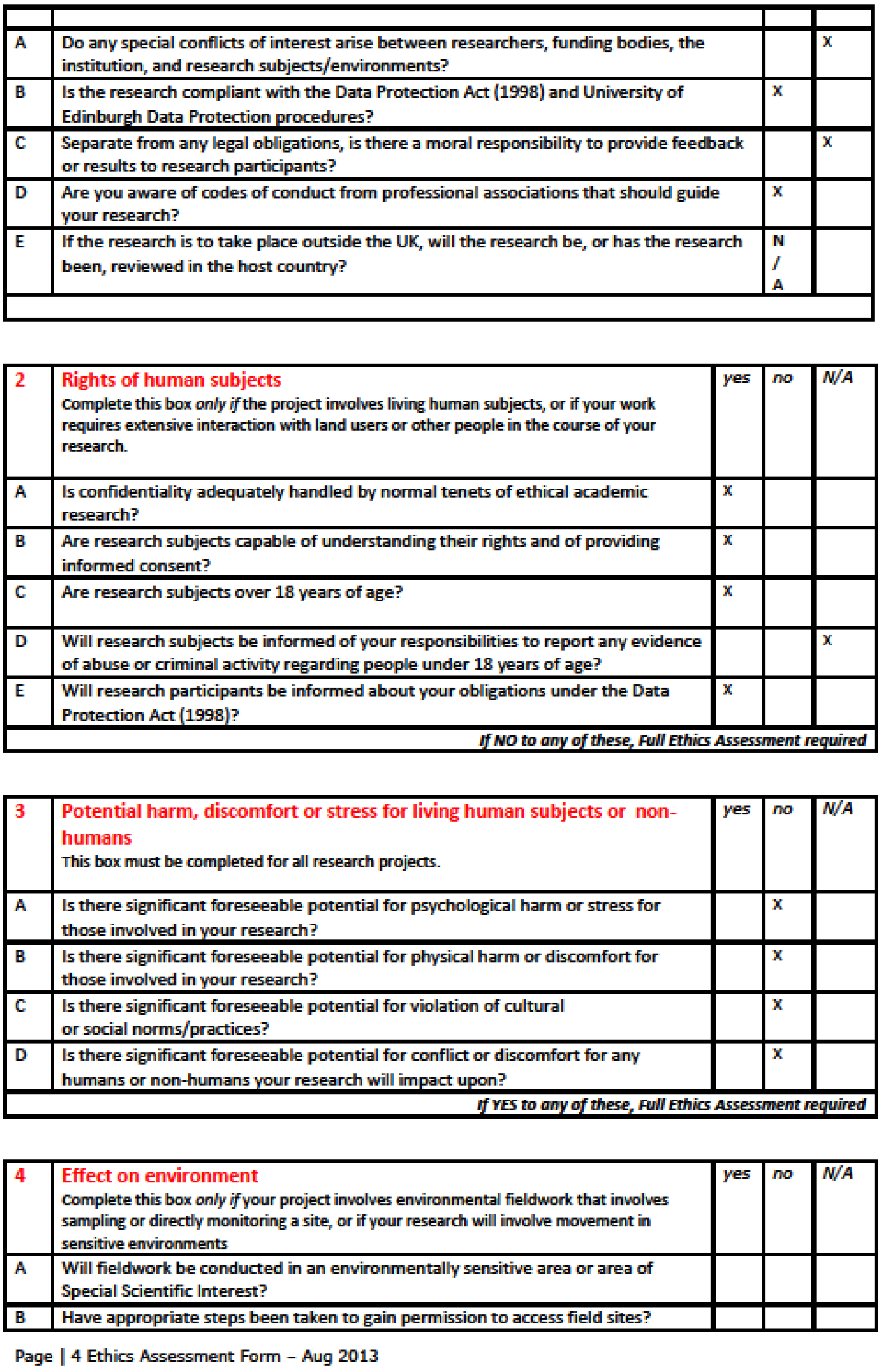
Focus groups would be carried out in the second phase of surveying at SRUC Cereal Trials Open Days across Scotland in the summer of 2016. Focus groups would be limited in size to a maximum of ten, to facilitate discussion, with an aim of conducting between three and six focus groups.

The focus group would begin with initial knowledge of/interest in implementing the specific IPM techniques for discussion. Information would be given regarding the results from the analysis of the long-term trial data, and discussion around these techniques would include physical and financial barriers to uptake, willingness to use these techniques on farm, and the utility of incentives/aid for uptake.

Interest in implementation following the session would be used to make a before-after comparison of interest in uptake, to understand if this additional information could impact farmer opinion.

In addition, one or more passive surveying activities are envisioned to run simultaneously with the focus groups. For example, posters describing the IPM techniques and their advantages and disadvantages could have boxes for anonymous voting about which technique is preferred. These would be used to collect additional information from participants to the Open Days who do not participate in the focus groups – this participation would be voluntary and completely anonymous.

1	**Legal, moral responsibilities, codes of conduct** This box must be completed for all research projects	*yes*	*no*



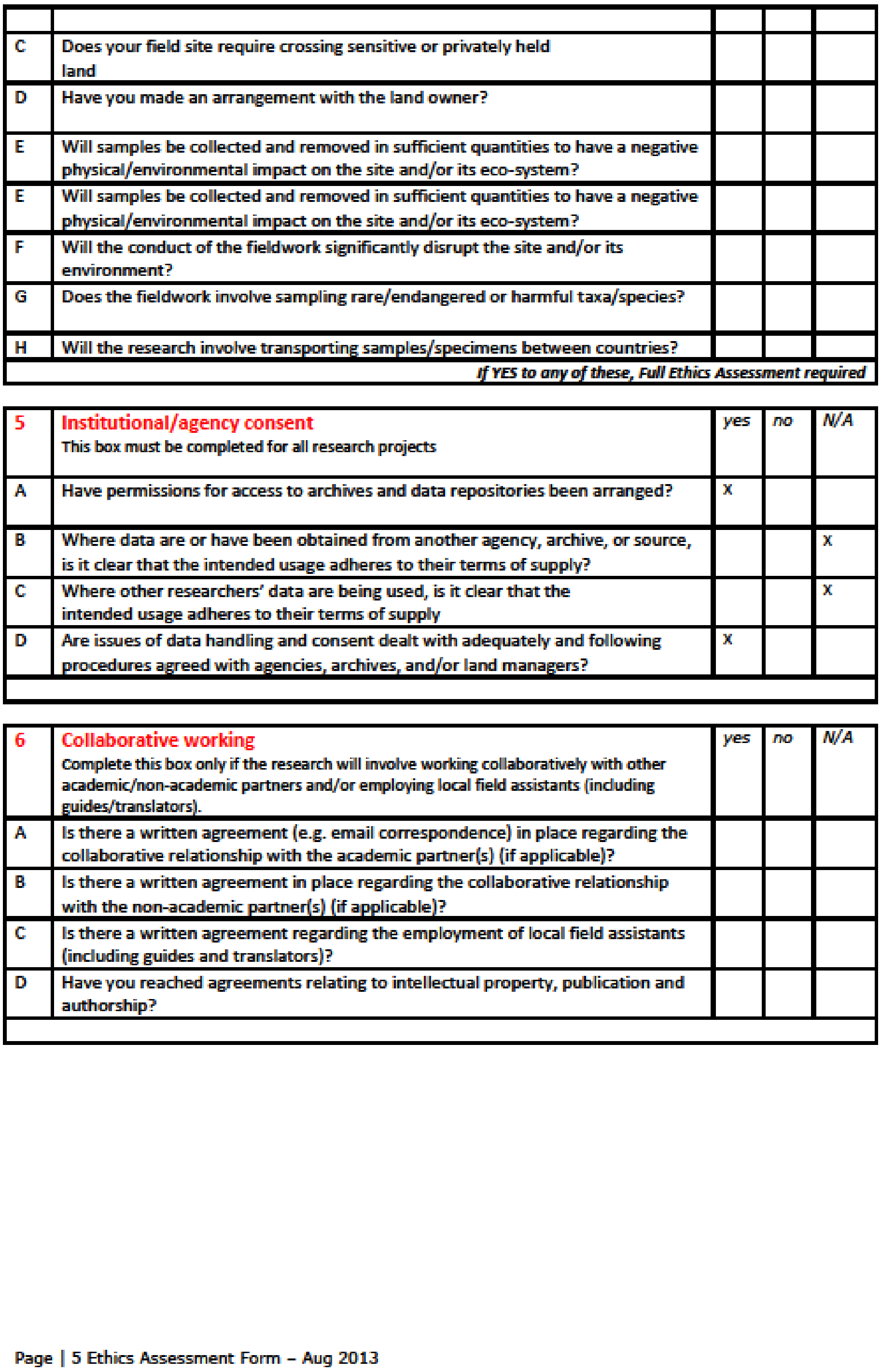
A	Do any special conflicts of interest arise between researchers, funding bodies, the institution, and research subjects/environments?		X
B	Is the research compliant with the Data Protection Act (1998) and University of Edinburgh Data Protection procedures?	X	
C	Separate from any legal obligations, is there a moral responsibility to provide feedback or results to research participants?		X
D	Are you aware of codes of conduct from professional associations that should guide your research?	X	
E	If the research is to take place outside the UK, will the research be, or has the research been, reviewed in the host country?	N/A	

2	**Rights of human subjects** Complete this box *only if* the project involves living human subjects, or if your work requires extensive interaction with land users or other people in the course of your research.	*yes*	*no*	*N/A*
A	Is confidentiality adequately handled by normal tenets of ethical academic research?	X		
B	Are research subjects capable of understanding their rights and of providing informed consent?	X		
C	Are research subjects over 18 years of age?	X		
D	Will research subjects be informed of your responsibilities to report any evidence of abuse or criminal activity regarding people under 18 years of age?			X
E	Will research participants be informed about your obligations under the Data Protection Act (1998)?	X		
	If NO to any of these, Full Ethics Assessment required			

3	**Potential harm, discomfort or stress for living human subjects or non-humans** This box must be completed for all research projects.	*yes*	*no*	*N/A*
A	Is there significant foreseeable potential for psychological harm or stress for those involved in your research?		X	
B	Is there significant foreseeable potential for physical harm or discomfort for those involved in your research?		X	
C	Is there significant foreseeable potential for violation of cultural or social norms/practices?		X	
D	Is there significant foreseeable potential for conflict or discomfort for any humans or non-humans your research will impact upon?		X	
	If YES to any of these, Full Ethics Assessment required			

4	**Effect on environment** Complete this box *only if* your project involves environmental fieldwork that involves sampling or directly monitoring a site, or if your research will involve movement in sensitive environments	*yes*	*no*	*N/A*
A	Will fieldwork be conducted in an environmentally sensitive area or area of Special Scientific Interest?			
B	Have appropriate steps been taken to gain permission to access field sites?			

Page | 4 Ethics Assessment Form – Aug 2013



C	Does your field site require crossing sensitive or privately held land			
D	Have you made an arrangement with the land owner?			
E	Will samples be collected and removed in sufficient quantities to have a negative physical/environmental impact on the site and/or its eco-system?			
E	Will samples be collected and removed in sufficient quantities to have a negative physical/environmental impact on the site and/or its eco-system?			
F	Will the conduct of the fieldwork significantly disrupt the site and/or its environment?			
G	Does the fieldwork involve sampling rare/endangered or harmful taxa/species?			
H	Will the research involve transporting samples/specimens between countries?			
	If YES to any of these, Full Ethics Assessment required			

5	Institutional/agency consent This box must be completed for all research projects	*yes*	*no*	*N/A*
A	Have permissions for access to archives and data repositories been arranged?	x		
B	Where data are or have been obtained from another agency, archive, or source, is it clear that the intended usage adheres to their terms of supply?			x
C	Where other researchers' data are being used, is it clear that the intended usage adheres to their terms of supply			x
D	Are issues of data handling and consent dealt with adequately and following procedures agreed with agencies, archives, and/or land managers?	x		

6	Collaborative working Complete this box only if the research will involve working collaboratively with other academic/non-academic partners and/or employing local field assistants (including guides/translators).	*yes*	*no*	*N/A*
A	Is there a written agreement (e.g. email correspondence) in place regarding the collaborative relationship with the academic partner(s) (if applicable)?			
B	Is there a written agreement in place regarding the collaborative relationship with the non-academic partner(s) (if applicable)?			
C	Is there a written agreement regarding the employment of local field assistants (including guides and translators)?			
D	Have you reached agreements relating to intellectual property, publication and authorship?			

Page | 5 Ethics Assessment Form – Aug 2013

7	**Dissemination and benefit sharing** This box must be completed for all research projects	*yes*	*no*	*N/A*
A	If the research was undertaken outside the UK, will the research findings, associated publications and, where feasible, data be made available in the country where the research took place?			X
B	Will you disseminate the findings to the study participants or land owners?	X		
C	Is the research expected to benefit the participants and/or local communities (directly or indirectly)?	X		
If you answer NO to a or b please include a statement justifying your decision in the Additional Statement box at the end of the form.				

8	**Other Approval**	*yes*	*no*	*N/A*
A	Does the sponsor require formal prior ethical review?	X		
	If Yes, by what date is a response required?	Before November 16th 2015		
B	Does the project require the approval of any other institution and/or ethics committee?	X		
	If Yes, by what date is a response required?	Before November 16th 2015		

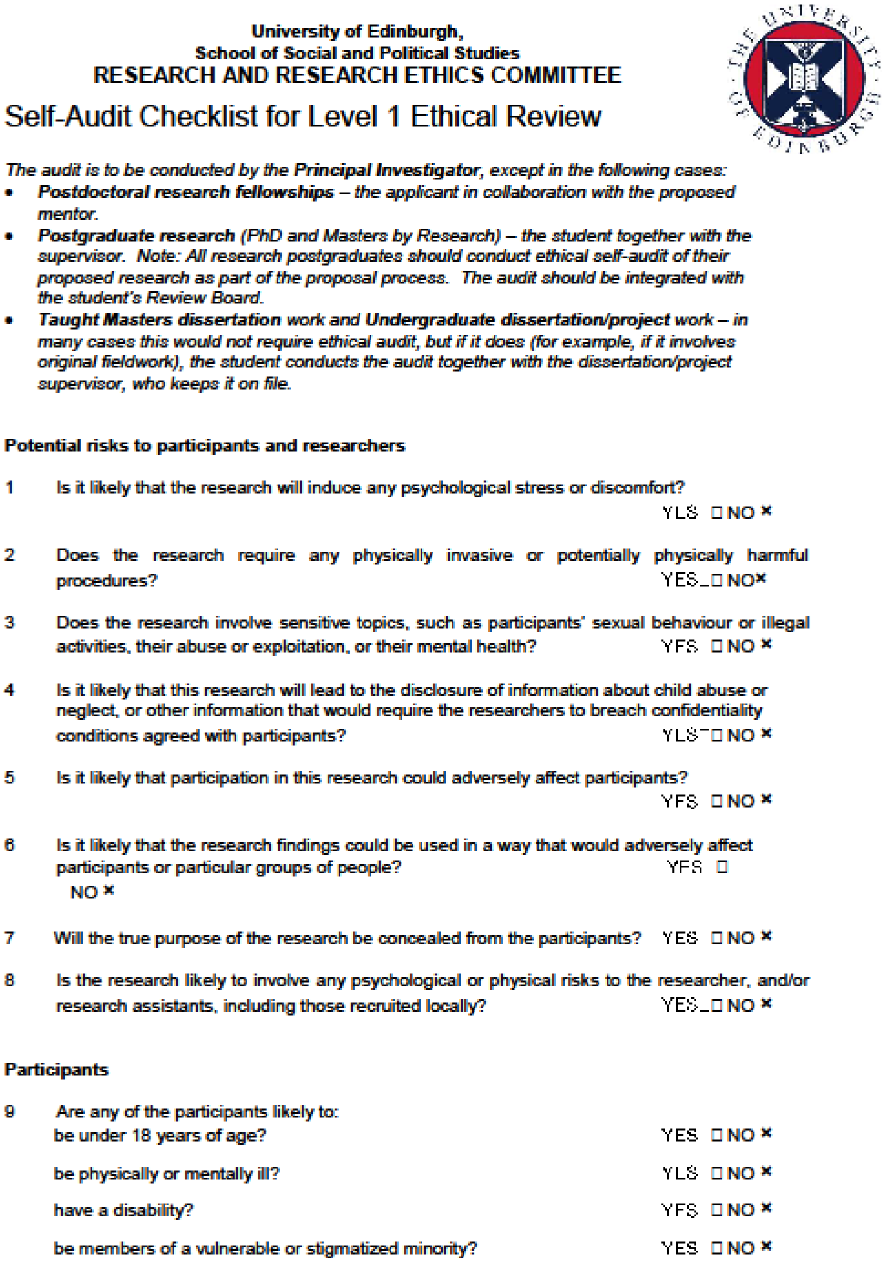
Additional Statement

If relevant, please add an explanation on how you will address the ethical issues identified above (250-500 max words). Full Ethics reviews can use up to 1,000 words.

The participants' demographic information and all answers will be stored securely and anonymously so that answers cannot be linked to individuals – a unique survey ID number will be allocated to each survey for this purpose.

END OF FORM TO SUBMIT

8.7 Appendix G – survey ethics procedure: Self-Audit Checklist for Level 1 Ethical Review for the University of Edinburgh School of Social and Political Sciences



University of Edinburgh,
School of Social and Political Studies
RESEARCH AND RESEARCH ETHICS COMMITTEE

Self-Audit Checklist for Level 1 Ethical Review

The audit is to be conducted by the ***Principal Investigator****, except in the following cases:*

- ***Postdoctoral research fellowships*** *– the applicant in collaboration with the proposed mentor.*
- ***Postgraduate research*** *(PhD and Masters by Research) – the student together with the supervisor. Note: All research postgraduates should conduct ethical self-audit of their proposed research as part of the proposal process. The audit should be integrated with the student's Review Board.*
- ***Taught Masters dissertation*** *work and* ***Undergraduate dissertation/project*** *work – in many cases this would not require ethical audit, but if it does (for example, if it involves original fieldwork), the student conducts the audit together with the dissertation/project supervisor, who keeps it on file.*

Potential risks to participants and researchers

1 Is it likely that the research will induce any psychological stress or discomfort? YES ☐ NO ×

2 Does the research require any physically invasive or potentially physically harmful procedures? YES ☐ NO ×

3 Does the research involve sensitive topics, such as participants' sexual behaviour or illegal activities, their abuse or exploitation, or their mental health? YES ☐ NO ×

4 Is it likely that this research will lead to the disclosure of information about child abuse or neglect, or other information that would require the researchers to breach confidentiality conditions agreed with participants? YES ☐ NO ×

5 Is it likely that participation in this research could adversely affect participants? YES ☐ NO ×

6 Is it likely that the research findings could be used in a way that would adversely affect participants or particular groups of people? YES ☐ NO ×

7 Will the true purpose of the research be concealed from the participants? YES ☐ NO ×

8 Is the research likely to involve any psychological or physical risks to the researcher, and/or research assistants, including those recruited locally? YES ☐ NO ×

Participants

9 Are any of the participants likely to:

be under 18 years of age? YES ☐ NO ×

be physically or mentally ill? YES ☐ NO ×

have a disability? YES ☐ NO ×

be members of a vulnerable or stigmatized minority? YES ☐ NO ×

be in a dependent relationship with the researchers? YES ☐ NO ✖

have difficulty in reading and/or comprehending any printed material distributed as part of the research process? YES ☐ NO ✖

be vulnerable in other ways? YES ☐ NO ✖

10 Will it be difficult to ascertain whether participants are vulnerable in any of the ways listed above (e.g. where participants are recruited via the internet)? YES ☐ NO ✖

11 Will participants receive any financial or other material benefits because of participation, beyond standard practice for research in your field? YES ☐ NO ✖

Before completing the next sections, please refer to the University Data Protection Policy to ensure that the relevant conditions relating to the processing of personal data under Schedule 2 and 3 are satisfied. Details are Available at: www.recordsmanagement.ed.ac.uk

Confidentiality and handling of data

12 Will the research require the collection of personal information about individuals (including via other organisations such as schools or employers) without their direct consent? YES ☐ NO ✖

13 Will individual responses be attributed or will participants be identifiable, without the direct consent of participants? YES ☐ NO ✖

14 Will datafiles/audio/video tapes, etc. be retained after the completion of the study (or beyond a reasonable time period for publication of the results of the study)? YES ☐ NO ✖

15 Will the data be made available for secondary use, without obtaining the consent of participants? YES ☐ NO ✖

Informed consent

16 Will it be difficult to obtain direct consent from participants? YES ☐ NO ✖

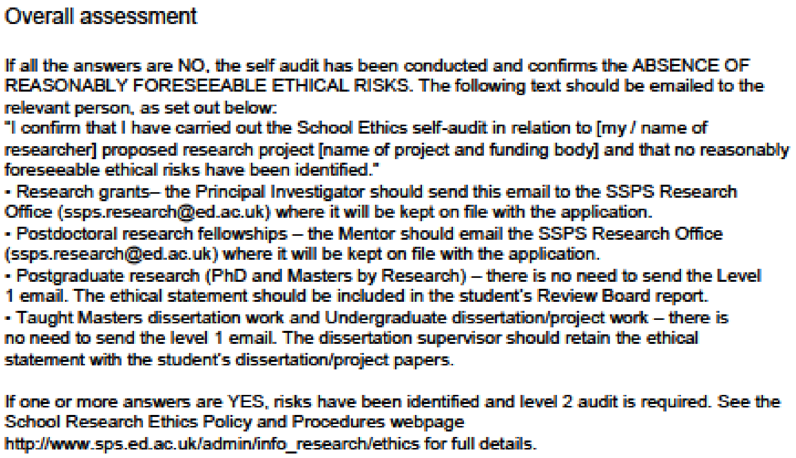
Conflict of interest

The University has a 'Policy on the Conflict of Interest', which states that a conflict of interest would arise in cases where an employee of the University might be "compromising research objectivity or independence in return for financial or non-financial benefit for him/herself or for a relative or friend." See: http://www.docs.csg.ed.ac.uk/HumanResources/Policy/Conflict_of_Interest.pdf

Conflict of interest may also include cases where the source of funding raises ethical issues, either because of concerns about the moral standing or activities of the funder, or concerns about the funder's motivation for commissioning the research and the uses to which the research might be put.

The University policy also states that the responsibility for avoiding a conflict of interest, in the first instance, lies with the individual, but that potential conflicts of interest should always be disclosed, normally to the line manager or Head of Department. Failure to disclose a conflict of interest or to cease involvement until the conflict has been resolved may result in disciplinary action and in serious cases could result in dismissal.

17 Does your research involve a conflict of interest as outlined above? YES ☐ NO ✖

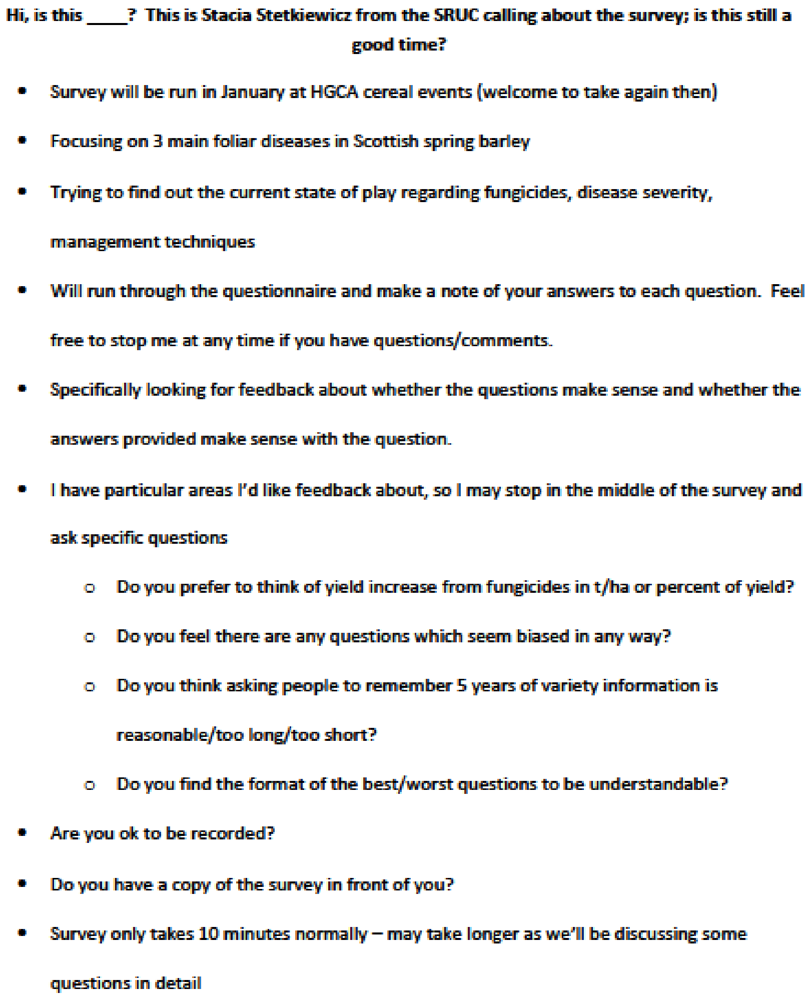


Overall assessment

If all the answers are NO, the self audit has been conducted and confirms the ABSENCE OF REASONABLY FORESEEABLE ETHICAL RISKS. The following text should be emailed to the relevant person, as set out below:
"I confirm that I have carried out the School Ethics self-audit in relation to [my / name of researcher] proposed research project [name of project and funding body] and that no reasonably foreseeable ethical risks have been identified."
- Research grants– the Principal Investigator should send this email to the SSPS Research Office (ssps.research@ed.ac.uk) where it will be kept on file with the application.
- Postdoctoral research fellowships – the Mentor should email the SSPS Research Office (ssps.research@ed.ac.uk) where it will be kept on file with the application.
- Postgraduate research (PhD and Masters by Research) – there is no need to send the Level 1 email. The ethical statement should be included in the student's Review Board report.
- Taught Masters dissertation work and Undergraduate dissertation/project work – there is no need to send the level 1 email. The dissertation supervisor should retain the ethical statement with the student's dissertation/project papers.

If one or more answers are YES, risks have been identified and level 2 audit is required. See the School Research Ethics Policy and Procedures webpage http://www.sps.ed.ac.uk/admin/info_research/ethics for full details.

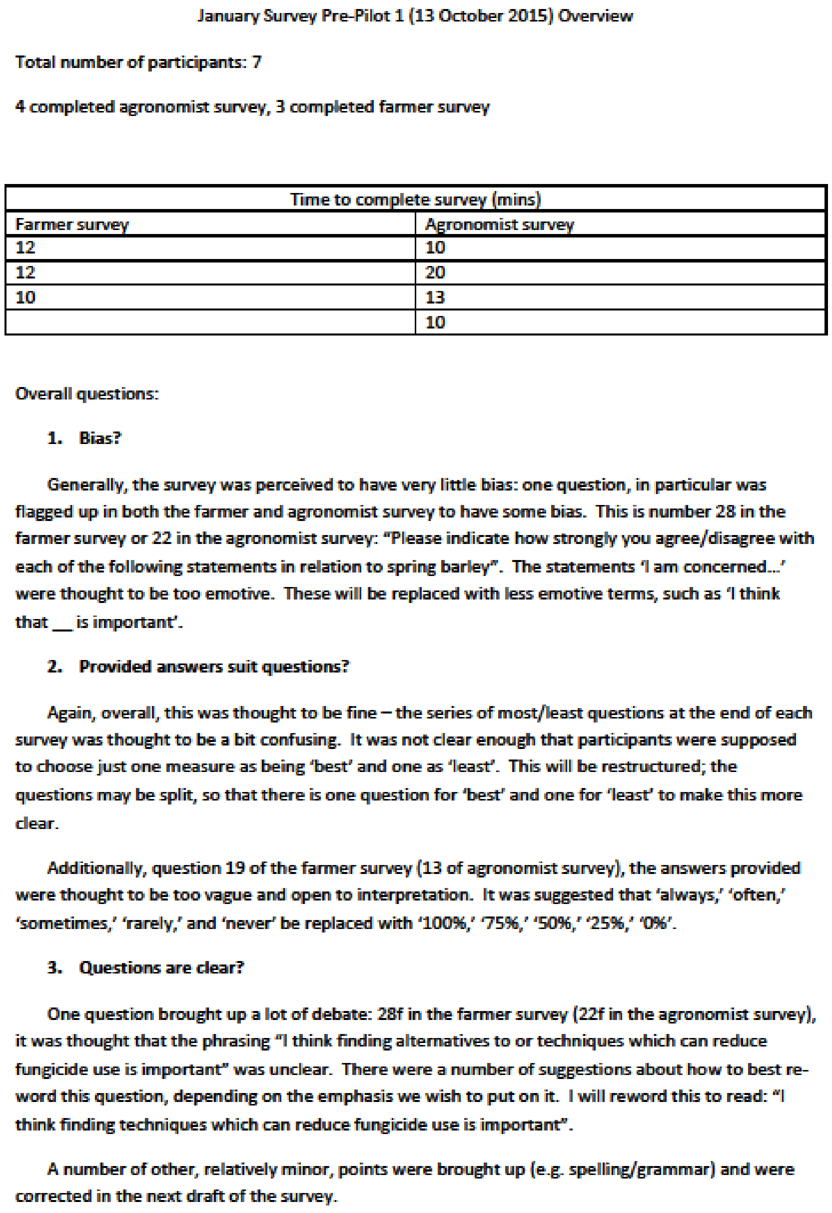
8.8 Appendix H – Protocol used for pilot survey



Hi, is this _____? This is Stacia Stetkiewicz from the SRUC calling about the survey; is this still a good time?

- Survey will be run in January at HGCA cereal events (welcome to take again then)
- Focusing on 3 main foliar diseases in Scottish spring barley
- Trying to find out the current state of play regarding fungicides, disease severity, management techniques
- Will run through the questionnaire and make a note of your answers to each question. Feel free to stop me at any time if you have questions/comments.
- Specifically looking for feedback about whether the questions make sense and whether the answers provided make sense with the question.
- I have particular areas I'd like feedback about, so I may stop in the middle of the survey and ask specific questions
    - Do you prefer to think of yield increase from fungicides in t/ha or percent of yield?
    - Do you feel there are any questions which seem biased in any way?
    - Do you think asking people to remember 5 years of variety information is reasonable/too long/too short?
    - Do you find the format of the best/worst questions to be understandable?
- Are you ok to be recorded?
- Do you have a copy of the survey in front of you?
- Survey only takes 10 minutes normally – may take longer as we'll be discussing some questions in detail

8.9 Appendix I – Summary of feedback from pre-pilot study



January Survey Pre-Pilot 1 (13 October 2015) Overview

Total number of participants: 7

4 completed agronomist survey, 3 completed farmer survey

Time to complete survey (mins)	
Farmer survey	Agronomist survey
12	10
12	20
10	13
	10

Overall questions:

1. **Bias?**

Generally, the survey was perceived to have very little bias: one question, in particular was flagged up in both the farmer and agronomist survey to have some bias. This is number 28 in the farmer survey or 22 in the agronomist survey: "Please indicate how strongly you agree/disagree with each of the following statements in relation to spring barley". The statements 'I am concerned…' were thought to be too emotive. These will be replaced with less emotive terms, such as 'I think that __ is important'.

2. **Provided answers suit questions?**

Again, overall, this was thought to be fine – the series of most/least questions at the end of each survey was thought to be a bit confusing. It was not clear enough that participants were supposed to choose just one measure as being 'best' and one as 'least'. This will be restructured; the questions may be split, so that there is one question for 'best' and one for 'least' to make this more clear.

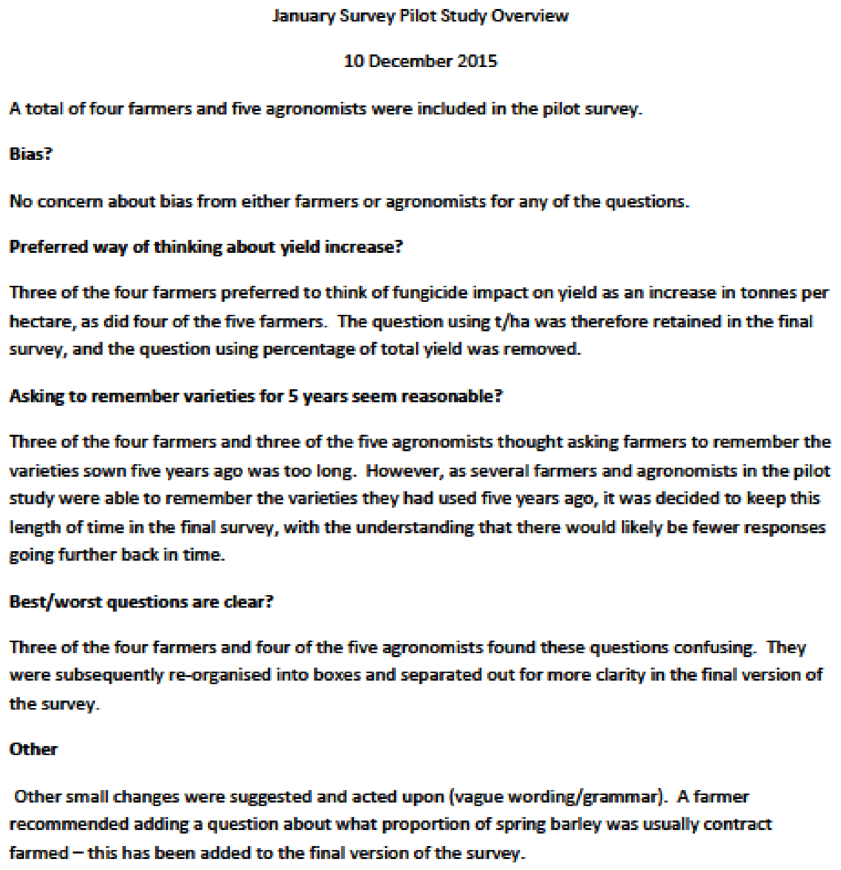
Additionally, question 19 of the farmer survey (13 of agronomist survey), the answers provided were thought to be too vague and open to interpretation. It was suggested that 'always,' 'often,' 'sometimes,' 'rarely,' and 'never' be replaced with '100%,' '75%,' '50%,' '25%,' '0%'.

3. **Questions are clear?**

One question brought up a lot of debate: 28f in the farmer survey (22f in the agronomist survey), it was thought that the phrasing "I think finding alternatives to or techniques which can reduce fungicide use is important" was unclear. There were a number of suggestions about how to best re-word this question, depending on the emphasis we wish to put on it. I will reword this to read: "I think finding techniques which can reduce fungicide use is important".

A number of other, relatively minor, points were brought up (e.g. spelling/grammar) and were corrected in the next draft of the survey.

8.10 Appendix J – Summary of feedback from pilot study



January Survey Pilot Study Overview

10 December 2015

A total of four farmers and five agronomists were included in the pilot survey.

Bias?

No concern about bias from either farmers or agronomists for any of the questions.

Preferred way of thinking about yield increase?

Three of the four farmers preferred to think of fungicide impact on yield as an increase in tonnes per hectare, as did four of the five farmers. The question using t/ha was therefore retained in the final survey, and the question using percentage of total yield was removed.

Asking to remember varieties for 5 years seem reasonable?

Three of the four farmers and three of the five agronomists thought asking farmers to remember the varieties sown five years ago was too long. However, as several farmers and agronomists in the pilot study were able to remember the varieties they had used five years ago, it was decided to keep this length of time in the final survey, with the understanding that there would likely be fewer responses going further back in time.

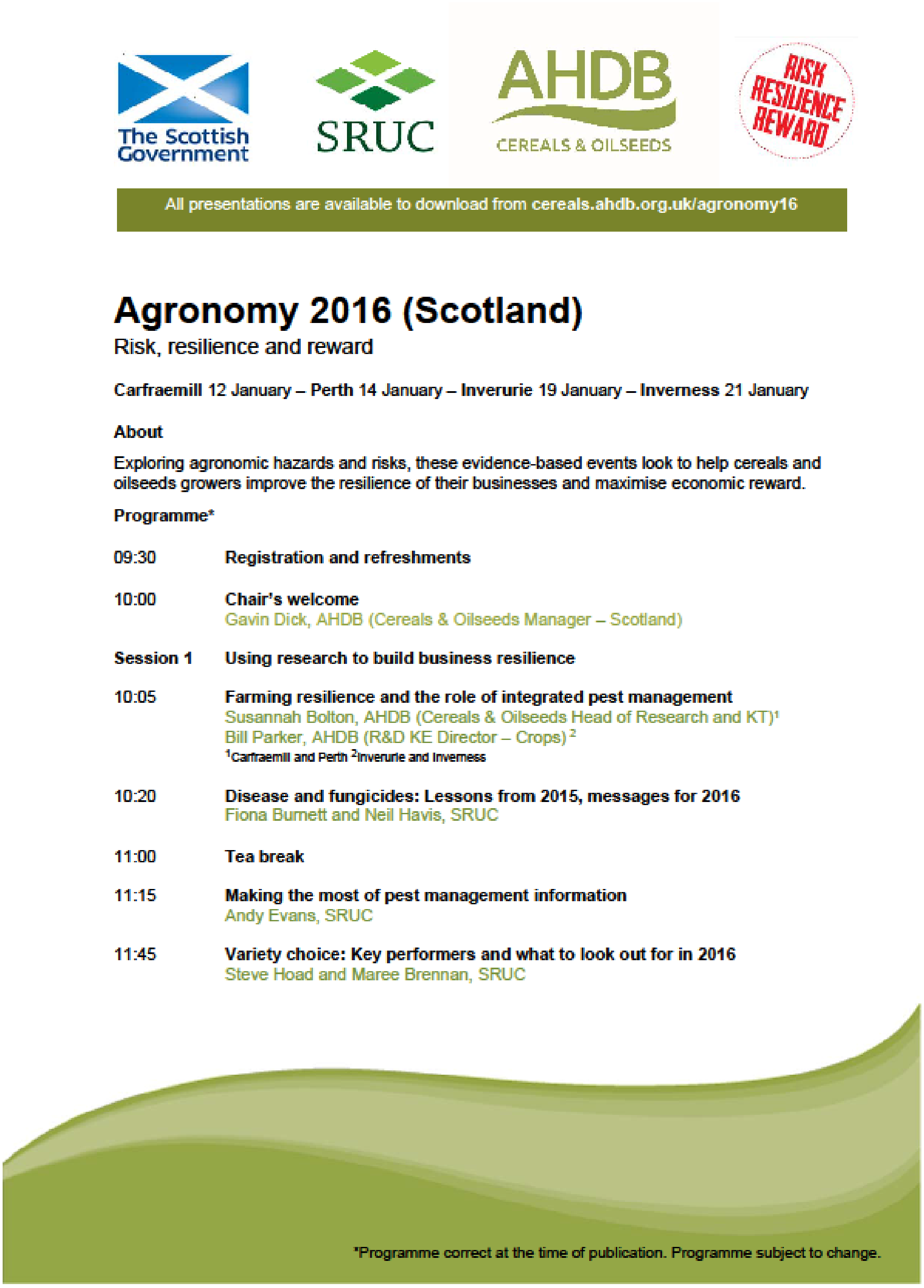
Best/worst questions are clear?

Three of the four farmers and four of the five agronomists found these questions confusing. They were subsequently re-organised into boxes and separated out for more clarity in the final version of the survey.

Other

Other small changes were suggested and acted upon (vague wording/grammar). A farmer recommended adding a question about what proportion of spring barley was usually contract farmed – this has been added to the final version of the survey.

8.11 Appendix K – Agronomy 2016 Agenda



All presentations are available to download from **cereals.ahdb.org.uk/agronomy16**

Agronomy 2016 (Scotland)

Risk, resilience and reward

Carfraemill 12 January – **Perth** 14 January – **Inverurie** 19 January – **Inverness** 21 January

About

Exploring agronomic hazards and risks, these evidence-based events look to help cereals and oilseeds growers improve the resilience of their businesses and maximise economic reward.

Programme*

09:30	**Registration and refreshments**
10:00	**Chair's welcome** Gavin Dick, AHDB (Cereals & Oilseeds Manager – Scotland)
Session 1	**Using research to build business resilience**
10:05	**Farming resilience and the role of integrated pest management** Susannah Bolton, AHDB (Cereals & Oilseeds Head of Research and KT)[1] Bill Parker, AHDB (R&D KE Director – Crops)[2] [1]Carfraemill and Perth [2]Inverurie and Inverness
10:20	**Disease and fungicides: Lessons from 2015, messages for 2016** Fiona Burnett and Neil Havis, SRUC
11:00	**Tea break**
11:15	**Making the most of pest management information** Andy Evans, SRUC
11:45	**Variety choice: Key performers and what to look out for in 2016** Steve Hoad and Maree Brennan, SRUC

*Programme correct at the time of publication. Programme subject to change.

Session 2 Farming fundamentals: AD and its contribution to farming resilience

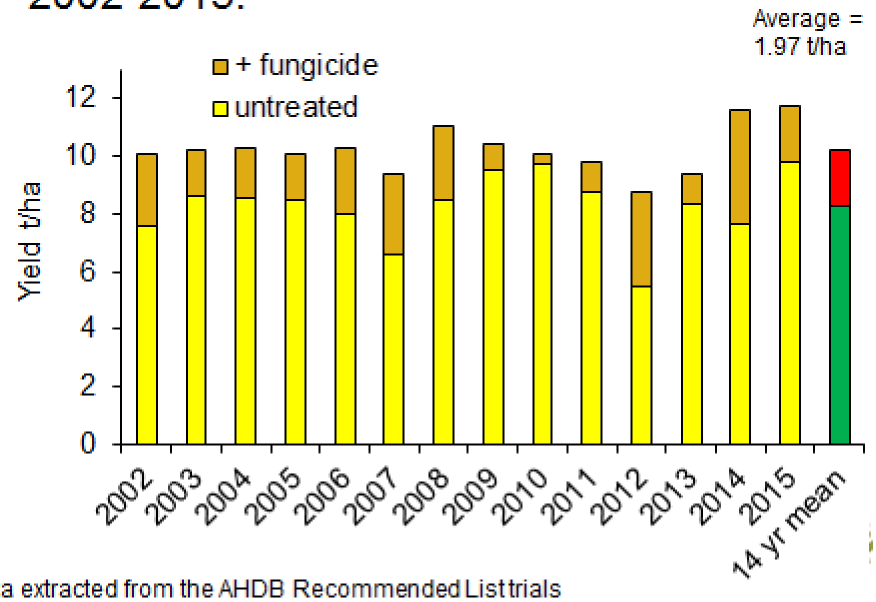
With many growers looking to extend rotations or comply with crop diversification rules, this session will look at the evolution in the anaerobic digestion (AD) market and the role it could play in resilient farming businesses in Scotland.

12:15	**Crop and variety choice: Considerations for AD** David Lawson, SRUC
12:30	**Lunch**
13:15	**Crop choice and market outlook: Simplify or diversify?** Julian Bell, SRUC
13:45	**Renewable energy and the role of AD** Jim Campbell, SRUC
14:05	**Using anaerobic digestate and compost in arable systems** Audrey Litterick, DC Agri
14:35	**Tea break**
14:45	**Renewables: The view of a local grower** Colin McPhail / Alistair Nicholson Meikle, Camoquhill Farm[1 and 2] William Rose, Mid Coul Farms[3] Andrew Booth, Savoch Farm, Foveran[4] [1] Carfraemill [2]Perth [3]Inverness [4]Inverurie
15:15	**The way ahead for energy markets in Scotland** David Lawson, SRUC
15:30	**Closing remarks** Gavin Dick, AHDB Cereals & Oilseeds Manager (Scotland)
15:45	**Event close**

*Programme correct at the time of publication. Programme subject to change.

8.12 Appendix L – Key slides from the 2016 Agronomy presentation “Disease and fungicides: Lessons from 2015, messages for 2016”

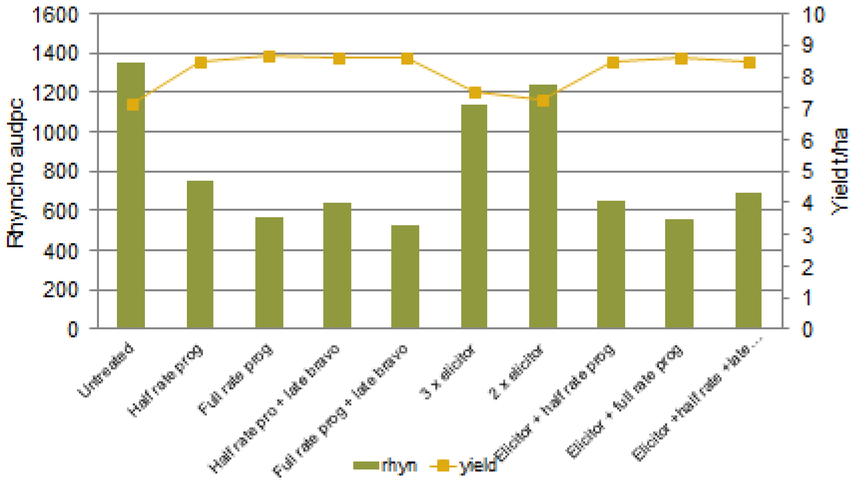
UK Wheat – response to disease control 2002-2015.



Data extracted from the AHDB Recommended List trials

IPM: Alternatives to fungicides

Elicitors in winter barley control programmes

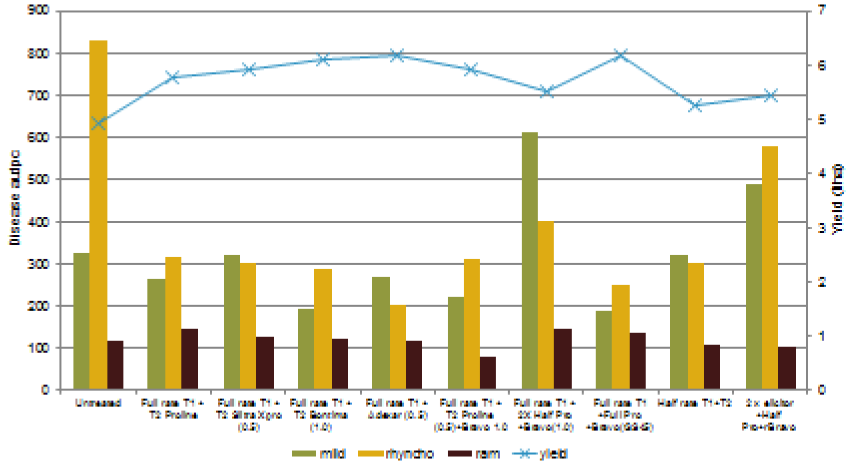


Mean of 2 sites over 2 years

Full Rate prog (T1-Proline 0.36+Comet 0.5)+T2 (Proline 0.36 + Bravo 1.0)

IPM: Alternatives to fungicides

Elicitors in spring barley control programmes

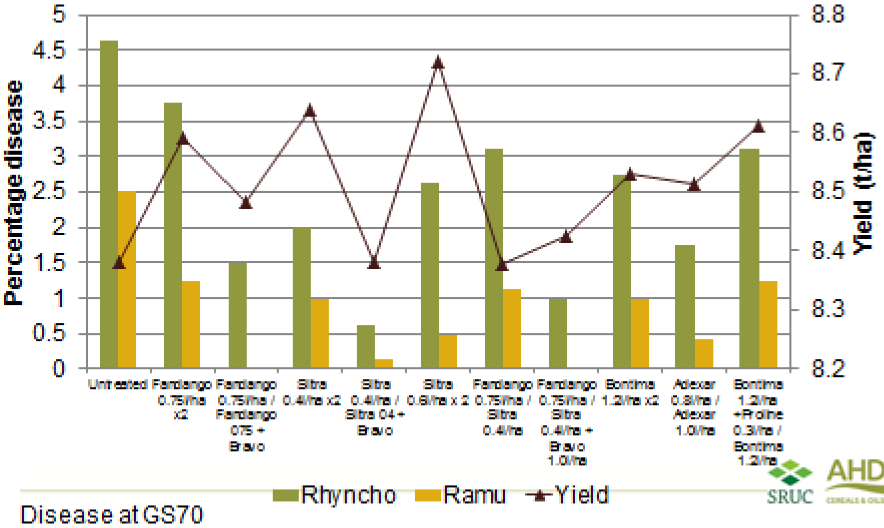


cv Optic Lanark 2015

Full Rate prog (T1-Proline 0.36+Comet 0.5)+ T2 (Proline 0.36 + Bravo 1.0)

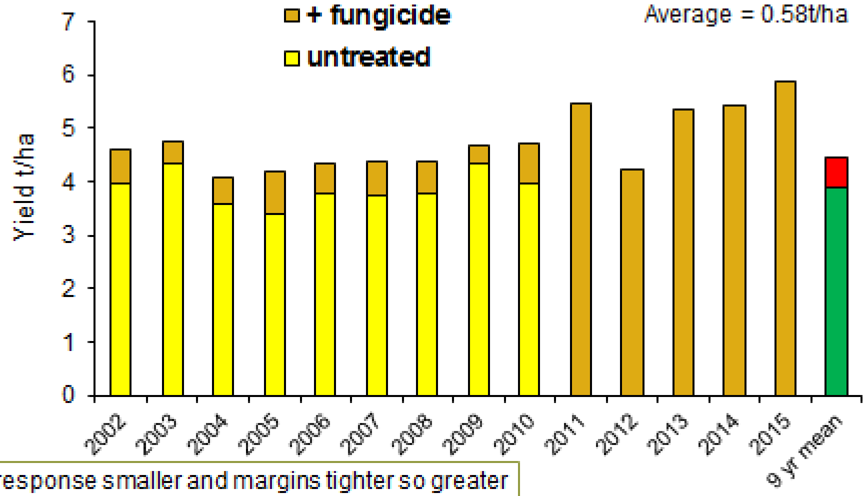
Spring barley programmes

(SD no2003)



Disease at GS70

UK oilseed rape – yields and benefits of disease control.



Yield response smaller and margins tighter so greater need to tailor inputs to likely risks and rewards

Data extracted from the AHDB Recommended List trials

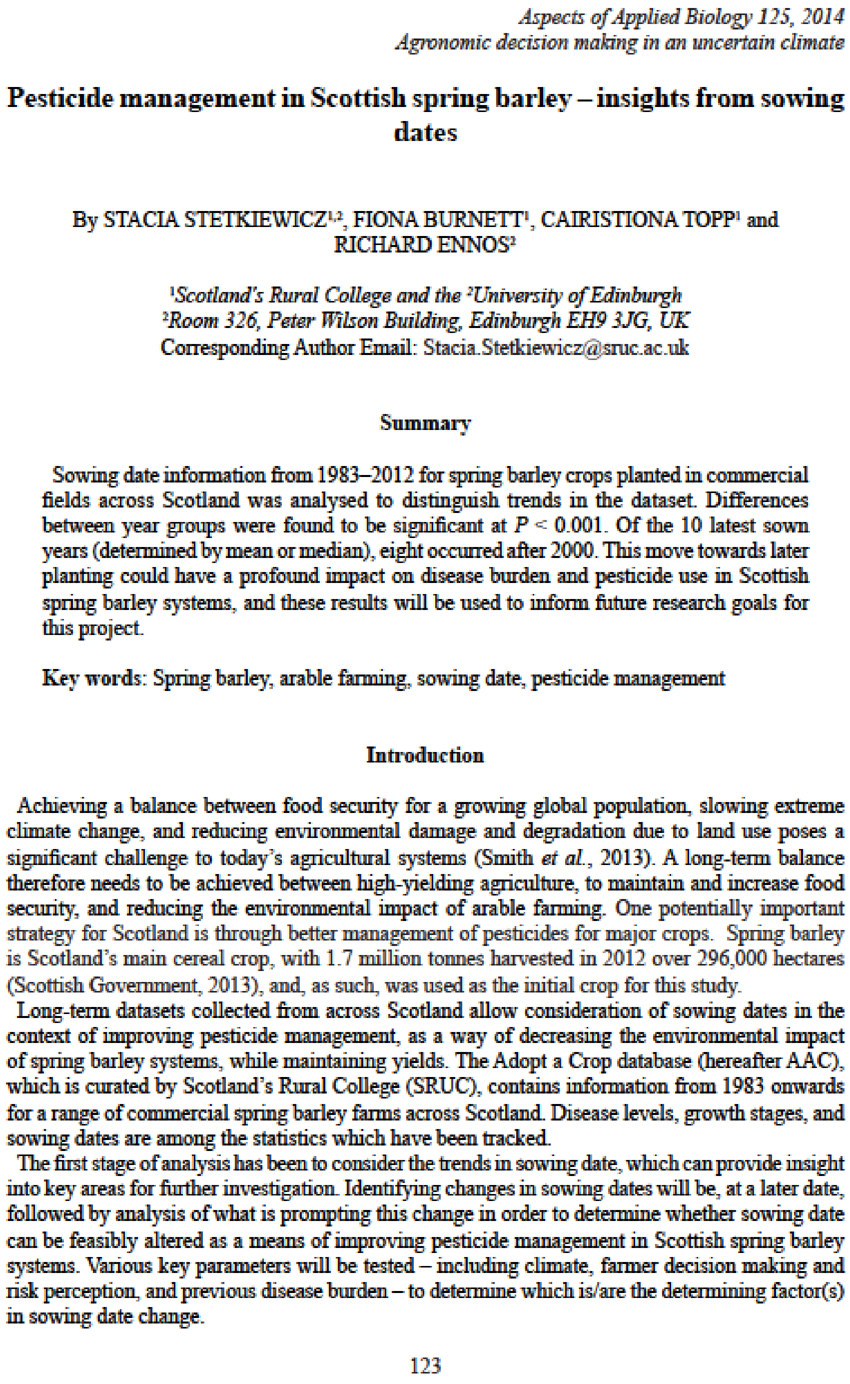
Attitudes and perceptions on IPM in barley – help with survey please!

- What counts as IPM
- How important are cultural methods of controlling disease
- What new practices would you consider
- How good value are fungicides

"Your input will help ensure IPM recommendations are of practical value to scientists, policy makers and farmers"

Stacia Stetkiewicz, SG funded PhD student at SRUC

8.13 Appendix M – Pesticide management in Scottish spring barley – insights from sowing dates (Conference Paper)



Aspects of Applied Biology 125, 2014
Agronomic decision making in an uncertain climate

Pesticide management in Scottish spring barley – insights from sowing dates

By STACIA STETKIEWICZ[1,2], FIONA BURNETT[1], CAIRISTIONA TOPP[1] and RICHARD ENNOS[2]

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[2]*Room 326, Peter Wilson Building, Edinburgh EH9 3JG, UK*
Corresponding Author Email: Stacia.Stetkiewicz@sruc.ac.uk

Summary

Sowing date information from 1983–2012 for spring barley crops planted in commercial fields across Scotland was analysed to distinguish trends in the dataset. Differences between year groups were found to be significant at $P < 0.001$. Of the 10 latest sown years (determined by mean or median), eight occurred after 2000. This move towards later planting could have a profound impact on disease burden and pesticide use in Scottish spring barley systems, and these results will be used to inform future research goals for this project.

Key words: Spring barley, arable farming, sowing date, pesticide management

Introduction

Achieving a balance between food security for a growing global population, slowing extreme climate change, and reducing environmental damage and degradation due to land use poses a significant challenge to today's agricultural systems (Smith *et al.*, 2013). A long-term balance therefore needs to be achieved between high-yielding agriculture, to maintain and increase food security, and reducing the environmental impact of arable farming. One potentially important strategy for Scotland is through better management of pesticides for major crops. Spring barley is Scotland's main cereal crop, with 1.7 million tonnes harvested in 2012 over 296,000 hectares (Scottish Government, 2013), and, as such, was used as the initial crop for this study.

Long-term datasets collected from across Scotland allow consideration of sowing dates in the context of improving pesticide management, as a way of decreasing the environmental impact of spring barley systems, while maintaining yields. The Adopt a Crop database (hereafter AAC), which is curated by Scotland's Rural College (SRUC), contains information from 1983 onwards for a range of commercial spring barley farms across Scotland. Disease levels, growth stages, and sowing dates are among the statistics which have been tracked.

The first stage of analysis has been to consider the trends in sowing date, which can provide insight into key areas for further investigation. Identifying changes in sowing dates will be, at a later date, followed by analysis of what is prompting this change in order to determine whether sowing date can be feasibly altered as a means of improving pesticide management in Scottish spring barley systems. Various key parameters will be tested – including climate, farmer decision making and risk perception, and previous disease burden – to determine which is/are the determining factor(s) in sowing date change.

This initial analysis of sowing dates will provide direction to further research, building on previous studies, to consider a variety of strategies and techniques for reducing environmental impact in the context of Scottish arable farming, using historic crop and input data.

Materials and Methods

Information about key parameters for spring barley was collected from extracts of the AAC database, including sowing date, year, and farm location. Sowing date, which was initially available in the format dd/mm/yyyy, was duplicated and converted to the format ndayinyear, (e.g. 05/01/2001 became 5, as did 05/01/1986) in order to allow the yearly information to be collated and compared. The database was then examined further, and any entries which lacked essential information, i.e. sowing date or location, were removed.

Farms are selected for inclusion in the AAC database by SAC advisors, in local SRUC/SAC offices; the farms are divided between these offices with the number of crops each office adopts broadly reflective of the acreage of that crop in the area. SAC advisors choose farms distributed throughout their area, with a maximum of 50% of these being client farms. The farms therefore varied from year to year, though certain farms have been included multiple times since 1983.

Summary statistics were produced for the dataset, and outliers were reviewed: outliers which were clearly errors, e.g. accidental inclusion of winter barley cultivar data, were removed. Summary statistics were again produced and reviewed for normality. Further analysis was run, including one-way ANOVA to test the null hypothesis that there was no significant difference in sowing date between year groups. Mean, median, and standard error statistics were also produced, and Tukey's multiple range test was carried out for the yearly means, using 95% confidence intervals. Mean sowing dates for before and after 2000 were also calculated for comparison.

Sites were divided into major agricultural regions of Scotland, as defined by the Scottish Government (2005). A one-way ANOVA tested the null hypothesis that there was no difference in sowing date between the regions. Mean, median, and standard error statistics for the regional data were produced, and a Tukey test was carried out. One region was selected for an initial case study (Tayside) as the largest producer of spring barley in Scotland for which a nearly complete dataset was available (covering most of the years 1983–2012). Summary statistics were run for the case study region, and analysis performed as for the Scotland-wide data.

Results

Trends in mean sowing dates – Scotland-wide

The majority of the latest sown years for Scottish spring barley since 1983 have occurred after 2000, as shown in Fig. 1. Both mean and median measurements indicate eight of the 10 latest sown years recorded in the AAC were post-2000. In all of these 10 years the mean and median sowing dates took place on or after 31 March; by contrast, in the earliest-sown year, 1993, the mean sowing date was 12 March, and the median 14 March. The mean sowing date before 2000 was the 26 March (day 85.83 of the year) while the mean sowing date from 2000 onwards was the 3 April (day 93.67 of the year).

Mean sowing dates for each year group (1983–2012, less 1990), and the 10 latest sown years, as determined by mean, have been plotted in Fig. 1. Despite variation in each sample year's size and standard deviation, a one-way ANOVA test indicated that there was more variation between the year groups than within the year groups at $P < 0.001$. Standard errors around the means of each year group were minimal (between 1.033 and 2.96), so are not displayed. Instead, the error bar shown in Fig. 1 indicates the minimum least significant difference, 3.882 at the 5% level.

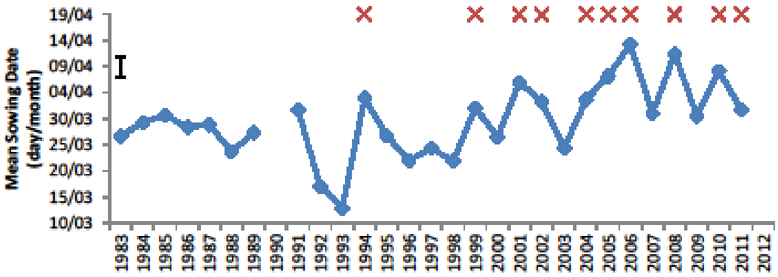

Fig. 1. shows the mean sowing date from the AAC database for each year group (-◊-), calculated for the whole of Scotland. The error bar indicates the minimum least significant difference. The ten latest sowing dates in the period, as determined by mean, are marked with an (X) – eight of these 10 occur after 2000.

Trends in mean sowing date – Scottish agricultural regions

The one-way ANOVA test conducted on the regional data indicated that there was more variation between the regions than within the regions, at $P < 0.001$, with a minimum least significant difference of 2.113 at the 5% level. Mean sowing date for each region, encompassing data from all year groups is summarised in Table 1, alongside standard error of the mean.

Table 2. *Sowing date variation – Scottish agricultural regions*

	Borders	Fife	Highlands and Islands	Lothians	North East	Tayside	West
Mean Sowing Date	March 28	March 27	April 7	March 25	April 4	March 31	April 7
Standard Error of Mean	0.953	1.011	1.380	1.105	0.706	0.70	1.597
Tukey Test Groups	AB	A	C	A	C	B	C

Trends in mean sowing date – Case study: Tayside

Tayside, encompassing Perthshire and Angus, showed a less marked trend towards later sowing than Scotland as a whole during the survey period, yet still had a large number of latest sown years occurring post-2000, as summarised in Table 2.

Table 2. *Sowing Date Variation – Case Study: Tayside*

Number of latest sown years occurring on or after 2000	Latest sown year determined by
6 of 10	Mean
5 of 10	Median

Discussion

As indicated in Fig.1 and through the change in mean sowing date before and after 2000, despite variation within year groups, a general trend towards later sowing of spring barley in Scotland is visible in this analysis. Yet, as the case-study indicates, this trend may be less pronounced in certain regions of Scotland.

Sowing date changes can profoundly impact on the system, as late sowing may increase the impact of aphids and barley yellow dwarf virus (Mann *et al*., 1997), while reducing yield and quality for malting barley (Conry, 1997). However, burdens of certain pests and diseases may be reduced by late sowing, such as wheat bulb fly, and, if sown after grass, leatherjackets (DEFRA, 2003). It is therefore important to consider what factors have caused this shift in sowing date, and how this change interacts with a variety of parameters, including disease levels and pesticide use, in order to more fully understand the impact of sowing date change on Scotland's spring barley systems.

Limitations

These preliminary results are limited in their scope, somewhat, by the lack of sowing date information for the year 1990, which is unavailable at the time of writing, but which will be considered in further research on this topic. Additionally, the case study results from Tayside may be skewed by the fact that the region's dataset is missing information for 2 years (in addition to 1990) – 1993 and 2008, and therefore may be less informative than the Scotland-wide results. This lack of data may also have implications for the national-level results – e.g. early sowing in 1993 for the whole of Scotland may be influenced by the lack of Tayside data for that year – an issue which will be reviewed in future.

Further research

Initial steps have been taken to analyse spring barley sowing dates by county as well as to consider each agricultural region, and further tests will examine links between climate change and sowing date. Parameters such as rainfall, soil temperature, and daily mean temperature will be examined for any correlation with sowing date. Further work will also be undertaken to identify trends within and between agricultural regions, to expand on the initial analysis summarised in Table 1.

Identifying trends within and links between the parameters in the AAC database will lead to a more thorough understanding of the current and past state of spring barley production in Scotland. This analysis should enable research to identify particular practices which could be improved upon, and gaps where techniques for reducing the environmental impact of Scotland's arable farms could be exploited, without decreasing yields.

The utility of such techniques in the decades to come, as well as the feasibility of introducing these methods, taking into account issues like regulation and farmers' attitudes towards risk, will also be analysed in future iterations of this work.

Acknowledgements

This project was funded through the Socio-economic and Interdisciplinary Research Capacity Building Project, under Theme 4: Additional Work in Economic Adaptation of the Scottish Government Rural Affairs and the Environment Portfolio. The Crop Health Advisory Activity under which the AAC date is collected is funded by Scottish Government through its Veterinary and Advisory Service (VAS) Programme.

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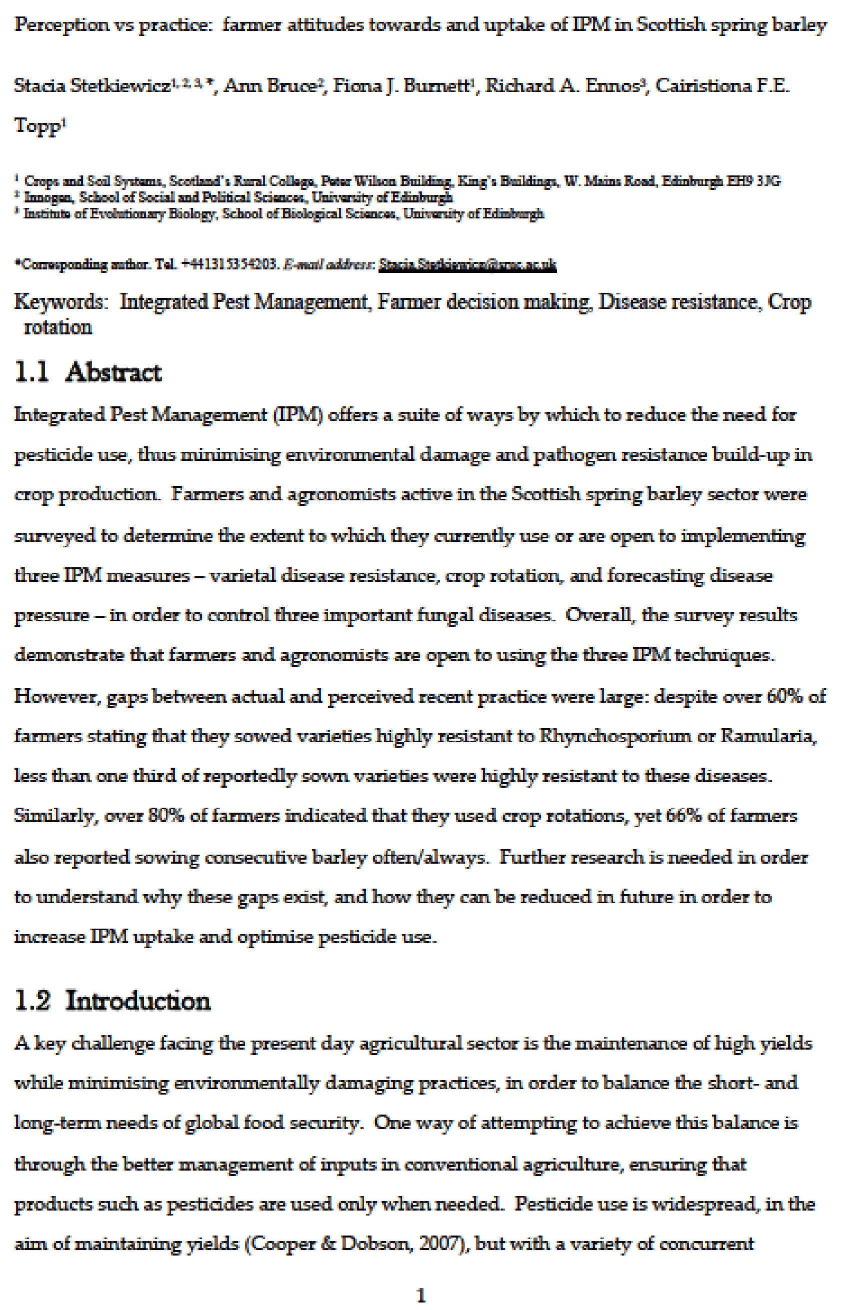
The Scottish Governement. 2013. *Statistical Publication*. <http://www.scotland.gov.uk/Publications/2013/12/8414>.

8.14 Appendix N – Stetkiewicz et al., 2017. Perception vs practice: farmer attitudes towards and uptake of IPM in Scottish spring barley (journal article, submitted to Crop Protection)



Perception vs practice: farmer attitudes towards and uptake of IPM in Scottish spring barley

Stacia Stetkiewicz[1, 2, 3, *], Ann Bruce[2], Fiona J. Burnett[1], Richard A. Ennos[3], Cairistiona F.E. Topp[1]

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Keywords: Integrated Pest Management, Farmer decision making, Disease resistance, Crop rotation

1.1 Abstract

Integrated Pest Management (IPM) offers a suite of ways by which to reduce the need for pesticide use, thus minimising environmental damage and pathogen resistance build-up in crop production. Farmers and agronomists active in the Scottish spring barley sector were surveyed to determine the extent to which they currently use or are open to implementing three IPM measures – varietal disease resistance, crop rotation, and forecasting disease pressure – in order to control three important fungal diseases. Overall, the survey results demonstrate that farmers and agronomists are open to using the three IPM techniques. However, gaps between actual and perceived recent practice were large: despite over 60% of farmers stating that they sowed varieties highly resistant to Rhynchosporium or Ramularia, less than one third of reportedly sown varieties were highly resistant to these diseases. Similarly, over 80% of farmers indicated that they used crop rotations, yet 66% of farmers also reported sowing consecutive barley often/always. Further research is needed in order to understand why these gaps exist, and how they can be reduced in future in order to increase IPM uptake and optimise pesticide use.

1.2 Introduction

A key challenge facing the present day agricultural sector is the maintenance of high yields while minimising environmentally damaging practices, in order to balance the short- and long-term needs of global food security. One way of attempting to achieve this balance is through the better management of inputs in conventional agriculture, ensuring that products such as pesticides are used only when needed. Pesticide use is widespread, in the aim of maintaining yields (Cooper & Dobson, 2007), but with a variety of concurrent detrimental effects, such as non-target organism toxicity (Beketov et al., 2013), reduced soil biodiversity and health (Walia et al., 2014), and threats to human health (Weisenburger, 1993). Additionally, overuse of, and overreliance upon, pesticides can lead to pests and pathogens developing resistance to active ingredients, thereby reducing their efficacy (E. Birch et al., 2011; Fungicide Resistance Action Committee, 2012). The Scottish Government (2016) recommends the use of Integrated Pest Management (IPM), to combat the development of disease resistance, reduce risks to human health, and provide environmental benefits.

IPM is an ecosystem approach which encompasses a variety of techniques for management of pests and diseases, used in combination, and aiming to decrease pesticide use (FAO, 2016). Pesticide use is not prohibited under IPM; rather, the aim is to reduce the need for pesticides, by minimising the likelihood of an epidemic. IPM was first conceptualised over 50 years ago (Stern et al., 1959), yet little is known about its adoption, the barriers to its uptake, and how it is perceived by farmers. In recent years, several surveys of farmers have been carried out in order to gain understanding of IPM-related attitudes, uptake, and priorities – some of these provide case-studies of specific systems (Ilbery et al., 2012; Sherman & Gent, 2014), while others consider a broader range of systems and questions (ADAS, 2002; Bailey et al., 2009; Lamine, 2011). Despite a growing body of literature, relatively little is known about farmer attitudes towards IPM, still less that is relevant in the context of Scottish spring barley (the principle arable crop in Scotland). Information on this topic could aid in focusing research and policy decisions. A number of key legislation changes have also occurred in recent years, including the EU Sustainable Use Directive, which requires member states to support the uptake of IPM (DEFRA, 2013). In light of these changes, revisiting the issues surrounding uptake and interest becomes a useful exercise.

As the uptake of and attitudes towards IPM are intertwined with market forces and product availability, surveying stakeholders may provide insight into the complex realities which influence IPM decisions. This survey builds on previous work which analysed risk, attitudes towards innovation, and sources of information relating to IPM in the UK (Bailey et al., 2009; ADAS, 2002; Ilbery et al., 2013), with a focus on three key fungal diseases affecting spring barley in Scotland – Mildew (caused by *Blumeria graminis f. sp. hordei*), Rhynchosporium (caused by *Rhynchosporium commune*), and Ramularia (caused by *Ramularia collo-cygni*). A case-study approach was taken, analysing farmer and agronomist perceptions of three IPM strategies in relation to key fungal diseases of spring barley, providing a snapshot of current barriers and attitudes.

1.2.1 **Survey Aims**

The primary goal of this survey was to understand the extent to which farmers would be open to implementing, or had already made use of, three IPM strategies identified as having the potential to reduce the need for fungicide use in the cultivation of Scottish spring barley, namely: planned crop rotation, varietal disease resistance, and forecasting disease pressure. Results from the latter IPM technique are not discussed in detail this paper, as sufficient data to compare actual and perceived uptake of forecasting were not gathered in this survey. The primary target population identified was Scottish spring barley farmers, with a secondary target population of agronomists involved in the production of Scottish spring barley, of which a convenience sample was taken in order to obtain a large number of responses despite limited resources. Surveying both farmers and agronomists also allowed for a direct comparison of their opinions and perceptions, providing insight into persistent patterns between the two groups.

1.3 Methods

1.3.1 **Designing the survey**

The survey was designed to be run at the annual agronomy events co-hosted by Scotland's Rural College (SRUC) and Agriculture and Horticulture Development Board (AHDB): Cereals and Oilseeds, where a series of presentations by experts were given around the theme of risk, resilience, and reward at Carfraemill (Scottish Borders), Perth (Tayside), Inverurie (North East), and Inverness (Highlands) during January 2016. These four sites represent a useful geographical spread for data collection, as they are distributed across the main cereal production areas in Scotland. Different farm structure, as assessed at regional level, is also captured by this sample; for example, the Tayside and Scottish Borders regions have more large holdings (>200ha) than average, while Highland has fewer than average (Scottish Government, 2015). A total of 288 surveys were given out across the four locations (Carfraemill – 100; Perth – 81; Inverurie – 71; Inverness – 36). The survey comprised six sections, where farmers were asked about a range of issues relating to IPM, as well as demographic details. Farmers were asked how often they sowed varieties which were highly resistant to each disease, and to list the varieties they had sown in the past five years, alongside how often they sowed consecutive barley/cereals. Questions were also included relating to attitudes towards fungicide use, and the perceived impact of fungicide use on spring barley yields. Best-worst scaling questions were included to assess which IPM techniques farmers would be most/least open to taking up and which were most/least practical overall and in terms of cost.

To obtain the most relevant information possible, participants were instructed to respond about their majority practices in the survey, recognising that there may be variation at field level within the farm. All farmers at the events who grew spring barley in some capacity were invited to participate, as were agronomists who were involved in decision making for spring barley. The appropriate ethical guidelines were followed for the University of Edinburgh, SRUC, and Scottish Government. The questionnaire went through a number of iterations with feedback given first by a pre-pilot group of seven PhD students, then by a pilot group of four farmers and five agronomists. Pilot participants were asked to give general feedback about the wording of questions and their answers, as well as specific feedback for key questions highlighted in the pre-pilot study and follow-on discussions.

1.3.2 **Analysis**

Final results from the questionnaire were first analysed for sampling bias. Consistency across sites was verified for demographic questions (e.g. age and education), as well as one question chosen at random from each survey section. A summary of the sample population was then developed, and compared with the target population statistics available from the Scottish Government. Finally, to verify a lack of attendance bias between sites, several key questions were summarised based on location of survey completion and compared. For questions relating to varietal resistance, comparisons were made using the SRUC/SAC Cereal Recommended Lists for the relevant year (2011; 2012; 2013; 2014).

1.4 Results

1.4.1 Survey demographic

A total of 43 farmers and 36 agronomists responded to the survey, giving an overall response rate of 27% (Carfraemill – 15%; Perth – 31%; Inverurie – 30%; Inverness – 44%). Farmers surveyed presented a young, highly educated population with slightly larger farms than average (Scottish Government, 2015). The spring barley producing regions of Scotland were well represented in the survey, with only two of the national sub-regions having a discrepancy of over 10% between the survey population and the Economic Report on Scottish Agriculture 2015 percentage of surveyed farms in each region: overrepresentation of the Highlands (15% difference); and underrepresentation of Tayside (18% difference). Distilling was the main spring barley market for more than three quarters of the surveyed farmers. A large proportion (45.24%) of the farmers were affiliated with an environmental scheme or programme, as compared to the 28% of Scottish agricultural land reported to be under an agri-environmental scheme in 2014 (Defra, 2015). The regions in which agronomists advised farmers were similar to those represented in the farmer survey, and all agronomists indicated that they were experts in relation to spring barley. More than half of the agronomists surveyed (55.6%) were affiliated with trade/distribution.

1.4.2 Disease perception and varietal choice

Farmer survey – disease perception

Most farmers (94.6%) believed that foliar diseases of spring barley were important or very important in determining yield, with Rhynchosporium indicated by the majority as being the most common of the three pathogens on spring barley in the past five years, as well as having had the greatest impact on yield.

Farmer survey - varieties

Farmers were asked to list the top three varieties of spring barley they had sown in the past five years – the large majority of these, for which information is available in the 2011 – 2015 SRUC Cereal Recommended Lists, were distilling varieties. Over 60% of farmers stated that the varieties they sow are often or always highly resistant (a rating of 7 or more on the Recommended List was specified as being 'highly resistant' in the survey) to each of the three diseases in question. However, while 84.6% of varieties sown by farmers were highly resistant to Mildew, for Ramularia only 27.3% were highly resistant, and for Rhynchosporium 23.1%. In most years the majority of varieties cultivated had lower disease resistance ratings than the 'best available choice' – that is, the distilling variety with the highest average disease resistance rating in that year (see Table 1). Over 75% of the varieties listed by farmers who stated that they always/often sow highly resistant varieties to mildew were, in fact, highly resistant to mildew – by contrast, for Rhynchosporium and Ramularia, less than 25% of these were highly resistant according to the Recommended Lists. Farmers who stated a given disease is the most common/impacts yield most did not sow a higher proportion of varieties which were highly resistant to that disease for Mildew or Ramularia, however, where farmers thought Rhynchosporium impacted yield most, a higher proportion of varieties they sowed were highly resistant. Despite farmer self-reporting that they often/always sow highly resistant varieties for all three diseases, then, this was not actual practice for Rhynchosporium in 2011-15 or Ramularia in 2012 – 15 (Ramularia was not included in the Recommended List resistance ratings prior to 2012, so published information is not available for comparison in 2011).

Table 1: Disease resistance of the varieties sown by surveyed farmers

Year	Disease	Percent of varieties listed which were highly resistant to this disease	Percent of varieties listed which were below the best possible choice	Average varietal resistance rating for this disease	Standard error of mean varietal resistance rating
2015	Mildew	88%	20%	8.5	0.14
	Rhynchosporium	0%*	70%	4.6	0.12
	Ramularia	15%	13%	6.1	0.13
2014	Mildew	90%	68%	8.0	0.15
	Rhynchosporium	31%	69%	5.7	0.19
	Ramularia	22%	78%	6.1	0.07
2013	Mildew	90%	75%	8.0	0.15
	Rhynchosporium	23%	77%	4.6	0.20
	Ramularia	23%	77%	6.1	0.08
2012	Mildew	76%	76%	7.5	0.02
	Rhynchosporium	18%	90%	4.6	0.22
	Ramularia	9%	5%	6.0	0.06
2011	Mildew	70%	78%	7.3	0.25
	Rhynchosporium	28%	100%	4.8	0.23

* No fully approved malting varieties on the Scottish Recommended List were highly resistant to Rhynchosporium in 2015

Agronomist survey

The varieties recommended by agronomists and those listed by farmers were broadly similar, with four of the five most commonly recommended also being the most commonly sown. The pattern of disease resistance for varieties recommended by agronomists was similar to that of the varieties sown by farmers – despite a majority of agronomists stating that they always/often recommended highly resistant varieties for each disease, most varieties listed were highly resistant to Mildew (84.6%) in clear contrast to Ramularia (11.1%) and Rhynchosporium (30.8%).

1.4.3 Use of rotations

Farmer survey

All but five of the surveyed farmers stated that they used rotations, and the factor which ranked most highly in terms of influencing the decision to use this rotation was 'to spread risk of low yields/crop failure' with disease reduction being second. Of the five farmers not using rotations, the need to fulfil contracts for their main crop, and thus the need to sow large amounts of land to a single crop was the mostly highly ranked factor influencing their lack of rotation use. However, the majority of farmers often or always sow barley and/or cereals consecutively – 66.67% and 82%, respectively (see **Error! Reference source not found.**). Farmers who chose disease reduction as one of their top two reasons for using a rotation were more likely to rarely/never sow consecutive barley/cereals than their counterparts, but consecutive sowing remained the norm in this group.

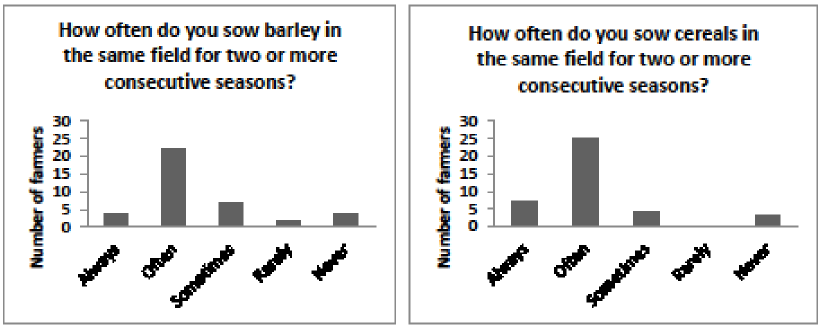

Figure 1: Self-reported frequency of use of consecutive barley or cereals

Agronomist survey

When recommending a rotation, the highest ranked factor involved in the decision was to reduce fungal disease, while the highest ranked factor when agronomists did not recommend a rotation was the need to fulfil contracts for the main crop. A majority of agronomists (60.6%) often/always recommended sowing consecutive cereals. Recommending sowing consecutive barley was less common, with just under half of the agronomists (48.5%) suggesting this often/always.

1.4.4 Fungicide use

Farmer and agronomist survey

Fungicide use was widespread amongst the surveyed farmers, with 37 of 39 applying fungicides to their spring barley crop every year. The impact of fungicide use on spring barley yields was thought to be an increase of 1-2 tonnes per hectare by most farmers

(72%) and agronomists (75%) (see Table 2). The majority of agronomists recommended fungicide use to farmers for foliar diseases in spring barley every year to every client.

Table 2: Farmer and Agronomist estimation of the increase in spring barley yields due to fungicide use

How much (in t/ha) do you think fungicide use increases spring barley yields by?

	Number of farmers	Percent of farmers	Number of agronomists	Percent of agronomists
Less than one tonne per hectare	5	12.8%	5	15.6%
1 - 2 tonnes per hectare	28	71.8%	24	75.0%
2 - 3 tonnes per hectare	5	12.8%	2	6.3%
3 - 4 tonnes per hectare	1	2.6%	1	3.1%
More than 4 tonnes per hectare	0	0.0%	0	0.0%

1.4.5 Perceptions of IPM strategies and fungicides

Farmer survey

More than 80% of farmers were open to reducing their fungicide use if they could achieve the same yields and/or have fungicide reduction be cost-effective. A majority were also concerned about fungicide resistance, the amount of fungicides that they themselves use, and felt that finding methods to reduce fungicide use is important (see Figure 2).

A series of best-worst scaling questions asked farmers first about the perceived practicality and second the perceived practicality in terms of cost of implementation of each IPM technique. For both of these questions some farmers chose each technique as most/least practical, with sowing only disease resistant varieties being most popular overall – this is shown in the bubble plot in Figure 3, which represents the combinations of choices made by farmers. The overall most preferred selections are in the top right hand corner of the graph – e.g. where a farmer has chosen a given technique as best both in terms of practicality and cost-effectiveness. As bubble size indicates the number of times a given combination was chosen, the outer colour of the bubble indicates the IPM technique which was most frequently chosen for this combination. Sowing only disease resistant varieties was most frequently chosen as the 'best' technique, both in terms of practicality and cost, though all three techniques were identified as both 'best' and 'worst' by some farmers. All three techniques are therefore suitable for some of the survey population, and not for others – none are universally unacceptable.

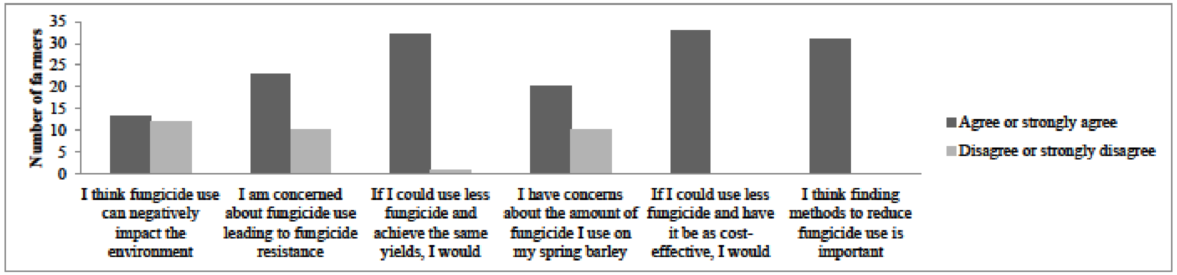

Figure 2: Summary of farmer's polarised attitudes towards fungicide use

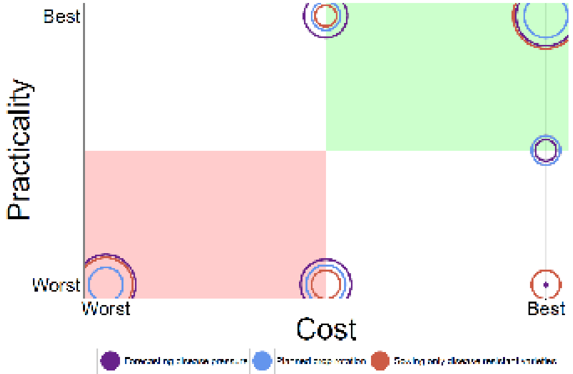

Figure 3: Best-Worst Scaling bubble plot of farmer perceptions of IPM techniques in terms of cost and practicality of implementation

Agronomist survey

A majority of agronomists strongly agreed or agreed that if using less fungicides could achieve the same yields or be as cost-effective, they would recommend using less fungicide, were concerned about fungicide resistance and felt finding methods to reduce fungicide use was important. Each IPM technique was chosen as best/worst by at least one agronomist in terms of practicality and cost. All three IPM techniques were already being recommended by agronomists.

1.5 Discussion

Farmer's reactions towards the IPM practices presented were generally positive, with some farmers willing to take up each measure. However, a contradiction between farmer perception of their own IPM uptake and their self-reported practices was noticeable, in regards to both varietal disease resistance and rotation use. Farmer openness to IPM and lack of uptake – as evidenced by low proportions of varieties being highly resistant to key diseases, and high proportions of farmers sowing consecutive barley – provide a clear suggestion that IPM application can be improved in Scottish spring barley production. The results presented here should be interpreted with caution due to the relatively small sample size of 43 farmers, as well as the bias potentially introduced through the sampling strategy.

1.5.1 Bias potentially introduced by Agronomy events

The similarity in topic between the survey and the focus of the events (Risk, Resilience, and Reward) presented both an opportunity to increase participation and an area of potential bias. A number of presentations specifically mentioned IPM, and discussed fungicide use on cereals, thus priming participants to consider these issues, possibly prior to completing the survey. Participants may have been influenced in particular by "Disease and fungicides: Lessons from 2015, messages for 2016," a presentation in which were discussed trial results from SRUC work during the past year regarding key fungicides for spring barley, oilseed rape, and wheat. In order to reduce bias, no results were presented which specifically stated the impact of fungicide use on yields of spring barley. Although this information was presented for both oilseed rape and wheat trials, the potential for generating bias may have been mitigated to some extent by the fact that the impacts of fungicide presented for these two crops were dissimilar (1.97 t/ha for wheat vs 0.58 t/ha for oilseed rape). An upper and lower conceptual limit of the extent to which fungicide use can impact yield may have been suggested by this presentation, however, of approximately two tonnes and a half tonne per hectare respectively.

While measures were taken to reduce the direct influence of the events on survey results, the self-selection bias which is inherent in all voluntary surveys will here be magnified by the initial self-selection of attendance at events relating to disease management. While not all presentations focused on IPM, and some farmers may have attended solely to discover which fungicides would be best suited to their crops in 2016, the impact of the numerous mentions of IPM on participant mentality while completing the survey must be recognised. Survey results should therefore be interpreted in this light – farmers represented not only an early adopter of innovation group, based on age, farm size, and education characteristics (Diederen et al., 2003; Rogers, 1961), but also a group which was primed to consider IPM in a positive light. The survey results should be seen as a best case scenario, from the perspective of openness to IPM.

1.5.2 Farmer attitudes towards IPM

That farmers had concerns about fungicide use leading to resistance was evident, as was their willingness to reduce fungicide use if this could be cost-effective. Interest in using the three IPM strategies presented was more variable within the group. All three strategies received some positive and some negative responses, with no single technique being preferred by a large majority of farmers. Agronomist responses were similarly open, with each technique being chosen as 'best' by some participants and 'worst' as others, with the use of highly resistant varieties being most commonly preferred.

1.5.3 Discrepancies between perception and practice

In spite of this generally positive attitude towards IPM, a clear mismatch was seen between perceptions/intent and actual practice for both IPM techniques investigated in detail in the survey – varietal disease resistance and rotation – as well as the impact of fungicide use on yield. First, a disparity was seen between farmer perceptions of their use of highly resistant varieties and the reality of varietal disease resistance, based on their own lists of varieties sown in the past five years. While the majority of farmers stated that they sowed highly resistant varieties to all three diseases, disease resistance ratings for the varieties listed by farmers for Ramularia and Rhynchosporium contradicted this. Differences between perceived and actual behaviour have long been studied in the field of psychology, and recent work, (e.g. Niles, Brown and Dynes, 2016) has expanded this to include studies of farmers and climate change, showing that intended and actual adoption of climate change mitigating management strategies were dissimilar. To the best of our knowledge, the contradiction between practice and perception has not, however, been reported in the context of IPM uptake before.

That this gap was mirrored in the agronomist survey highlights how widespread the pattern is, and may, in fact, perpetuate the discrepancy. Recent work on relationships between farmers and agronomists has shown that, though there are a number of agronomist-farmer relationship types, agronomists are frequently seen as experts whose advice is crucial in decision making (Ingram, 2008; Sherman & Gent, 2014). A similar gap was seen in relation to rotation use in the survey. Nearly all farmers surveyed stated that they used rotations, with disease reduction being the second most highly ranked reason for using a rotation, after spreading risk. Due to the nature of a rotation, it is not possible from the data collected to be certain which crop disease(s) farmers are primarily using rotations in order to manage. The fact that the majority of farmers are often/always sowing both consecutive barley and cereals, despite disease reduction being a highly ranked reason for using rotation is, however, concerning, as consecutive sowing may undermine any disease reduction objectives farmers have, by maintaining inoculum sources across years.

These disparities between perception and reality have concerning implications for the uptake of IPM techniques. If farmers and agronomists believe themselves to be using IPM to its fullest, e.g. sowing highly resistant varieties and using crop rotations, they may be more likely to dismiss these as options for further reducing disease burden. Further, farmer surveys should be cautious when interpreting self-reported farmer information, as answers to indirect questions (e.g. 'How often do you use crop rotations' vs 'How often do you sow consecutive barley') may be misleading.

Market forces, which have long been recognised as a key driver in the complexities of farm risk and innovation (Ghadim & Pannell, 1999; Marra et al., 2003; Hughes et al., 1999), are likely to be influencing farmer uptake of IPM methods, as varietal choice is restricted to the varieties preferred by the market, and rotation plans may change in response to grain prices. That varietal choice is not simply a matter of resistance rating versus potential yield is clear, as illustrated by the varieties sown by surveyed farmers in 2015: 55% of farmers sowed Concerto, while 10% chose Odyssey. Both varieties had full brewing and distilling approval, and the same disease ratings for Mildew and Ramularia; Odyssey had a Rhynchosporium rating of 6, while Concerto had a rating of 4. The estimated yield for Odyssey was also higher, at 6.94 t/ha versus 6.53 t/ha for Concerto. By these metrics, then, Odyssey is the variety which would be expected to be widespread. That the reality is the inverse suggests other factors are at play, such as barley contracts which specify the variety to be produced, seed availability, or farmer preference for other varietal characteristics. Resistance rating may therefore be used in decision making as a 'deal breaker' when choosing between two or more varieties of equal market value, rather than vice versa.

Other IPM techniques may be seen in a similar manner – for example, farmers may generally use crop rotations, but alter this when market prices indicate it would be beneficial to do so. Clearly, this approach makes financial sense in the short-term, however as benefits from IPM are cumulative, breaks in IPM use reduce efficacy in the long-term. This, in turn, may cause stakeholders to question their effectiveness, and thus break the cycle again. It is crucial for farmers to both understand their actual practice on farm to ensure IPM perceptions are based on reality, as well as to be willing to continue using IPM in a longer term context in order to see full the full benefits.

1.6 Conclusions

Farmer attitudes towards the IPM measures of interest were broadly positive – each technique was thought to be most practical and cost effective by some farmers, and can therefore be posited as feasible options in relation to IPM uptake in Scottish spring barley. However, the two IPM techniques which were investigated in further detail – planned crop rotation and sowing disease resistant varieties – showed a substantial gap between farmer perception and practice, such that where these techniques were being used by farmers they were not fully optimised. This has implications for overall uptake of IPM measures. If farmers believe themselves to be using an IPM technique to its fullest and yet not reaping any benefits, this could cause drop off in usage and/or dissuade them from taking up new

IPM measures. The reasons behind this gap are not fully understood, but could include lack of trust in official sources of information (e.g. Cereal Recommended Lists) or an inaccurate reflection of practices on farm in the survey results, for example due to poor memory of varieties sown. There may be a need for more targeted information transfer between scientists and farmers, as has been recommended for integrated weed management (Wilson et al., 2009), in order to improve knowledge about disease resistance and rotations. Further research into gaps between perceived and actual practice could deepen understanding of this phenomenon and help to produce relevant policy and scientific recommendations.

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