Institution: University of Edinburgh / Scotland's Rural College		
Unit of Assessment: 6		
Title of case study: A: Improving disease management practice in barley leads to increased yields and safeguards against pathogen resistance		
Period when the underpinning research was undertaken: 2001 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Ian Bingham	Chair of Crop Physiology	1987 – present
Fiona Burnett	Chair of Applied Plant Pathology	1992 – present
Neil Havis	Senior Lecturer	1996 – present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Underpinning Research: Our research has defined the optimal timing and chemical composition of fungicides to maximise yield from barley crops and has quantified changes over time in fungicide efficacy and pathogen resistance to fungicide.

Significance and Reach of Impact: Our research has, since 2006, formed the basis of the definitive national farming advice in the UK through two Agriculture and Horticulture Development Board (AHDB) Guides (*Barley Growth* and *Barley Disease Management*), latest editions of which were published in 2018 and 2016, respectively. Our research also shaped the advice offered to Irish farmers through the Teagasc Spring Barley Guide, published in 2015. Adherence to this guidance leads to the use of optimal fungicide programmes, through use of the most efficacious fungicides and optimal timing of fungicide application. This helps to minimise barley yield loss and benefits the UK and Irish barley industries by up to GBP113,609,000 and EUR18,300,000 (GBP16,220,235; 08-20) per year, respectively.

Our research on the development of pathogen resistance to fungicide allows the AHDB to advise farmers on the best practices for preventing resistance development. Uptake of this advice has extended the effective lifespan of key fungicides by 2 years, which according to a leading agrochemical company has a value of EUR3,700,000 [GBP3,315,792; 08-20].

2. Underpinning research

The Challenge: How to optimise barley disease management in the UK and Ireland
Barley is the most widely grown crop in Scotland and the Republic of Ireland, and the second most widely grown in the UK. Diseases of barley crops are managed through annual application of fungicides. However, inappropriate use of fungicides, whether through incorrect timing of application or use of lower efficacy products, can adversely affect yield and is a major contributor to pathogens developing resistance to fungicides. Optimal fungicide programmes, comprising both optimal timing of application and selection of the most efficacious fungicides, are therefore important, for both maximizing productivity and safeguarding against fungicide resistance.

Our research has developed a thorough understanding of the effects of disease and the timing and selection of fungicides on the levels of yield in barley, as well as an understanding of how optimising fungicide programmes can prevent the development of fungicide resistance in pathogens and protect the overall efficacy of disease control.

Defining the optimal timing and selection of fungicides to maximise yield
In 2001, in collaboration with the Agricultural Development and Advisory Service (ADAS) and the University of Nottingham, we began to investigate the limitations on the yield of UK-grown winter barley crops. This research showed that, unlike wheat, winter barley yield is sink-limited, i.e. limited by the number and capacity of grains to store dry matter, rather than the supply of assimilates for grain filling [3.1]. Subsequent research in collaboration with Teagasc (2011-2014) demonstrated that the yield of spring barley is also sink-limited, even in high-

yielding temperate climates [3.2, 3.3]. This work suggested that disease management with fungicides should be targeted early in the life of barley crops first to maximise grain number formation prior to flowering, and then protect the canopy during grain filling.

Further projects funded by the UK Government's Department for Environment, Food and Rural Affairs (Defra; 2004-2008; 2009-2013) and Scottish Government (2006-2010) established the optimum timing and chemical composition of fungicides to maximise yield. This work showed that the canopy does not need to be protected for the entire duration of grain filling [3.4], and that early applications of fungicides containing triazole and strobilurin can increase grain numbers and yield even when there is little or no disease present [3.5]. This response appears to be the result of direct physiological effects of the fungicides that occur before flowering. This research further highlighted the importance of early application of fungicides to maximise yield.

Annual assessments of fungicide performance to maximise efficacy and minimise development of resistance to disease

There is a range of fungicide active ingredients on the market, with new products containing new chemical components introduced regularly. However, the efficacy of fungicide products varies greatly, primarily as a result of the evolution of resistance to fungicides in key pathogens. We have characterised how resistance to chemicals in fungicides develops in key pathogens including *Ramularia collo-cygni* [3.6].

Informed by this understanding, our researchers have worked together with ADAS, the National Institute of Agricultural Botany (NIAB) and Teagasc, to conduct annual field assessments of fungicide performance. Through these assessments, between 2013 and 2018, we have demonstrated for example:

- efficacy of new succinate dehydrogenase inhibitor (SDHI) products and prothioconazole (member of the azole group) against *rhynchosporium* leaf blotch
- good efficacy of multi-site fungicides such as chlorothalonil against *ramularia* leaf spot
- poor efficacy for folpet against *ramularia* leaf spot
- declines in the efficacy of strobilurin group fungicides and older azoles
- benefits of using a diverse range of active ingredients and balanced mixtures

The results of these assessments are published annually by AHDB for UK farmers and by Teagasc for Irish farmers to provide up-to-date advice on best anti-resistance practices and on selecting the most efficacious fungicides [5.2].

3. References to the research

[3.1] Bingham IJ, Blake J, Foulkes MJ, Spink J. (2007). Is barley yield in the UK sink limited? Post-anthesis radiation interception, radiation-use efficiency and source-sink balance. *Field Crops Research* 101: 198-211. doi: 10.1016/j.fcr.2006.11.005

[3.2] Kennedy SP, Bingham IJ, Spink JH. (2017). Determinants of spring barley yield in a high-yield potential environment. *Journal of Agricultural Science* 155: 60-80. doi: 10.1017/S0021859616000289

[3.3] Kennedy SP, Lynch JP, Spink J, Bingham IJ. (2018). Grain number and grain filling of two-row malting barley in response to variation in post-anthesis radiation: Analysis by grain position on the ear and its implications for yield improvement and quality. *Field Crops Research* 225: 74-82. doi: 10.1016/j.fcr.2018.06.004

[3.4] Bingham IJ, Young CS, Bounds P, Paveley ND. (2019). In sink-limited spring barley crops, light interception by green canopy does not need protection against foliar disease for the entire duration of grain filling. *Field Crops Research* 239: 124-134. doi: 10.1016/j.fcr.2019.04.020

[3.5] Bingham IJ, Hoad SP, Thomas WTB, Newton AC. (2012). Yield response to fungicide of spring barley genotypes differing in disease susceptibility and canopy structure. *Field Crops Research* 139: 9-19 doi: 10.1016/j.fcr.2012.10.004

[3.6] Piotrowska MJ, Fountaine JM, Ennos RA, Kaczmarek M, Burnett FJ. (2016). Characterisation of Ramularia collo-cygni laboratory mutants resistant to succinate dehydrogenase inhibitors. *Pest Management Science* 73: 1187–1196 doi: 10.1002/ps.4442

4. Details of the impact

Impact on farming guidelines

AHDB and Teagasc publish the definitive industry guides that set out the founding principles for barley growth and disease management in the UK and Ireland, respectively. Both confirm that aspects of our research on optimal fungicide programmes – timing and selection of product in the UK, timing in Ireland – have made key contributions to these guides:

AHDB advice on Barley Growth and Disease Management

Our research [3.1] led to the first publication, and forms the foundation, of the AHDB *Barley Growth Guide*. First published in 2006, each subsequent revision (the most recent of which was in 2018) has recommended early timings of fungicide application [5.1a, b]. More than 12,000 copies have been distributed to growers and agronomists since 2013 [5.1a].

AHDB also confirms that our work [3.1; 3.4; 3.5] has been key to optimising the use of fungicide products for winter and spring barley, and forms the theoretical basis of the AHDB *Barley Disease Management Guide* [5.1c]. This is one of AHDB's more popular publications, with more than 55,000 copies distributed since 2013 [5.1a]. The latest edition was published in 2016.

In addition to the main *Barley Disease Management Guide*, AHDB maintains a website (Fungicide Activity Rating [5.2]) of up-to-date advice on the selection of appropriate fungicide product and dose to maximise disease management and safeguard against resistance development. This website is updated each year based on our annual field assessments (described above) and constitutes the main avenue for publicising those findings. AHDB considers this ongoing project "*one of [it's] most valued pieces of work*" [5.1a] and the website received an average of 1,780 visitors per month in the peak season of March-May in 2020 [5.1d].

Teagasc Spring Barley Guide: Advice on optimal timing of application

We collaborated with a Teagasc team generating a series of papers [3.2.-3.3]. The findings of these, together with follow-up research by Teagasc staff, led directly to recommendations of earlier timings of fungicide application in the Teagasc *Spring Barley Guide* (2015), which forms the basis of spring barley farming advice in Ireland [5.3a, b]. More than 10,000 hard copies of this have been distributed, and the online version has been downloaded 9,500 times [5.3b]. Teagasc staff also found our research findings on winter barley applicable to Irish conditions, leading to adoption of earlier timings of fungicide application for winter barley [5.3a].

Impact on farmer practice

AHDB advice is widely used by growers, independent agronomists and the agrochemical trade to select the most efficacious fungicide products for each year's farming. UK Pesticide survey statistics [5.4] highlight the uptake of this advice by growers; for example, between 2014 and 2016 there was increased usage of the members of the azole and SDHI groups identified as most effective (prothioconazole and bixafen, respectively), and multisite fungicides such as chlorothalonil, alongside a decline in use of the least effective fungicides (e.g. folpet; **Figure 1**).

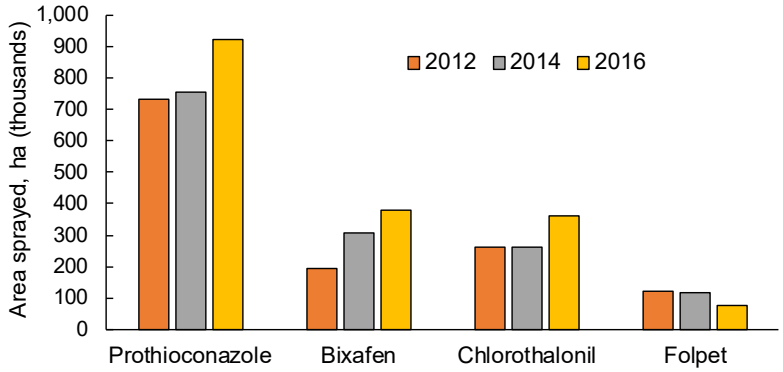

Figure 1. Number of hectares of barley sprayed between 2012 and 2016 [5.4].

Economic impact

Use of optimal fungicide programmes results in improvements to barley yields that are worth up to an additional GBP113,609,000 and EUR18,300,000 (GBP16,220,235; 08-20) annually to the UK and Irish barley industries, respectively (see below). In the UK, the economic impact of our work is derived chiefly from the optimal *selection* of fungicide product, while in Ireland it arises predominantly from optimal *timing* of fungicide application.

United Kingdom

In the UK, following the 2006 publication of the *AHDB Barley Growth Guide*, the timing of fungicide application had already been optimised everywhere to the recommended early timings prior to the REF2021 census period. However, product selection changes each year based on AHDB advice, which is informed by our annual assessments. Based on data recorded by AHDB (2014), the difference in barley yield between the most (Proline/prothioconazole) and least (Phoenix/folpet) effective fungicides at the time, as assessed by our research, is 0.78t/ha of barley (**Figure 2**; 5.5a). Based on a combined spring and winter barley-growing area of 1,080,000ha [5.5b] and weighted average price of GBP135/t in 2014 [5.5c], the value of the increase in yield achieved by optimal fungicide use was GBP113,609,340 in 2014. This varies year by year according to changes in barley growing area, price, and weather conditions affecting yield; for example, in 2017 the added value of optimal fungicide programmes was GBP104,521,200 [5.5d-f].

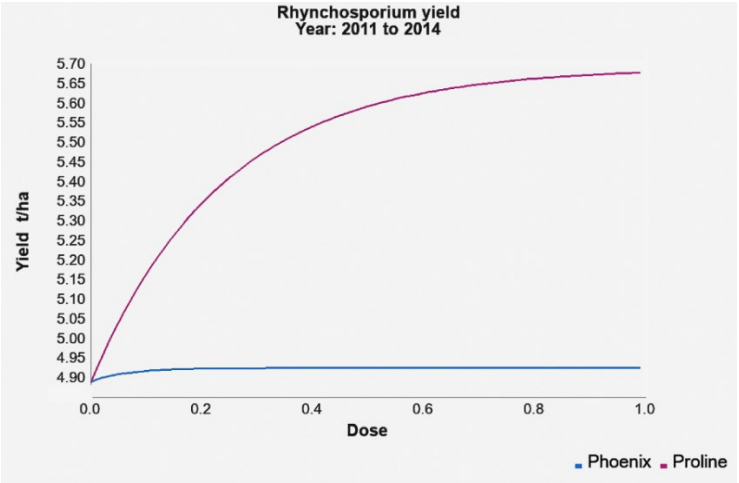

Figure 2. The difference in barley yield (t/ha) between the best (Proline) and worst (Phoenix) performing fungicides, calculated from data reported by AHDB based on our assessments [5.5a].

Ireland

In Ireland, the advice on fungicide product selection is provided by other sources, but the timing of application had not been optimised prior to our joint research with Teagasc. Teagasc confirms that through altered timing of fungicide application based on our research, without additional spending on fungicides, the yield of spring barley has improved by 0.5t/ha since 2015 [5.3]. With an average spring barley production area in Ireland of 121,000ha between 2015 and 17, and a spot price of EUR140/t (GBP123; 08-20) [5.6], yield gains from the revised timings are estimated to be worth EUR8,500,000 (GBP7,531,738; 08-20) annually to spring barley production in Ireland. For winter barley, the altered timings of fungicide application improve yield by over 1t/ha [5.3a]. With an average production area of 70,000ha between

2015 and 2017, and a spot price of EUR140/t, this improvement is worth EUR9,800,000 (GBP8,683,651; 08-20) annually to Irish winter barley production. In total, our research optimising the timing of fungicide application is worth EUR18,300,000 annually to the Irish barley industry.

Impact on effective lifespan of fungicides via reduced risk of resistance development
Our research (e.g. [3.6] and annual field assessments) has contributed to extending the effective lifespan of fungicides by 2 years, through helping farmers select the best practices to safeguard against development of resistance in barley pathogens [5.9].

Farmers learn of the insights from our research through 3 key routes:

- AHDB advice, including the Fungicide Activity Rating website [5.2] for which our research has "*played a key role in identifying emergent resistance to fungicides in barley diseases, allowing AHDB to alert farmers and provide advice to help slow the spread of resistance and mitigate against the decline in efficacy of fungicides*." [5.1a].
- A programme for UK-wide dissemination, run by the Fungicide Resistance Action Group (FRAG-UK) and hosted by AHDB [5.7]. This programme publishes a suite of guidelines, underpinned by our research, including "*Practical measures to combat fungicide resistance in pathogens of barley*" (2019), designed to help farmers select the best practices to minimise the development of resistance.
- The Scottish Quality Crops (SQC) scheme, which encompasses over 95% of the cereal acreage in Scotland. In July 2018, SQC instated an online integrated pest management planning tool that prompts users to consider the use of diverse ranges of fungicides and balanced mixtures and other measures that our research has shown to maximise fungicide efficacy and minimise the risk of pathogens developing resistance. Completion of this tool is required for farmers to market grain as quality assured [5.8a]. Some 2,228 farmers across Scotland had used the tool by the end of 2020 [5.8b].

BASF Agricultural Solutions, a leading global solution provider to the agricultural sector, summarises the impact of the uptake of this advice by UK farmers: "*When we talk about resistance management and the corresponding advice and support given to farmers by SRUC, we can estimate that by offering stewardship advice and delivering anti-resistance messaging, the lifespan of agrochemicals can be extended.* […] *With the annual value of products targeted at the barley market alone, this has value in excess of EUR1,800,000* [GBP1,613,016; 08-20] *per annum, equating to EUR3,700,000* [GBP3,315,792; 08-20] *for an extra 2 years lifespan and close to EUR10,000,000* [GBP8,962,400; 08-20] *over 5 years*." [5.9].

5. Sources to corroborate the impact

[5.1] Impact on AHDB guidance a. Letter of Corroboration from Crop Production Senior Scientist at AHDB b. AHDB Barley Growth Guide (2018) c. AHDB Barley Disease Management Guide (2016) d. AHDB Fungicide Activity Rating website views in 2020
[5.2] AHDB Fungicide Activity Ratings website
[5.3] Impact on Teagasc guidance a. Letter of Corroboration from Head of Environment Crops and Land Use Programme at Teagasc b. Teagasc Spring Barley Guide
[5.4] UK Pesticide Survey (2016)
[5.5] Increased yield achieved by optimal fungicide programmes. a. AHDB Fungicide data archive, 2014 b. Defra farming statistics c. Average price of barley from Savills Arable Benchmarking Survey 2014 d. Defra farming statistics 2017 e. Price of barley 2017 f. Difference between most and least effective fungicides 2017
[5.6] Ireland Central Statistics Office data on area, yield and production of crops 2017
[5.7] AHDB/FRAG-UK Fungicide Futures programme website, including links to guidelines
[5.8] a. Scottish Quality Crops quality assurance requirements, October 2018 b. Email from Scottish Government with data on use of online integrated pest management tool
[5.9] Letter of Corroboration from BASF Agricultural Solutions