Integrated Crop Management (ICM) for potato late blight

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CONTENTS

What is ICM for blight control?

Integrated Crop Management (ICM) can be defined as a sustainable system for food production that is efficient, and environmentally and economically viable. There are four key steps in best practice of ICM to control late blight:

- Control of primary inoculum sources,
- Use of more blight resistant cultivars,
- Targeted fungicide application using disease forecasting and decision support systems (DSS)
- Control of tuber blight - to avoid storage losses and primary inoculum for the following season through seed.

The implementation of an Integrated Pest Management Plan (IPMP) is a requirement of the Sustainable Use Directive on Pesticides and farm assurance schemes (such as Red Tractor and LEAF) require these as part of their audit process. The IPMP was developed by the NFU and rolled out to growers as part of the Voluntary Initiative. There were nearly 17,000 IPM plans for 4.4 million hectares in the UK in 2016/2017.

This review envisages a combination of traditional and new approaches for integrated blight control; combining pathogen population monitoring to enable decisions to respond to population changes, improved cultivars, fungicide treatment guided according to cultivar resistance and disease forecasting, and on-farm hygiene.

Why use ICM?

<u>ICM for effective control</u>

Current scientific evidence can help identify ICM approaches to achieve effective control of potato late blight. For example, research from the UK and worldwide has shown that integrating cultivars with better resistance to late blight with appropriate fungicide doses provides control at least as consistently effective as current methods (Fry, 1978, Neilsen, 2004, Kirk et al., 2001, Kirk et al., 2005, Kessel et al., 2006, Nærstad et al., 2007, Bain et al., 2011). But there are barriers to be addressed, actual and perceived, to integrating management strategies in practice; from growing the crop, through the supply chain and to the consumer. This review describes the proven steps that can be adopted to create an integrated approach to late blight management and identifies what limitations still need to be addressed.

The review starts from the context that late blight is controlled effectively in the great majority of UK potato crops in most seasons by current methods. Hence, there is little immediate practical pressure for change and reluctance to risk moving away from familiar methods. However, current practice is highly dependent on fungicides and similar dependence on chemistry in other cropping systems has not proved sustainable; blackgrass control in arable rotations, and the increasing costs and declining efficacy of septoria control in wheat, are key examples. The fresh produce supply chain has to be particularly mindful of consumer and environmental concerns around pesticides, and growers face loss of fungicides due to regulation. These sustainability risks are considered in the following sections.

ICM to slow pathogen evolution to maintain effective control

The *Phytophthora infestans* population in the UK and Europe has proved adept at evolving to:

- Overcome host resistance genes in potato cultivars (virulence evolution)
- Reproduce faster or under a wider range of environmental conditions (aggressiveness evolution)
- Overcome fungicides (resistance evolution).

Over the last forty years, research and practical experience with fungicide resistance in a range of crops worldwide has demonstrated that relying on multiple applications of single-site acting fungicides is not sustainable. Alternation or mixture of different fungicide modes of action (MOA) have long been practised for blight control and are effective methods to slow fungicide resistance evolution. Nevertheless, loss of effective fungicides (through regulation and resistance) threatens control. ICM can further improve resistance management, to ensure effective control is maintained. Recent modelling research indicates that integrated control may prolong the effective life of host resistance genes in cultivars as well as fungicides (Carolan *et al.,* 2017b). The rationale for this comes from new understanding about the principles that govern pathogen evolution (van den Bosch *et al.,* 2014). These principles, and their practical implications are described in the sections below on 'Key components of ICM for blight'.

Key components of ICM for blight

Four main areas will be addressed: hygiene, cultivars, forecasting to guide fungicide treatment and tuber blight control. Each area targets a different stage in the pathogen lifecycle, to maximise benefits from the ICM approach.

Hygiene to delay epidemic onset

Many years of field evaluations of fungicide performance show that the efficacy of protectant fungicides is inversely related to the inoculum density challenging the crop. Limiting the quantity of viable inoculum emanating from sources both internal and external to the crop has the potential to considerably boost the effectiveness of ICM.

The threat from any inoculum source depends on several factors:

- Size, because this determines the potential amount of inoculum
- Distance from the crop at risk, because of dilution of the concentration of sporangia in the air increases with distance from the source of inoculum
- Location of the source relative to the crop at risk, e.g. upwind or downwind in relation to the prevailing wind direction
- Whether the source is treated with fungicide or not (in general the only source likely to be from a source treated with fungicides is "other crops")
- The timing of inoculum release from the source in relation to both crop growth stage and crop protection history.

There are multiple sources, listed below.

Seed tubers (planted): Blighted seed tubers are a very important source of inoculum. One survey, from The Netherlands, that systematically investigated the sources of crop outbreaks over several years revealed that c. 30% of outbreaks were due to infected seed. This finding is not surprising because if a few blighted seed tubers produce an infected plant, the inoculum source is within the crop. The timing of the challenge from this source can be from emergence onwards. Visual inspection of seed stocks does not necessarily detect all seed tubers infected with *P. infestans*. A PCR-based test to quantify *P. infestans* loading on seed tubers is available but is only rarely used to test commercial stocks of seed.

Current standard advice where there is a known risk of seed tuber-borne blight is to use a robust fungicide programme from emergence so that spread from stems with symptoms is prevented. The efficacy of ICM tools against this phase of disease development is untested, except insofar as blight in ICM experiments might arise from seed.

Outgrade piles: Current AHDB guidance on outgrade piles recommends:

- Zero tolerance to foliar growth
- Keeping outgrade piles small
- Levelling the pile to encourage frost kill
- Preventing growth by covering with plastic sheeting.
- Where sheeting is not appropriate, chemistry can be used. A maximum of two applications of Reglone (diquat: Syngenta UK Ltd) at 0.4 ml product per m^2 can be applied under an Extension of Authorisation (EAMU: 201118820). Glyphosate can also be used on outgrade piles.

The European Commission has indicated that Member States shall withdraw authorisations for plant protection products containing diquat as active substance by 4 May 2019 at the latest. Any grace period granted by Member States shall be as short as possible and shall expire by 4 February 2020 at the latest. As a consequence of this and the revocation of the approval for dichlobenil herbicide granules to control haulm growth on outgrade piles there are now only two control measures that comply with a zero tolerance of green haulm growing from tubers in such piles, i.e. covering the pile with black plastic sheeting or the disposal of tubers as a co- digestion product in an anaerobic digester.

Groundkeepers and volunteers: Volunteers (‘ground keepers’) can act as a source of inoculum, and can become infected and allow late blight to cycle on unprotected foliage during the season. Current guidance recommends cultural and chemical control for volunteers (Bain & Collins, 2013). Control requires the integration of multiple control measures, some of which are ICM tools: a high standard of agronomy to achieve the optimum tuber size distribution leading to few tubers being left in the field; as many tubers as possible harvested from the field; use of penetrating frosts to kill blighted tubers (some locations and in some years only). Glyphosate has several suggested uses for volunteer control including application pre-harvest, although timing of volunteer emergence in relation to the crop being grown, such as sugar beet or oilseed rape, may mean other chemistry is more appropriate.

Gardens & allotments: Control of these sources is largely dependent on the education of gardeners and allotment holders about blight risk.

Other crops of potatoes: Once an epidemic has been initiated in a region, blight in potato crops will spread and exacerbate the epidemic. The majority of inoculum emanating from infected crops will have been produced on fungicide-treated plants therefore its viability might be reduced, although there is no evidence for this.

<u>The role of groundkeepers and cull piles in the evolution of new blight strains</u>

The proportion of different *P. infestans* strains (identified as clonal lineages) which infect tubers at the end of a season largely determines the mix of strains which re-start the epidemic the following seasons, through groundkeepers and cull piles. It is possible that there are differences in the ability of particular strains to survive during the winter, but in general if a new resistant, aggressive or virulent strain has reached a particular frequency in the population at the end of one season, that strain will be represented in the 'founder population' at the start of the next season at a similar frequency. If a strain has a competitive advantage over other strains, it will increase during each season and that increase will be passed on to the next season.

As a consequence, monitoring of *P. infestans* populations at the end of one season can provide growers with some intelligence, several months in advance, about what levels of virulence, aggressiveness and fungicide sensitivity they are likely to encounter the following season. This could potentially inform variety choice and treatment strategies. The information could then be updated from early season samples from blight scouting, or sampling of air-borne sporangia. For the information about frequencies of strains to be useful to growers, new strains need to be tested (phenotyped) for the key traits: virulence, aggressiveness and fungicide sensitivity. Clonal lineages are defined genotypically in surveys, but there can sometimes be phenotypic variation in these important traits within one genotypically defined lineage. For example, some individuals of a lineage may be resistant or sensitive to a particular mode of action. Hence, sufficient strains of each lineage need to be phenotyped to interpret the range of variation, or the target site mutations conferring insensitivity needs to be identified so they can be tested for directly.

Both A1 and A2 mating types have been identified on volunteers as part of ‘Fight against Blight’ monitoring so there is a risk that volunteers could allow oospores to form. Oospore outbreaks have not been reported in the UK and, with rotations of at least 5 years between potato crops, it is likely that oospore survival is negligible. There are areas where higher proportions of “miscellaneous” genotypes are found, which suggest sexual recombination is occurring, however, there is still no strong evidence for oospores as a cause of primary inoculum in GB (Cooke et al., 2003, Cooke et al., 2015).

<u>Cultivar resistance to slow late blight epidemics</u>

Cultivar resistance to foliar blight will slow the epidemic in crops for all sources of *P. infestans* inoculum, including seed tuber-borne blight, once the spread is between aerial plant parts. The contribution of cultivar resistance to foliar blight control, i.e. the magnitude of differences between cultivars, is critical to ICM. Using cultivars with good resistance to late blight reduces the number of infections and restricts the number of spores produced per lesion. Switching to a cultivar with a 1 point difference in resistance rating can provide a useful reduction in the severity of late blight. This has been demonstrated previously, where using Saturna (foliar resistance rating of 4) instead of King Edward (foliar resistance rating of 3) resulted in substantially lower levels of disease, even when fungicides were applied (Bain *et al.,* 2009). This finding is supported by a subsequent study using three varieties (foliar resistance rating at time of experiments): Shepody (2), Maris Piper (4) and Lady Balfour (8) (Bain *et al.,* 2011).

One issue is that information on cultivar differences is generally based on results from cultivar screening trials. It should be remembered that such trials were set up by potato breeders to screen out the worst clones from breeding programmes (Wastie, unpublished). Whilst such trials clearly produce the necessary ranking orders for the clones tested they generally don't quantify the magnitude of the differences between cultivars and therefore the potential value of more resistant cultivars in ICM. The reasons are because the trials use small plots of fungicide non-treated potatoes exposed to a very high inoculum concentration of a highly aggressive genotype. For cultivar resistance-based ICM it is critical to quantify the contribution of cultivar foliar resistance using an experimental set up that closely matches commercial potato growing, or as a minimum includes fungicide treatments. The Sustainable Arable LINK project demonstrated very clearly that differences between susceptible and more resistant cultivars in the field were greater where fungicide sprays were applied, presumably because of a restriction on inoculum concentration so that cultivar resistance differences were not obscured.

In the UK, the majority of cultivars planted have a foliar resistance rating of 4 for late blight and a rating of 4 or 5 for tuber blight resistance (Figure 1). Although reduced resistance in some cultivars, associated with changes in the *P. infestans* population (Lees *et al.,* 2012), appears to be a setback to implementing integrated control, there remain substantial differences between cultivars and these can be exploited. This was illustrated clearly by the results from LINK project field trials for the integrated control treatments for varieties with current and representative levels of foliar resistance, i.e. Cara (foliar resistance rating 5) and Markies (5). In these trials cultivar resistance-based integrated control proved to be highly effective in controlling foliar blight caused by the new population genotypes of *P. infestans* (especially 13_A2), even when disease pressure was high to very high, compared with that for the vast majority of commercial crops.

Integrated strategies, where disease control is achieved by combining a cultivar with good resistance to *P. infestans* with a lower dose of fungicide than the label recommendation, has been demonstrated to provide robust control of late blight in studies in the UK, Europe and the USA (Fry, 1978, Neilsen, 2004, Kirk et al., 2001, Kirk et al., 2005, Kessel et al., 2006, Nærstad et al., 2007, Bain et al., 2011). Improved blight resistance of cultivars also makes losses less likely if fungicide applications are delayed by adverse weather.

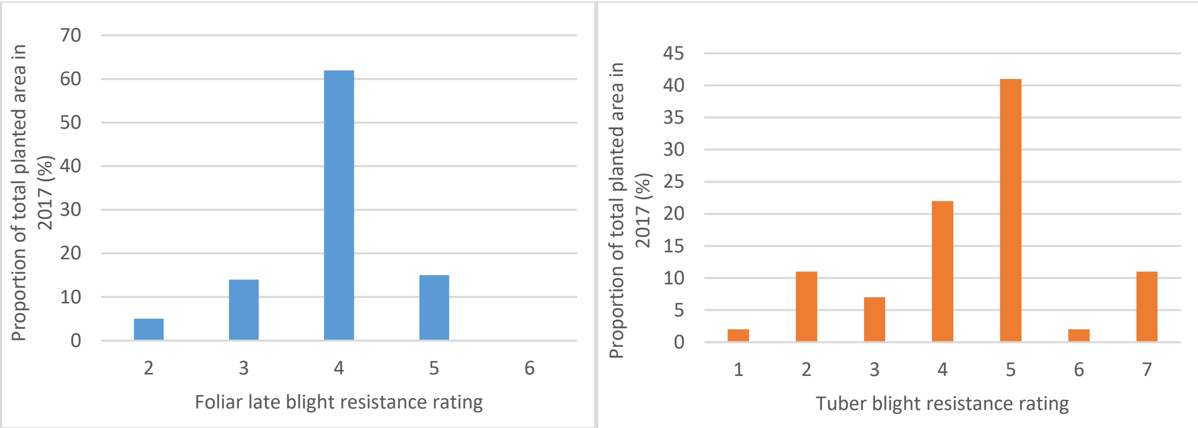

Figure 1. The proportion of varieties in each category of foliar and tuber blight resistance ratings for the top 50 cultivars planted in Scotland, England and Wales in 2017.

<u>Evolution of virulence and aggressiveness</u>

The level of host resistance of cultivars is subject to change due to virulence evolution in the pathogen population. Virulence is the capacity of a strain to infect a particular host genotype by overcoming specific resistance (R) genes (van der Plank, 1968). It is usually a qualitative trait – a virulent strain can infect, an avirulent strain cannot. Aggressiveness is, in principle, a separate trait from virulence. Aggressiveness is a quantitative increase in the fitness of the pathogen (measured through its *per capita* rate of population growth) across a range of cultivars, across a range of environments.

In potato blight two factors blur the boundaries between virulence and aggressiveness. Firstly, host resistance genes in potatoes are often partial in their effect, so a change in virulence is expressed as a quantitative change in epidemic growth on a cultivar. Secondly, new strains of blight typically occur as clonal lineages, so a set of alleles determining virulence are combined with a set of alleles determining aggressiveness in each lineage. For example, 13_A2 carried new virulences (which affected the resistance ratings of certain cultivars, but not others) and was also more aggressive. These two factors make it more complex to phenotype virulence and aggressiveness of strains separately, but we will maintain the distinction when considering how ICM is likely to affect pathogen evolution.

Anything which delays or slows the epidemic should help reduce selection for virulence and aggressiveness. Delay (for example, by good hygiene reducing initial inoculum) works by reducing the time period (and number of pathogen generations) over which selection operates. Slowing the epidemic works by decreasing the *per capita* growth rates of both the virulent and avirulent strain. This decreases the difference in growth rates that drives selection (Carolan *et al.,* 2017b). Hence, for example, fungicide use (which delays and slows epidemic progress) should help to reduce selection for new virulent strains and therefore help to protect host resistance. This has yet to be proven experimentally.

Recent evolution of virulence

In National List trials in 2008 to 2010, a switch to using genotype 13_A2 resulted in the downgrading of resistance ratings of previously very blight resistant cultivars including Cara, Lady Balfour and Stirling (Lees *et al.,* 2012). This was subsequently associated with changes in virulence of the population, with 13_A2 being able to overcome particular R genes. Strains of *P. infestans* isolated from potato cultivars with low, medium and high resistance to foliar late blight have been shown to differ indicating that particular host resistance genes select for particular virulences (Stellingwerf *et al.,* 2018). On very resistant cultivars, Sarpo Mira and Bionica, only 13_A2 was isolated and, across a range of cultivars, there was a positive selection for 13_A2 and 6_A1 with increasing late blight resistance ratings at the expense of 8_A1 strains. A similar study focussing on Sarpo varieties with controls included confirmed the increased susceptibility of Lady Balfour, along with Sarpo Una, in the presence of 13_A2 (White and Shaw, 2009). Despite the observation for Sarpo Una, it was concluded that resistance for Sarpo Mira and other Sarpo varieties tested were durable in the presence of 13_A2. A series of experiments conducted 2014 to 2016 in Ayrshire and Ceredigion demonstrated that 8_A1 was more frequently found on King Edward than Cara (Carolan *et al.,* 2017a).

Weather, particularly temperature, has been implicated as an abiotic factor that may affect the evolution of virulence for *P. infestans* in China (Wu *et al.,* 2016). *P. infestans* populations originating from cooler areas have a higher frequency of virulence and race complexity than warmer regions. The relevance of this for the evolution of virulence in GB and also across Europe, where the clones affecting GB usually arise, is not known.

Strategies to slow selection for virulence

A range of strategies have been identified that may delay the evolution of virulence. These include:

- Deployment of cultivar mixtures with different host resistance genes
- Increasing the diversity of resistance genes in cultivars deployed across different fields and different seasons
- Combining (pyramiding) host resistance genes within cultivars
- Delaying the start of epidemics or slowing the growth rate of the entire population (Carolan *et al.,* 2017b).

Fungicides

Fungicides are a key component of late blight control. Given the short latent period of *P. infestans,* the predominant usage pattern in the UK is applications at 7 day intervals at full label rates. The average ware crop in the UK in 2016 received 12 fungicide applications, with late blight specified as the main reason in 98% of cases (Garthwaite et al., 2016). There are 13 modes of action available for late blight control in the UK, an unprecedented number compared to other arable and horticultural crops (Table 1). The five most frequently applied active ingredients in 2016 were (highest area treated first): fluazinam (FRAC code 29), cymoxanil/mancozeb (27 and M03), cyazofamid (21), cymoxanil (27) and mandipropamid (40), which represent 5 out of the 13 modes of action available.

Decreased sensitivity to fungicide active ingredients has been associated with several *P. infestans* strains in the last 10 years including 13_A2 (metalaxyl) and 33_A2 and 37_A2 (fluazinam). N ew guidance on how to control late blight now that strains with decreased sensitivity to fluazinam are present has highlighted the difficulties in controlling late blight with appropriate mixtures and alternation strategies, particularly for tuber blight control (Bain et al., 2018).

A late blight ICM strategy is not just about fungicide choice, other aspects are also key to success, including appropriate application and coverage, starting a fungicide programme at the correct time/crop growth stage, fungicide interval, positioning of different fungicides in the programme to ensure effective tuber blight control, effective and timely desiccation relative to harvest, and effective alternation/mixture of modes of action for resistance management.

Table 1. The thirteen FRAC modes of action (MOA), and their insensitivity risk, that are currently available for potato late blight control in the UK

FRAC code	4	11	21	22	28	40		27	29	M3	M5	43	45	49
Late blight a.i.s in MOA.	1	3	2	1	1	3		1	1	1	1	1	1	1
	metalaxyl-M[3]	QoI	QiI[1]	zoxamide	propamocarb	CAA		Cymoxanil	fluazinam[1, 3]	mancozeb	chlorothalonil	fluopicolide[1]	ametoctradin	oxathiapiprolin
Risk[2]	H	H	?	LM	LM	LM		LM	L	L	L	?	MH	MH

[1]known to be strongly effective against tuber blight

[2] H = high; MH = medium to high; LM = low to medium; L = low; ? = risk unknown

[3] Resistance documented

Reducing risks to human health and the environment

The UN's Food and Agriculture Organization defines IPM as "the careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and **reduce or minimize risks to human health and the environment**."

Interpreted literally this means that for potato late blight the risk to human health and the environment can be reduced by substituting fungicide products with lower hazard ratings for those with higher ones. This is perhaps an unusual view of ICM but it is a logical one. It is not the case that all blight fungicides necessarily carry a greater hazard than non-pesticide control measures for this disease. The potential hazards of all pesticides to the environment and human health are very thoroughly investigated and documented, but currently this is not the case for non-pesticide chemical control agents.

Substitution towards less hazardous fungicides operates through the regulatory process, e.g. by the revocation of the fentin hydroxide and fentin acetate approvals in 2003, and the approval of new products with improved environmental and human health profiles. The general trend is for more recently approved products to be less hazardous to the environment and human health than those approved much earlier.

There is scope for agronomists and growers to select fungicides that are less hazardous but this adds a further level of complication to the fungicide selection process. It would require fungicides to be chosen on hazard in addition to cost and efficacy considerations.

Further ICM measures are: using a reduced fungicide dose integrated with elevated cultivar resistance; applying a lower fungicide dose tank mixed with an adjuvant to boost fungicide efficacy; using a lower dose of fungicide integrated with a host resistance elicitor. No elicitor products are approved yet for use on potatoes in the UK. An elicitor, currently commercially confidential, has given good control of late blight in the field at Auchincruive in 2018, far superior to the Bion and BABA tested previously.

It has been proposed, as ICM, that the first application of fungicide can be delayed until elevated risk for the crop location is indicated or forecast, e.g. through the Hutton

Criteria or inoculum detected through spore sampling and rapid diagnostics. For this approach to be successful requires crop growth to be monitored because once plants reach a certain size there is likely to be shading of the lower leaves from fungicide spray, even where angled nozzles are used. Such a strategy has an elevated risk because potato plants are most susceptible from emergence until they have approximately ten leaves because leaves produced higher up in the canopy are more resistant than basal leaves.

Also, it has been proposed that cultivar resistance could be utilised to reduce fungicide input in terms of the necessary fungicide efficacy rating. However, this would only be ICM, as opposed to an economic saving, if the less effective fungicide used on more resistant cultivars had a superior environmental and human health profile.

Variable rate of fungicide within a crop in relation to canopy size has been trialled in The Netherlands but not the UK. The principle is that a reduced fungicide dose is applied in areas of the field where the crop canopy is thinner, due to soil conditions for example. The technique was reported to have a positive cost-benefit ratio in trials (Kempenaar et al., 2017).

Managing evolution of fungicide insensitivity

P. infestans belongs to a taxonomic class, the oomycetes, which also includes the downy mildew pathogens. This class has proved to be high risk for the evolution of fungicide resistance, typically evolving resistance twice as fast as other classes of important pathogenic fungi, such as the ascomycetes (Grimmer *et al.,* 2014). Across all pathogen fungi studied there is an underlying relationship that those pathogens which complete many lifecycles in a season (typically because they have a short latent period and hence generation time) evolve fungicide resistance more quickly than pathogens which complete few lifecycles per season (Grimmer *et al.,* 2015). On this basis, it would be expected that *P. infestans* would be high risk of fungicide resistance. Fortunately, there have been fewer cases of resistance than expected. This may reflect resistance management practices implemented after resistance against phenylamides occurred in the 1980s; particularly the use of protectant multi-site acting fungicides (principally mancozeb) that are low resistance risk, and mixtures or alternation of modes of action. However, resistance management practices should be reviewed in the light of new knowledge on resistance evolution, and to identify effective strategies if multi-site acting fungicides (principally mancozeb and chlorothalonil) are lost due to regulation.

The measure of success of a resistance management strategy is the ‘effective life’ of a fungicide mode of action, defined as the number of years from introduction until resistance erodes field performance to the point where effective control can no longer be obtained. Effective life is determined mainly by the rate of selection for insensitive strains, i.e. how quickly a new insensitive strain increases in frequency in the pathogen population by displacing sensitive strains. When the insensitive strain reaches a high frequency, control is eroded.

The evolutionary principles governing selection of insensitive strains have been derived and tested extensively against experimental data (van den Bosch *et al.,* 2014). These principles show that the rate of selection (the selection coefficient) is determined by the difference in the *per capita* growth rate of the resistant and sensitive pathogen populations in the presence of the fungicide. The resistant strain outcompetes, and eventually replaces the sensitive population, because it can infect and reproduce despite fungicide treatment.

It can be inferred from these principles that there are only three underlying strategies that can be used to manage resistance (van den Bosch *et al.,* 2014, Milgroom & Fry, 1988):

1. Reduce the population growth rate of the resistant and sensitive strains
2. Reduce the population growth rate of the resistant strain relative to the sensitive strain
3. Shorten the exposure time, during which the fungicide is present, causing a competitive advantage for the resistant strain.

Strategy one can be achieved, for example, by adding a second fungicide of a different mode of action as a mixture partner. The partner should be effective against both strains, thus reducing the difference in their growth rates. The evidence for the effect of mixtures on resistance is given in van den Bosch *et al*. 2014b.

By extension, it can be inferred from the governing principles that partial (rate-limiting) host resistance, which is effective against fungicide sensitive and insensitive strains, should slow selection for fungicide insensitivity. In effect, host resistance is acting as a ‘mixture partner’. Because selection for new virulent strains follows the same evolutionary principles, it follows that fungicide treatment, which is effective against both virulent and avirulent strains, should slow selection for virulence – thus prolonging the effective life of disease resistance genes in potato cultivars (Carolan et al., 2017b). However, these benefits of integrating fungicides and host resistance have not been proved experimentally.

Deploying more than one fungicide mode of action in a mixture creates concurrent selection for strains which may be insensitive to either or both. Similarly, deploying a ‘mixture’ of fungicides with host resistance genes, creates concurrent selection for clonal lineages which may be insensitive and virulent. The need for high efficacy and low selection can, in principle, be best reconciled by an integrated approach, where most of the control is obtained from the control method at lowest risk of erosion by pathogen evolution.

Strategy two is affected by the dose of fungicide. A lower dose reduces the population growth rate of the resistant strain relative to the sensitive strain. Hence, reducing dose (where this might be possible while still achieving the level of efficacy required, for example, on a more blight resistant variety) reduces selection. One practical consequence is that the total dose of the two components in a mixture should be sufficient to achieve robust control, but the dose of each component should be lower than if either component was being used alone. The theoretical and experimental evidence for the effect of dose on resistance is given in full in van den Bosch et al. (2011) and van den Bosch et al. (2014).

Strategy three (reducing exposure time) can be achieved by reducing the number of applications of a mode of action in a season, by two methods. Firstly, good hygiene can delay the start of the late blight epidemic and reliable disease forecasting could enable better targeting of treatments, thus reducing the total number of treatments required. Exploiting this safely depends on accurate blight reporting and disease forecasts. Secondly, alternation of modes of action enables protection throughout the season, whilst reducing the number of applications of any one mode of action.

The use of mixtures or alternation are both effective strategies to extend the effective life of fungicides. The multiple spray programmes used against blight mean that there are a large number of possible combinations of alternation, mixtures and alternation of mixtures. Optimal combinations for resistance management have not been explored experimentally.

ICM to maximise the effective life of fungicides and host resistance genes

Findings from a recent Horticulture and Potato Initiative (HAPI) funded project 'Blight integrated strategies to maximise duration of effective control by integrating host resistance and fungicides' are summarised in Appendix 2. In brief, mathematical modelling, based on field data, was used to explore strategies for integrating the use of varieties and fungicides. Strategies were compared for the number of years of effective control that could be achieved from a given number of fungicide modes of action and a given number of host resistance genes. The former subject to erosion by insensitivity evolution and the latter to erosion by virulence evolution. Over-reliance on control by fungicides, or over-reliance on host resistance, both resulted in earlier loss of effective control than balancing control by the two methods.

Liability for treatment decisions

Currently there is no standard way in which disease control failures are dealt with. Compensation claims tend to be resolved on a case by case basis, involving detailed negotiations. Liability will be a crucial area for ICM and is likely to be more complex than for current control methods, because ICM has more factors involved and fungicide treatments may deviate from product label recommendations.

Fungicide product labels define the full (also the maximum) label rate of fungicide and some tank mixes (those which have been checked for efficiency and crop safety and are therefore supported by the manufacturer). It has been common practice for decades in many major crops to use doses lower than the label rate and to use tank mixtures which are not on the label. Many tank mixtures have only been tested for physical compatibility and therefore use is stated to be at the grower's own risk.

ICM may involve the use of a reduced dose of fungicide combined with at least one alternative control measure. Liability for recommendations which differ from the label recommendation is likely to reside primarily with the agronomist making the recommendation. Depending on circumstances, there could be elements of wider liability if materials or information provided were found to have contributed to control failure. This wider liability could extend to: fungicide manufacturer, distributor, agronomist, advisor, grower and/or sprayer operator. Where cultivar resistance-based ICM is used and fails two other organisations could potentially be targeted for compensation, i.e. the company with ownership of the variety and/or AHDB as conveyor of cultivar resistance ratings via the Potato Variety Database. A further broadening of liability could occur where decision support systems, host resistance elicitors and/or adjuvants are deployed in ICM.

Pathogen population monitoring

Monitoring late blight populations, and strain phenotyping can support field observations by identifying important changes in the pathogen population (Figure 2). One of the most significant changes was the shift from a predominately A1 mating type population to an A2 population, initially through 13_A2 predominating in the population. 13_A2 was found to be more aggressive than previous *P. infestans* strains and carried new virulences, resulting in the downgrading of some cultivar resistance ratings (Lees *et al.,* 2012). 13_A2 was subsequently largely replaced by 6_A1, which was also found to be highly aggressive. Strains with decreased sensitivity to fungicides, 33_A2 and 37_A2, have also been identified through monitoring. A fitness cost was associated with fluazinam resistance in 33_A2 resulting in it being outcompeted by other strains when fluazinam is not present. As a consequence, 33_ A2 has been at undetectable levels since 2012. In contrast, 37_A2 appears to be fit, is increasing in the population, and has been shown to have decreased sensitivity to fluazinam (Schepers *et al.,* 2018).

The combination of monitoring and strain phenotyping can provide information on the effect of changes in the pathogen population on susceptibility of varieties, efficacy of fungicides and the aggressiveness of novel strains. This information can, in principle, be used to make informed decisions about choice of cultivars (based on virulence) and fungicides (based on sensitivity), and blight risk (based on aggressiveness). In practice, the value of the information for tactical decisions is limited by the intensity and frequency of sampling. For example, a grower requiring information on which fungicides are likely to be effective or ineffective, needs a high degree of certainty about the absence of resistant strains in their area. Intense and frequent sampling would be required to achieve that degree of certainty.

At a strategic level, monitoring and phenotyping information is being linked and harmonised through the EuroBlight network, creating a European database on the frequency of strains. Many of the strains identified in GB have originated in other parts of Europe, so the network acts as an early warning. Research in the Netherlands has been key in identifying the sensitivity of new strains to fungicides before they reach GB. For example, 33_A2 and 37_A2 were identified and phenotyped for fluazinam sensitivity in Denmark and the Netherlands, prior to their appearance in GB in 2011 and 2016 respectively.

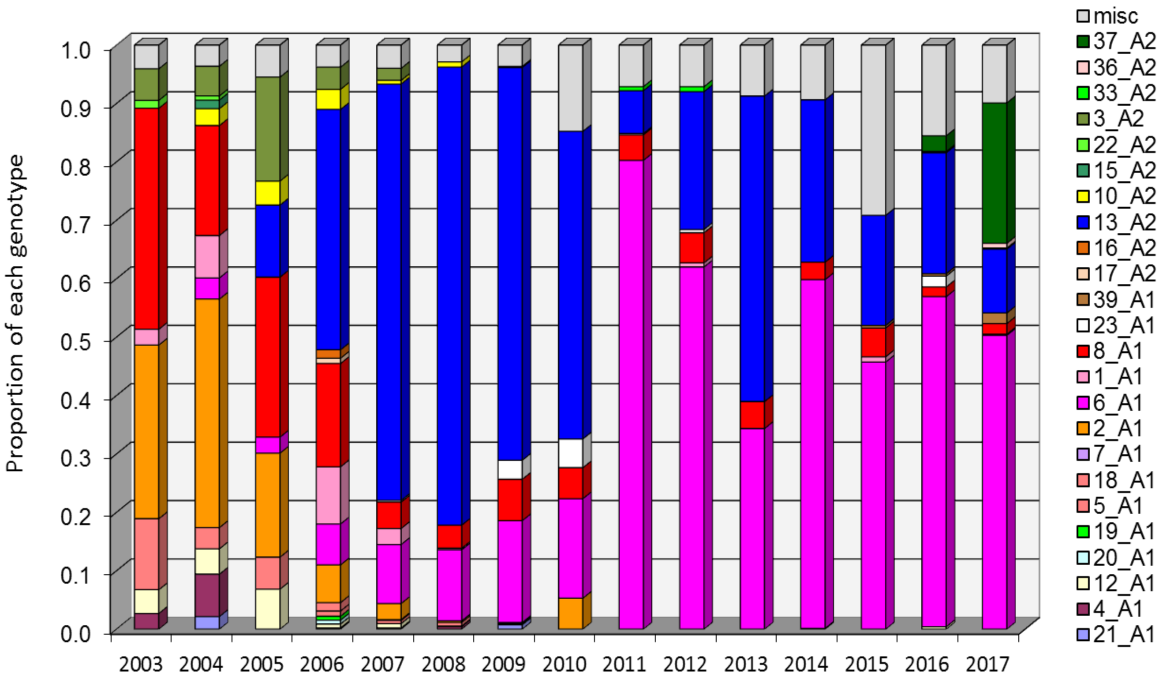

Figure 2. Frequencies of *P. infestans* genotypes in GB, 2003 to 2017 (Cooke *et al*. AHDB Fight against Blight monitoring)

Forecasting and Decision Support Systems

The Smith Period (two consecutive days with a minimum temperature of 10˚C and relative humidity >90% for at least 11 hours per day; Smith, 1956) has been used for decades to indicate weather conducive to late blight epidemics. With increased aggressiveness of the most common strains of *P. infestans*, and evidence that the Smith Period was no longer identifying risk before field symptoms were visible, recent research has focussed on revising weather criteria for infection. The key change has been to reduce the number of humidity hours. The Hutton Period represents two consecutive days with a minimum temperature of 10˚C and relative humidity >90% for at least 6 hours per day. Both BlightWatch and BlightCAST have been updated to include the Hutton criteria, however, performance has yet to be fully evaluated or compared with more sophisticated DSS.

Decision support systems (DSS) integrate information for disease control decisions. This could include information on the pathogen lifecycle, weather, cultivar resistance, fungicides and their mode of action/characteristics, as well as crop growth stage and current disease pressure. A range of DSS have been developed across Europe, all using different criteria for calculating risk. They run on different platforms. Examples include Simphyt (Germany), PLANT-Plus (Netherlands), NegFry and Blight Management (Denmark), ProPhy (Netherlands), Mileos (France), PhytoPre (Switzerland) and Irish rules (Ireland). A range of tools to support risk forecasting and also more complex DSS for late blight are available in the UK (Table 2). These range from simple weather-based risk forecasts at postcode level to more complex systems that are designed for use on individual farms. It has been estimated that around 8% of the UK area uses commercial DSS, in contrast to Nordic countries where it is estimated that nearly 40% of growers use recommendations based on commercial DSS (Cooke et al., 2011). DSS can reduce the amount of fungicide applied by between 8 to 62% and sub-models used by different countries can be tested using the EuroBlight platform (Hansen et al., 2010).

Table 2. Examples of weather and crop-based risk assessments for late blight used in the UK.

System (supplier)	Pros	Cons
BlightWatch (AHDB)	• Free • Uses latest criteria for identifying weather risk for blight	• Forecast to postcode level only • Forecast limited to 24hr • Data not specific to individual farms
BlightCAST (Syngenta)	• Free • Uses both Smith and Hutton criteria for identifying weather risk for blight • Provides information on suitable spray days	• Forecast based on network of supplier weather stations • Data not specific to individual farms • 48 hour forecast
Dacom (via Howard Hinds Crop Consultancy)	• All predictions based on in-field measurements • Regular updates to forecasts • Provides information on suitability of available spray days • Model developed specifically to control potato blight	• Does not use Hutton criteria at present • Requires subscription • Requires weekly crop measurements (crop height and ground cover)

Weather-based models are the backbone of late blight forecasting, however, additional components have been shown to contribute to risk assessment. One strategy is to include regional spore dispersal in disease risk warnings (Kessel *et al.,* 2006, Kessel *et al.,* 2008). This method was particularly effective in reducing inputs on resistant cultivars. The same study reported that amending the fungicide dose proportionally to the critical period, calculated as days of sufficiently long leaf wetness duration to allow infection, allowed reductions in fungicide dose on moderately resistant or resistant varieties. A series of experiments in a relatively low disease pressure season (2008), at five sites in the Netherlands, reported that between 6 and 9 sprays were not applied as a result of using the Plant Plus system, which calculates favourable conditions for late blight development, and 1 to 2 sprays were saved using the Prophy system (Evenhuis *et al.,* 2005).

Other considerations for late blight control include the application timing of fungicide products with a particular characteristic. For example, the effectiveness of a fungicide strategy can be dependent on just one or two key sprays in the programme and, although straightforward to identify retrospectively, it is not currently possible to predict when those occur during the season (Bain & Bardsley, 2009). The order of fungicides, applied as blocks, was also found to be more important than whether the fungicides were blocked or alternated in the same study, and the order of the blocks required for good control over two years of experiments was different.

New information for DSS

Other forecasting tools are being developed which incorporate detailed studies of pathogen biology with weather-based risk. Spore traps and trap plants have been combined with a series of sub-models to understand the importance of each step in the disease cycle (Nærstad *et al.,* 2007). This includes spore production, spore release, survival and infection. Spore survival has been identified as a key component of forecasting models, with sunlight promoting the release of spores but reducing spore survival. In contrast, leaf wetness inhibited spore release but encouraged germination and infection. These models can be very effective, but may be limited by the availability of appropriate meteorological data, particularly leaf wetness (Nærstad *et al.,* 2007).

The risk of inoculum spread could be used to forecast the onset of epidemics and incorporated into DSS and the potential to use models to predict epidemics has been evaluated using *P. infestans* as an exemplar (Skelsey *et al.,* 2018). There is experimental evidence that taking a pro-active approach to target the most effective fungicide to the part of the season when risk is highest is critical to maintain control (Bain & Bardsley, 2009). This was associated with the time when actively sporulating late blight lesions were present, therefore an estimate of the number of sporangia challenging the crop has been suggested as way to rationalise the use of fungicides and to enhance the risk assessment beyond weather data alone.

Fungicide application, varieties and application timing

Decreasing fungicide inputs on moderately resistant potato cultivars compared with susceptible cultivars has been shown to be an effective control strategy against late blight in the UK, Europe and the USA (Fry, 1978, Gans *et al.,* 1995, Nærstad *et al.,* 2007, Bain *et al.,* 2011). These studies have demonstrated that fungicide inputs can be substantially reduced with good resistance to late blight. Inputs on susceptible and moderately susceptible varieties can also be reduced. As part of a Sustainable Arable LINK project in the UK, completed between 2009 and 2012, moderately resistant and resistant potato cultivars (foliar ratings of 5 and 7 respectively) were treated with different doses of fungicide (from 0 to 1.0 of the recommended label dose) during specific phases of canopy growth (rapid haulm and stable canopy). Treatments were also evaluated at two spray intervals: 7 and 10 days. This was to determine whether lower doses of fungicides could be used on cultivars with good resistance to *P. infestans* and evaluate the impact of longer intervals between sprays on disease control. It was found that 95% of the integrated control treatments applied during rapid canopy growth provided better control than a standard treatment [full label dose applied to a susceptible variety (foliar blight rating of 3) at 7 days intervals]. During stable canopy, 83% of integrated control treatments gave control better than or equivalent to the standard treatment. Treatment success during stable canopy was lower than that achieved during rapid haulm growth, however, this was predominately associated with poor control of the late blight epidemic prior to the stable canopy treatments being applied. This work demonstrates the feasibility of integrated control, however, good control during all growth phases of the potato crop, especially the tuber phase, is necessary for it to be successful.

Tuber blight and DSS

Tuber blight control is rarely incorporated in to DSS yet it is a key component of late blight control as infected tubers can cause rots in store and act as a primary inoculum source for new epidemics. To incorporate tuber blight risk into DSS would require the following: as assessment of whether inoculum is present, transfer of inoculum from foliage to tubers (e.g. rainfall), sporangia/zoospore survival and infection, soil properties (e.g. temperature, structure and moisture) as well as tuber depth and tuber resistance rating (Olanya *et al.,* 2009). Substantial differences in the ability of *P. infestans* genotypes to infect potato tubers has been demonstrated in GB populations, with 13_A2 significantly more aggressive in inoculated studies than older genotypes (Cooke *et al.,* 2014). The reported duration for sporangia survival in soil in the USA and Netherlands varies from 3 weeks (Porter & Johnson, 2007) to 8 weeks (Evenhius *et al.,* 2005). Further work, including understanding the survival of *P. infestans* strains currently present in GB populations would be required to develop a tuber blight model.

The potential for integrating DSS with ICM strategies

Thirty-six percent of Dutch potato growers use a DSS (Cooke *et al.,* 2011), including Plant-Plus which is used by some growers in the UK. This platform allows for flexibility in fungicide dose and spray interval, taking into consideration cultivar resistance and weather-based risk. Many growers in the UK apply fungicides on a weekly schedule and moving to a strategy where intervals are flexible may be less convenient. An alternative would be to base the fungicide programme on a 7 day interval, altering fungicide dose and product in response to weather-based risk. This is the approach being tested in Nordic countries and offers a compromise. A current European project, IPMBlight2.0 (2016 to 2019) aims to improve DSS models and track the emergence of novel strains of *P. infestans* to offer a disease risk assessment based on epidemiological, weather and pathogen phenotype data.

Areas of late blight ICM being researched

Research projects that have included research on late blight and were completed within the last five years are summarised below, sorted according to funders. Some research e.g. annual screening of cultivars to determine resistance ratings, is ongoing and not included here. Only selected BBSRC projects are included below (a full list can be accessed via UK Research and Innovation). Much of the BBSRC research focusses on the genetics and signalling processes underpinning resistance responses. This research may ultimately improve cultivar resistance, but is not of immediate practical relevance. AHDB Potatoes and industry funded research focusses on practical problems that are relevant to UK growers, and the crop protection companies focus on fungicide efficacy. Novel technology to guide on-farm decisions is being developed and tested through Innovate UK projects. RESAS ICM research is investigating the development and evaluation of risk models for late blight, facilitate adoption of IPM, the effectiveness of elicitors in IPM systems and fungicide scheduling using weather-based risk.

Wholly or part-funded by AHDB Potatoes

- Spatiotemporal analyses of potato late blight outbreaks (September 2017 to August 2019). Fellowship: 11120032
- Late blight models (PhD) develop an accurate and predictive method of assessing blight risk across GB (May 2014 to April 2017) 115R473
- Blight integrated strategies (HAPI) maximise duration of effective control by integrating host resistance and fungicides (October 2013 to September 2016) 114R477
- Timing of curative blight fungicides (PhD) aid optimisation of application of curative fungicides (October 2014 to September 2017) 115R486

Crop protection companies

- Efficacy of new and existing fungicides against foliar and tuber blight.
- A new active ingredient representing a novel mode of action which is highly active against *P. infestans*, oxothiapoprolin, was released in 2017.
- The companies make cash and in-kind contributions to Innovate UK and AHDB projects.

Innovate UK

Three collaborative projects have been developing novel ways of detecting and predicting late blight risk using technological solutions:

- Smartspray: aims to optimise detection and control of potato blight using sensing technology to inform spray decisions. Led by Burkard Manufacturing, it will develop a prototype automated device to sample air-borne spores of *P. infestans* and Alternaria spp.. The sample will be processed in the field and the result sent via text message. This technology is in the development stage but could be linked to weather based risk models when units are deployed on farm in future. Led by SoilEssentials Blightsense: aims to develop an antibody-based acoustic biosensor device for in-field detection of sporangia of *P. infestans* with the potential to develop for other targets. This may offer an opportunity in future to link the presence of inoculum in a field with weather-based risk models.

- CropForecast: provide farmers with early warning system, based on weather topography and satellite data linking with modelling and was led by Magnellium Ltd.

Project funded wholly or partly by BBSRC

- Responses of the *Phytophthora infestans* metabolome and transcriptome to mock infection and chemical inhibition (March 2013 to March 2017). Doctoral Training Partnership. James Hutton Institute.
- *Phytophthora infestans* effector PexRD54 associates with host Rab GTPase RAB8-1 to reprogram endomembrane transport (April 2015 to September 2018). Research Grant BB/M002462/1. Imperial College London.
- Next generation disease resistance breeding in plants (April 2012 to March 2017). Intramural BBS/E/J/000A485. John Innes Centre.
- Defining and deploying Rpi gene diversity in S. americanum to control late blight on potato (July 2018 to July 2020). Research Grant BB/P019595/1. University of Dundee.
- Blightsense – development of a rapid biosensor system for in-field detection of potato blight (July 2015 to December 2018). Research Grant BB/M028356/1. University of Cambridge.
- New UK potato varieties with late blight and potato cyst nematode resistance, reduced bruising and improved processing quality (October 2015 to September 2020). Research Grant BB/M017834/1. University of East Anglia and University of Leeds.
- What are the roles of oomycetes RXLR effectors in the establishment of plant disease? (May 2009 to November 2014). Research grant BB/G015066/1. University of Warwick and University of Dundee.
- Strategies for integrated deployment of host resistance and fungicides to sustain effective crop protection (October 2013 to October 2016). Research Grant BB/K020447/1. SRUC and Rothamsted Research.

European funding

- There is a European C-IPM project, IPMBlight 2.0, led by INRA which is currently looking at updating and developing new models for several European countries, including the UK, to improve late blight risk assessment, incorporating information on epidemiology, weather risk and the *P. infestans* phenotype.

Barriers to uptake of ICM

According to Nix (2018), the average cost of fungicide product per ha is £20, with spray application costs of between £9.30 (farmer's average cost) and £12.50 (contractor charge). This accounts for approximately 11% of the total variable costs (excluding contracting). There is also public and regulatory pressure to reduce pesticide use, so there are incentives for growers to reduce the need for fungicide treatments and to target treatments according to need. However, there are some key factors which constrain implementation of ICM:

1. One of the key barriers to the industry using reduced fungicide inputs on cultivars with elevated resistance to leaf blight is the concern over tuber infection. This concern is greatest for cultivars with moderate to high resistance to leaf blight, but low to moderate resistance to tuber blight. The concern is that reduced fungicide inputs matched to foliar resistance may increase the risk of tuber blight, especially if there is an extreme weather event. Tuber blight is a key driver of high inputs of fungicide to potato crops. If blight was a disease of the haulm only then the consequences of foliar blight would be restricted to yield reduction, proportional to the severity of the symptoms. However, tuber blight has a much greater economic impact than haulm blight alone, and can occur where the severity of foliar blight is very low.
2. The average area of potatoes per grower increased from the 1960s, then remained relatively stable from 2011, at an average of 53 ha per grower. Hence, many growers operate on a 7-day fungicide programme due to practicalities of having to treat a large area.
3. The losses associated with even a small frequency of false negative predictions from a DSS (where an epidemic is not predicted, treatments are reduced as a result, but an epidemic does occur) will substantially outweigh the economic savings resulting from many true predictions.

4. The varieties grown are determined largely by specific markets. Some of the most widely grown varieties, which have the required quality traits for the fresh market or processing, are blight susceptible.
5. Currently the most widely used system of blight control is simple to manage and time efficient: in any week the same fungicide is applied irrespective of cultivar resistance, and fungicide applications are made at 7-day intervals. ICM systems of control will add complexity to late blight management. For example, cultivars with different resistance ratings are likely to require different fungicide inputs (products and/or doses) and the use of a DSS may result in a variable day of the week that fungicide application is required. The complexity will be greater for those growing a large number of cultivars, e.g. seed producers.
6. ICM brings together a range of strategies to decrease foliar and tuber blight risk and information from research projects is often in reports or scientific papers. These are not as accessible to growers and agronomists compared to factsheets and short updates, and academic evidence is not as compelling for practitioners as field demonstrations.
7. Lack of information to demonstrate how new components of ICM can be combined in blight management: Growers and agronomists are provided with a range of information from companies regarding fungicide characteristics and efficacy, but there is rarely information to combine, for example, adjuvants and fungicides.
8. Lack of a premium price for produce, or subsidy, means that the 'public good' benefits of ICM (protection of the environment and human health) are not rewarded financially.

Current status of ICM tools

For the range of ICM tools, this section summarises whether they are fully or provisionally recommended, the extent of practical implementation in commercial crops, and the scale of the potential benefit. The information in this section is used in the subsequent sections of the report to prioritise future actions:

- Specific ICM tools are a high priority for knowledge transfer if they are already fully recommended, have moderate or high potential impact, but low current uptake.
- Specific ICM tools which are provisionally recommended are a high priority for research and demonstration to move them from provisional to full recommendation, if they have moderate or high potential impact (all provisionally recommended tools have low current uptake).

The principles of ICM are based on combining multiple interventions to maximise benefits. In reality, the capacity to change multiple interventions simultaneously is constrained by limited research, demonstration and knowledge transfer resources, and barriers to industry adopting innovation. Hence, the ICM tools are prioritised here individually.

Fully recommended ICM tools

Table 3 shows ICM tools which can be fully recommended now, because there is already good evidence supporting their use. Current implementation is categorised as ‘complete’ (implemented in >75% of potato crops), ‘partial’ (between 25% and 75% of crops) or ‘low’ (<25% of crops). Potential impact is categorised as ‘Low’, ‘Moderate’ or ‘High’. The categories indicate the size of the benefit which could accrue if the tool was implemented by all growers. The potential impact includes aspects of: (i) providing cost effective and robust control of blight, (ii) maintaining control in future, by combating pathogen evolution, and (iii) reducing usage and hazard associated with blight fungicides. The categorisations are based on expert opinion and it is accepted that other expert opinions could be debated.

Table 3. Fully recommended ICM tools.

ICM tools	Control target	Current implementation	Potential impact
Ensure adequate soil cover of progeny tubers in the ridge to fully protect them	Tuber blight	Low	High

ICM tools	Control target	Current implementation	Potential impact
Chit seed to escape the foliar epidemic , or reduce the fungicide inputs required	Foliar blight	Low	Moderate[1]
Use DSS to optimise fungicide timing in relation to high-risk weather periods and therefore reduce fungicide input	Foliar blight	Low	Moderate
Substitute fungicide products with lower hazard ratings for those with higher ones	Foliar blight	Low[2]	Moderate
Use fungicide tank mixed with an adjuvant to boost fungicide efficacy	Foliar blight	Low	Moderate
Use mixtures/alternation of fungicide modes of action to maximise the effective life of fungicides	Foliar and tuber blight	Partial	High
Use multi-site acting fungicides to reduce risk of fungicide resistance	Foliar and tuber blight	Partial	High
Delay harvest until a sufficient number of sporangia in soil are no longer viable, especially on tuber-susceptible cultivars	Tuber blight	Partial	High
Prevent re-growth of haulm after desiccation	Tuber blight	Partial	High
Control groundkeepers and volunteers	Primary inoculum	Partial	Moderate

ICM tools	Control target	Current implementation	Potential impact
Use long and clean rotations to minimise the risk of oospores contributing to outbreaks	Primary inoculum	Partial	Low[3]
Use seed of higher health (blight) status	Primary inoculum	Complete	Moderate
Prevent outgrade piles being a source of *P. infestans*	Primary inoculum	Complete	Moderate
Avoid or restrict the irrigation of crops with foliar blight	Tuber blight	Complete	Moderate
Ventilate and dry tubers immediately after harvest	Tuber blight	Complete	Moderate/High[4]

[1]Moderately effective in early crops only, except in exceptional years

[2]Low implementation except where supply chain has placed restrictions on use of specific fungicides

[3]This low impact could change if oospore-derived epidemics became significant in GB

[4]Moderate impact on risk of blight infection, high impact on risk of blight-induced soft rots in store

Definite recommendations for fully recommended ICM tools (in priority order)

Aim: to increase commercial uptake of ICM strategies for which there is already good evidence

- Ensure adequate soil cover of progeny tubers in the ridge to fully protect them during crop growth

Barriers to uptake: Deeper planting will require deeper cultivation and deeper stone separation. It is likely to slow crop emergence and result in more soil to separate tubers from at harvest. Deeper planting may not be appropriate for certain cultivars or smaller sizes of seed tubers.

Actions: There is limited scope for greater implementation, e.g. for certain cultivars, crops grown in lighter soils and short-lived crops that can be harvested under good conditions (first earlies, seed crops or salad crops). Increased implementation of the tool could be achieved through a demonstration of its effectiveness and a cost: benefit analysis.

- Use DSS to optimise fungicide timing in relation to high-risk weather periods and therefore reduce fungicide input

Barriers to uptake: There is the potential for yield loss and tuber blight if fungicide inputs are reduced inappropriately. Information on using DSS to guide fungicide inputs is not widely available.
Actions: Produce up to date information, as a factsheet, on the options for using DSS and ICM. This should also address the risks associated with both foliar and tuber blight.

- Substitute fungicide products with lower hazard ratings for those with higher ones

Barriers to uptake: There is a preference for simple fungicide programmes with fewer products that are decided at the start of the season. The definition of what makes a low or high hazard product is not widely known.
Actions: Produce industry guidance on the definition of products with high and low hazard ratings. This could be incorporated with guidance regarding other ICM strategies.

- Use fungicide tank mixed with an adjuvant to boost fungicide efficacy

Barriers to uptake: Some adjuvants (e.g. Zin Zan applied with Valbon) are already recommended with specific fungicide products. There is limited information on using adjuvants with the many other fungicide products available and this information tends to be spread across different websites.
Actions: Make data on the effectiveness of adjuvants available and easy to access. Independent trials would support claims for the effectiveness of adjuvant/fungicide combinations. Industry guidelines on the use of adjuvants and on farm demonstrations would help to support their use.

- Chit seed to escape the foliar epidemic or reduce fungicide inputs required

Barriers to uptake: Using fungicides is a low risk strategy to protect the crop from foliar and tuber blight compared to the risks associated with relying to a greater extent on cultural control.
Actions: This strategy could allow early crops to avoid late blight and not require as much fungicide input. Guidance on using this as a strategy could be produced along with on farm demonstrations to show what is possible.

- Use mixtures/alternation of fungicide modes of action to maximise the effective life of fungicides

Barriers to uptake: There is a potential increased cost associated with using tank mixtures compared to solo active substances.

Actions: Use evidence from across all crop pathogens to raise awareness of the effectiveness of resistance management. Conduct experiments to demonstrate the effectiveness of mixtures and alternation slowing resistance selection in *P. infestans*, using 37_A2 as an example case.

- Use multi-site acting fungicides to reduce risk of fungicide resistance

Barriers to uptake: Risk of loss of multi-site active substances to regulation. Risk of using a protectant fungicide solo, when there may be latent infections at the time of treatment.

Actions: Use evidence from across crop pathogens to raise awareness of the effectiveness of multi-site acting fungicides protecting single-site acting fungicides in a mixture. Demonstrate the effectiveness of mixture with multi-sites slowing selection for 37_A2. See point below (under provisional recommendations) about using DSS to determine when a protectant fungicide solo would be a safe option. Ensure regulators are aware of the critical role of multi-sites in resistance management.

- Delay harvest until a sufficient number of sporangia in soil are no longer viable, especially on tuber-susceptible cultivars

Barriers to uptake: Early harvest is a key tool for the health of the harvested crop for a large number of diseases. For many crops a delay in harvest means harvesting in poorer soil conditions.
Actions: This tool should be targeted at crops for which it was known, or suspected, that there was significant sporangial contamination of the soil. The development of a diagnostic tool to quantify the concentration of viable sporangia in soil at intervals after desiccation would be of considerable benefit. Maintain industry awareness of the subject; raise awareness of the particular issue for tuber-susceptible cultivars.

- Control groundkeepers and volunteers

Barriers to uptake: Control is difficult because it is complex and protracted. There is no single highly effective control measure and effective control relies on putting in place a package of partially effective measures.
Actions: The importance of this potential source of blight inoculum is frequently conveyed at technical update meetings and in potato crop management literature. Maintain industry awareness.

- Prevent re-growth of haulm after desiccation

Barriers to uptake: Some crops now distant from farm, e.g. those grown on rented land, therefore some crops may not be monitored frequently enough.
Actions: Provide technical updates on desiccation programmes that eliminate or minimise the risk of haulm re-growth, especially because there is a question mark over the approval of diquat.

- Use long and clean rotations to minimise the risk of oospores contributing to outbreaks

Barriers to uptake: The rotations currently used in GB are determined by factors other than blight control. The link between length of rotation and blight risk isn't uppermost in growers' minds.
Actions: Short rotations, including double cropping, substantially increase the risk of oospore-derived outbreaks in GB. The potential risk from oospores has been

flagged up to the industry since the 1980s. However, in the absence of any confirmed oospore-derived outbreaks the industry won't give long rotations a high priority. However, long, clean rotations are required to **prevent** oospores being responsible for soil-borne epidemics. It is therefore important that the industry is reminded at intervals of the key role long rotations play in prevention.

- Use seed of higher health status to reduce seed as a source of initial blight inoculum

Barriers to uptake: Classified seed is more expensive than farm-saved, especially high-grade stocks. The physiological state of bought-in seed may not match the buyer's requirements as well as once-grown.
Actions: The potential role of PCR diagnostics in aiding the identification of blight-free seed stocks should be examined because although certified seed has maximum tolerances for tuber blight, some tuber infections can go undetected by seed inspectors.

- Prevent outgrade piles being a source of *P. infestans*

Barriers to uptake: There are too few methods that remain available to control haulm growth on outgrade piles. Black polythene sheeting can be difficult to keep intact and in place and generates plastic waste; the disposal of tubers to an anaerobic digester often requires them to be washed; disposal to landfill is expensive; the use of herbicides to treat haulm on outgrade piles requires frequent applications; glyphosate can be too slow acting to be effective; there is a current threat to the approval of diquat.
Actions: Investigate new methods of dealing with surplus, or outgrade, potatoes.

- Avoid or restrict the irrigation of crops with foliar blight

Barriers to uptake: The crop may need to grow on to reach target tuber size distribution.
Actions: Deeper planting will reduce the risk of tuber infection. The demonstration for point 1 in this list should include irrigation as a factor.

- Ventilate and dry tubers immediately after harvest

Barriers to uptake: Ventilation capacity may be limited. The cost is high.
Actions: Greater implementation requires either more growers to have a suitable positive ventilation system or for capacity to be increased.

Provisionally recommended ICM tools

Table 4 summarises the range of ICM tools which can be provisionally recommended now, but the tool requires further research, development or demonstration before it can be fully recommended. The extent of current practical implementation of these tools in commercial crops is low (<25% of crops) in all cases.

Table 4. Provisionally recommended ICM tools

ICM tools	Control target	Current implementation	Potential impact
Use reduced fungicide dose integrated with high cultivar foliar resistance, and DSS to guide variable intervals	Foliar blight	Low	High
Use reduced fungicide dose at set (7 day) intervals, integrated with good cultivar foliar resistance	Foliar blight	Low	Moderate
Optimise fungicide resistance management strategies	Foliar and tuber blight	Low	Moderate
Use decision aid (incorporating e.g. Hutton criteria) to avoid unnecessary use of curative active ingredients	Foliar blight	Low	Moderate
Use sampling of air-borne sporangia and DNA diagnostics to avoid the use of ineffective fungicides	Foliar blight	Low	Low[1]
Use reduced fungicide dose integrated with a host resistance elicitor	Foliar blight	Low	Low[1]

Vary the rate of fungicide within the crop, based on canopy density	Foliar blight	Low	Insufficient evidence

[1] Low impact with current technology

Research gaps for provisionally recommended tools (in priority order)

Aim: to move ICM tools from being provisionally recommended to fully recommended

- Use reduced fungicide dose integrated with high cultivar foliar resistance, and DSS to guide variable intervals

Barriers to uptake: perceived risks from foliar and tuber blight, availability of information from integrated control projects and accuracy of DSS.
Actions: develop a cultivar resistance-based ICM system for GB that incorporates weather-based risk, through research on DSS options (e.g. Based on Hutton and those commercially available), testing how they would work for UK growers. Produce industry guidance outlining DSS use and link with information on integrated control, on-farms demonstrations of integrated control options

- Use reduced fungicide dose at set (7 day) intervals, integrated with good cultivar foliar resistance

Barriers to uptake: most varieties used in UK have a rating of 4 or lower
Actions: on-farm and industry demonstrations (at sites typical of commercial blight risk situations), address the lack of uptake of integrated control and the negative effects of susceptible variety choice with the industry more widely e.g. with breeders, growers, large processing/packing companies. Quantify the risk of tuber blight infection associated with reduced fungicide inputs on cultivars with good resistance ratings for foliar resistance. Determine to what extent higher ratings for cultivar resistance to tuber blight negate this risk. Include fungicide treatments in varietal resistance screening experiments to identify the relative contribution of cultivars to integrated management strategies. Identify the subset of cultivars with suitable foliar and tuber resistance scores for ICM.

- Optimise fungicide resistance management strategies

Barriers to uptake: Lack of evidence on the relative effectiveness for preventing fungicide resistance of the huge number of possible combinations of product, dose, alternation, mixture, or alternation of mixtures.
Action: Field experiments using selection for fluazinam insensitive 37_A2 to compare the effectiveness of different strategies and optimise.

- Use decision aid (incorporating e.g. Hutton criteria) to avoid unnecessary use of curative active ingredients

Barriers to uptake: requirement for simple fungicide programmes, there is no publicly available evidence that Hutton can be used as a decision tool after the first application.
Action: use research findings to produce a factsheet, commission testing of the decision aid under commercial conditions (e.g. not a high disease risk trial site), set up farm demonstrations.

- Use sampling of air-borne sporangia and DNA diagnostics to avoid the use of ineffective fungicides

Barriers to uptake: the research is in the early stages, difficult to link occurrence of air-borne sporangia with disease risk with current technology, need to link sampling/diagnostics with weather-based risk.
Actions: investigate whether risk prediction strategies used for other air-borne pathogens could be applied to blight research, improve the turnaround time for samples for real-time detection of blight by investing in technology, identify the specific mutations associated with decreased fungicide sensitivity, assess the practicalities and costs of deploying the technology on farms and benefits to growers.

- Use reduced fungicide dose integrated with a host resistance elicitor

Barriers to uptake: no elicitors registered as crop protection products

Actions: evaluate evidence of elicitors and their effectiveness in other crops, gather current evidence on elicitors and their control of late blight, test the effectiveness of elicitors selected based on current evidence.

- Vary the rate of fungicide within the crop, based on canopy density

Barriers to uptake: Research in early stages, lack of publicly available evidence on methods, risks and benefits.

Actions: Await evidence from other countries.

In addition to the tools described above, the literature suggests that delayed harvest could allow blighted progeny tubers to rot prior to lifting. However, early harvest is a key tool for tuber health for a number of important diseases. A delay in harvest may also mean harvesting in poorer soil conditions, and research at SRUC has shown that delaying harvest whilst soil conditions are cool can maintain, or even increase, the incidence of blighted tubers. Complete decay of blighted tubers in the field is mediated by secondary soft rot bacteria, rather than blight alone. Consequently its use may result in fewer blighted tubers being harvested, but increase the risk of contamination by soft rot bacteria. Hence, delayed harvest should not be recommended.

Building confidence in ICM

Cultivar resistance ratings: Cultivar resistance underpins ICM. Ensure that the published 1 to 9 ratings for cultivar resistance to foliar and tuber blight, for the cultivars making up a high percentage of the national crop, are sufficiently up-to-date to allow growers to trust them completely in ICM. New cultivars with resistance ratings suitable for ICM need to be identified for the future.

Workshop: Hold a workshop primarily to consult with industry (i.e. AHDB, growers, agronomists, NFU, breeders, plant protection product manufacturers and distributors, packers, processors, researchers) over what is possible in a commercial environment. A key objective of the workshop would be to establish which tools growers and agronomists would consider using, and which they wouldn't, and the reasons why.

Produce an ICM best practice document for the industry: This should condense information from previous ICM projects and the literature, to support the use of ICM strategies for late blight control in practice. The document would be produced after consultation with the industry representatives listed in the point above.

Provide demonstrations relevant to growers: Trials are usually conducted using small replicated plots in areas where weather is conducive for very high levels of disease - considerably higher than those experienced by almost all commercial crops. Demonstrations of ICM systems for blight control need a realistic blight challenge. This can't be achieved at the normal demonstration sites. It is proposed that such demonstrations are conducted in isolation from other field trials and researcher experience is used to ensure that the disease pressure is realistic for a commercial crop. Visits can be arranged to the sites or drone technology used to permanently capture treatment efficacies. The treatments to be tested can be influenced by an industry panel. On-farm demonstrations using a range of cultivars with resistance ratings from 2 to 7 and treated with fungicide, as standard farm practice vs ICM or DSS guidance, would enable growers and agronomists to see and discuss ICM in practice at commercially relevant scales. Demonstrations using DSSs are being done on SPot farms and elsewhere, and it would be useful to link these demonstrations to previous AHDB-funded research on ICM.

Cost, benefits and risks of ICM systems: Calculate the costs and economic benefits for growers from using selected ICM systems compared with a routine fungicide approach. Risks associated with using DSSs: Identify whether the initial outlay for equipment and ongoing costs such as a subscription to use a DSS platform, is cost effective. Determine if the economic benefits outweigh the costs and the potentially elevated risk to crop health. Methods for this analysis have been developed (Te Beest *et al*., 2009, Te Beest *et al*., 2013) which could be applied to late blight.

Monitoring changes in the GB and European P. infestans populations: The continuation of genotyping (and phenotyping) of the GB *P. infestans* population is valuable for assessing future changes in cultivar resistance ratings and fungicide efficacy due to resistance. Given that the *P. infestans* strains currently dominating the GB population most likely originated in mainland Europe, maintaining good links with

European researchers will be key to understanding what strains are emerging and whether their characteristics pose a risk to the use of ICM techniques in GB. Population monitoring has reported strains of *P. infestans*, such as 37_A2, in seed producing areas in England, but not yet in Scotland. Checking where seed was grown and the risk of late blight in that area will be important to gauge risk from novel strains when selecting seed.

Appendix 1: Summary of Sustainable Arable LINK project, 2009 to 2012

Sustainable and effective control of potato late blight: matching fungicide inputs to cultivar resistance level

The LINK project investigated aspects of ICM for potato blight. The objectives and conclusions relevant to ICM are listed below.

Provide robust information on the resistance of important cultivars to the contemporary UK population of *P. infestans*

Glasshouse experiments can be used to provide guidance on the likely changes in cultivar foliar blight resistance to novel genotypes of *P. infestans*.

- Cultivar resistance ratings for foliar blight can vary depending on the *P. infestans* strain used to inoculate field experiments.

Evaluate the performance of different levels of integrated control against a routine standard during three growing seasons with different levels and patterns of risk

- Cultivar resistance-based integrated control in GB proved to be highly effective in controlling foliar blight caused by the new population of *P. infestans*, even when disease pressure was high to very high compared with that for the vast majority of commercial crops.
- The reported study demonstrated that integrated control based on cultivar resistance and reduced fungicide inputs can be used successfully to control leaf blight during both rapid canopy and stable canopy phases of growth.
- Using a moderately resistant cultivar Cara with a foliar blight resistance rating of 5 was sufficient to reduce the fungicide dose required to control leaf blight substantially and maintain equivalent control to the reference treatment (the very susceptible King Edward treated with the full label rate at 7-day intervals).
- Where a resistant cultivar with a foliar resistance rating of 7 (Sarpo Mira) was used, foliar disease control was superior to the reference treatment regardless of fungicide rate and application interval.

- Although reduced foliar resistance in some cultivars, associated with changes in the *P. infestans* population (Lees *et al.,* 2012), is a setback to implementing integrated control, there remain substantial differences between cultivars and these can be exploited. This is illustrated clearly by the results for the integrated control treatments for varieties with current and representative levels of foliar resistance, i.e. Cara (foliar resistance rating 5) and Markies (5).
- Furthermore, results presented suggest that the contribution of cultivar foliar resistance in commercial potato growing, in which a very high percentage of the national crop is protected by fungicide, may be underestimated by resistance ratings obtained in screening trials using the more aggressive genotypes without managing inoculum density, e.g. through fungicide use.
- The field experiments demonstrated that, in general, for the same total fungicide input it was more effective to apply less fungicide more frequently to control leaf blight, than have fewer applications with greater fungicide input for each application. This result indicates that retaining 7-day spray intervals but lowering the fungicide input per application is the more robust approach.

Evaluate the impact of fungicide input on foliar late blight development on cultivars differing in resistance

- Results from thirteen field experiments provide clear evidence that relative AUDPCs for cultivars differ substantially for different levels of fungicide input.
- Where experimental disease pressure was very high, larger differences in foliar blight between varieties were observed where fungicides had been applied compared with the same varieties left completely untreated.
- Treating cultivars with at least some fungicide input during screening offers a more realistic indication of the contribution of more resistant ones to control where integrated management strategies are implemented.
- There is evidence from the literature that cultivars may not provide the protection from leaf blight, as suggested by their resistance ratings, early and late in the growing season.
- The resistance ranking orders obtained for untreated and fungicide-treated plots were not significantly different. However, additional experiments are required to confirm this result.

Model the interaction of host resistance with fungicide product, dose and spray interval

- Modelling has demonstrated that cultivar resistance has only a limited effect on the width of the spray window.
- A more appropriate strategy would be to use an appropriate dose of fungicide which takes into account host resistance, the onset of the epidemic and how conducive to blight the weather is.
- The fungicide dose required to achieve commercially-acceptable control will vary between fields and seasons according to the balance between disease pressure and cultivar resistance.

Provide cost benefit analyses for the different combinations of cultivar resistance, fungicide product, fungicide dose and spray interval

- Economic losses were generally proportionately lower on cultivars with intermediate resistance (e.g. Cara) where they received the same fungicide dose as a susceptible cultivar (King Edward).
- It was not possible to demonstrate an economic benefit to yield of applying fungicides to a resistant cultivar (Sarpo Mira) in either the rapid or stable canopy experiments.
- There were no negative effects on yield where fungicides were applied to resistant cultivars in the absence of substantial disease.
- Only one product (Revus) was tested during rapid canopy growth and given the differences between the products tested during stable canopy, further investigation of different products at reduced doses applied during rapid canopy growth as part of an integrated control strategy is necessary.

Environment Impact Quotient and Field Use Rate calculations for late blight fungicide programmes

- The EIQ/FUR system has been peer reviewed, is used by major potato companies in the UK and produces a single value to allow straightforward comparisons.
- Fungicide programmes that were both effective and of low potential environmental impact could be identified.

- Environmental risk indices are not the only factor in determining what blight product or programme to use, e.g. cost and resistance management must also be considered.
- Dithiocarbamates, as multisite fungicides, are recommended as mixing partners to improve resistance management, however, had a much higher EIQ rating and higher FUR.

Assess the value to risk assessment from monitoring the concentration of air-borne *P. infestans* sporangia near crops

- The method used demonstrated that sporangia can be collected and quantified using spore samplers and DNA diagnostic methods.
- There was a poor relationship between the number of sporangia counted and the DNA quantified; the methodology requires refining.

Appendix 2: Strategies for integrated deployment of host resistance and fungicides to sustain effective crop protection (Horticultural and Potato Initiative Project 2014 to 2016)

Pathogens such as *Phytophthora infestans* may evolve insensitivity to fungicides used to control their populations and evolve virulence to overcome cultivar resistance, resulting in a reduction or loss of disease control and yield. Classical population genetic theory predicts that integrating chemical and genetic control should delay the evolution of insensitivity and the evolution of virulence, providing more durable effective control.

The project was developed to test three hypotheses:

H1: Deployment of partial cultivar resistance will reduce selection for fungicide insensitivity.

H2: Deployment of fungicides will reduce selection for virulence.

H3: How crop resistance genes and fungicides are integrated is a key determinant of the durability of effective disease control.

To test these hypotheses two approaches were used.

Firstly, three years of field trials were conducted in Wales and Scotland from 2014 to 2016. These compared the selection for either a known fungicide insensitive strain on susceptible and moderately resistant cultivars (Hypothesis 1), or the selection for a known virulent strain at low and high fungicide doses (Hypothesis 2). In each experiment two key variables were recorded, epidemic growth rate and selection ratio. Population genetic theory predicts that higher epidemic growth rates are associated with higher selection ratios.

To measure the selection ratio, leaf samples showing disease lesions were collected from each of the trials at two different sampling times. Genotype analysis of the DNA recovered from these lesions allowed the subsequent quantification of pathogen population composition. The increase or decrease in the frequency of a given strain in the population is the selection ratio. Environmental conditions and naturally occurring inoculum had a large effect on the epidemic timing and growth rate, to the extent that environmental conditions had a larger effect on population growth rates than the treatments. However, the hypothesised positive relationship between epidemic growth rate and selection ratio was observed. This demonstrates experimentally that a reduction in population growth rates reduces selection.

Secondly, an epidemiological model was constructed to test the hypotheses. This model described the growth and senescence of a standard UK potato crop, with epidemics of *Phytophthora infestans* being controlled by a combination of cultivar resistance and fungicide application. The model describes the evolution of insensitivity and virulence in *P. infestans*, agreeing with the results of the field trials in the testing of H1 and H2; that reduction in epidemic growth rates reduces the time taken to evolve insensitivity or virulence. The model was then used to test hypothesis 3, exploring optimum integrated control programmes to maximize the effective life of fungicides and cultivar resistance.

This work demonstrates that the use of cultivar resistance delays the evolution of fungicide insensitivity (hypothesis 1), and the use of fungicide delays the evolution of virulence (hypothesis 2). Integrating these two control methods extends their durability (hypothesis 3). This provides a practical set of tools to manage the evolution of pathogen populations, extending the durability of disease control.

Appendix 3: Development of a simple decision aid to identify when curative fungicides will be effective or not

Control of Phytophthora *infestans (*late blight*)* is achieved through routine applications of fungicide throughout the growing season. Some of the fungicides used to combat *P. infestans* can have curative properties: they can affect the pathogen in its incubation period, after infection but before disease symptoms become visible. There is evidence that the curative properties of some fungicide treatments are an important component of late blight control, but there is a need for additional information and also tools to ensure that they are not used at times when they won't be effective. The use of curative fungicides has increased very substantially in the last two decades.

The project had two primary goals:

G1. Gather detailed information on the curative control window, and how it can be modified by factors such as temperature and host resistance.
G2. Use the information from G1 to produce a simple decision aid to assist growers identify when the use of a curative product will be most effective.

Experiments were conducted in the laboratory under controlled conditions, but also in the field to ensure that the decision aid was relevant to commercial practice. A representative fungicide (propamocarb-HCl + fluopicolide,) which is rated as providing a 'good' curative effect, was used through the project to ensure consistency. A key hypothesis of the study was that more rapid disease development during the incubation period would lead to a reduced 'curative time window'. In order to assess this the project measured disease development using two methods: classical disease symptom measurements, and quantification of *P. infestans* DNA in infected tissue. The second method estimated pathogen load within the incubation period, which is of critical relevance for the curative window.

A series of controlled experiments with detached potato leaves were used to measure growth rates, both in terms of lesion growth and pathogen DNA accumulation. Both of these measures were strongly dependent on temperature, and subtle differences were found for isolates representing different genotypes. A large number of mathematical models of biological growth were gathered from the literature, and compared to see which provided the best description of the *P. infestans* growth data. Several gave very good characterizations, and the best performing was selected for use in the decision aid.

A detailed description of the relationship between disease development time and curative control was critical for the decision aid, and a series of bioassays were performed using precisely timed curative fungicide applications to infected leaflets or leaf discs. Previously, studies that measured curative activity generally used large intervals between treatment times or did not cover all of the time points that may be relevant. In this project data were produced at 4-hour intervals between 8 and 72 hours of disease development time. The relationship between control and disease development time obtained was best described by a sigmoid curve, which is very frequently used for dose-response relationships. This relationship was used for the final decision aid.

The project also included an investigation of the effect of cultivar foliar resistance rating on the curative window. An impact was demonstrated in some cases but more work is needed before it can be incorporated into the decision aid.

The project specified and tested a simple decision aid consisting of two linked equations. The aid produces a simple categorical 'likelihood' score (*i.e.* 'very likely', 'unlikely', *etc.*) for curative control, based on thermal time from the end of a high infection risk (Hutton Period) until the fungicide application timing. The decision aid has potential to reduce unnecessary and ineffective use of curative active ingredients. Crucially the decision aid fits the very common current practice in GB of fungicide applications being made at 7-day intervals (i.e. spray timing does not need to be modified) therefore avoiding one of the major barriers to the uptake of ICM by growers. The decision aid is intended to provide justification for one of three possible actions:

Include a curative active ingredient with the protectant

Apply a protectant only

Apply a protectant plus adjuvant. The adjuvant provides additional canopy coverage to replace that afforded by the translaminar properties of the missing curative.

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