Managing and Reducing Plant Diseases (Pathogens)

Summary

Key Policy Messages

The analysis finds that climate change could make the Government's 25 Year Environment Plan outcome of 'managing and reducing the impact of existing plant and animal diseases; lowering the risk of new ones and tackling invasive non-native species' significantly more difficult for many species, though there could be a reduction in risk from others.

The risks to meeting this outcome involve potential lock-in and threshold effects, because once certain diseases are established (endemic), they are difficult and costly to eradicate, and can cause large economic costs. While the evidence on the likely changes are difficult to estimate, the study has explored potential economic costs through some indicative 'what-if' analysis for plant pathogens: this reveals large potential damages from climate change for three of the pathogens (*Phytophthora ramorum*, *Chalara fraxinea* and *Dothistroma)*, but potential benefits from a reduction of *Septoria* on wheat. The damage estimates for these diseases range from the tens to the hundreds of £millions (total benefits to 2050s, discounted), with a similar magnitude of benefit for *Septoria*.

The case study has also looked at adaptation. There are a number of existing actions set out in the NAP to address disease risks, however, it is highlighted that the 25 YEP – and NAP2 – do not outline a measurable goal for managing and reducing the impact of existing plant and animal diseases, e.g. managing to acceptable levels (e.g. based on the balance of costs and benefits) or even to minimal damage (or as close as possible to this). Similarly, the actions in Defra's Tree Health Resilience Strategy (the tables of action) do not seem to match its ambitions for adaptation, and there is very little in the Strategy on how to address future climate challenges. The Strategy does report that such actions will be covered in the Forestry Sector Climate Change Action Plan, however, analysis of this latter document shows it does not have a strong focus on pests and diseases. Therefore, while there are some actions that could help manage changing pathogen risks, we consider there is a gap, and further, given the possible large increase in resource costs and further public intervention needed to tackle future pests (especially as the size of these effects could exceed private actors' past experience), further action is warranted. Based on the analysis, we therefore identify that there is a strong economic argument for greater Government intervention in research, monitoring, awareness raising and co-ordination of reactive response toward potential and emerging threats (including invasive species): this would require enhanced Government action, but is projected to have high economic benefits compared to costs (at least 10:1).

What is the outcome?

This case study is focused on the biosecurity theme in the 25 year Environment Plan (25YEP) (HMG, 2018) and the goal and target for 'managing and reducing the impact of existing plant and animal diseases; lowering the risk of new ones and tackling invasive non-native species'. This target is also set out in the National Adaptation Programme (2018). More detailed actions are listed in the Tree Health Resilience Plan (Defra, 2018a), which includes a focus on resistance, response and recovery, and adaptation. The strategy does highlight the potential role of climate change, but it does not assess how this will affect the strategy's objectives.

There are an extremely large number of possible plant and animal diseases that could be covered by the outcome. To make the study manageable, the case study has focused on four plant-based pathogens that are currently established in England, and that might be exacerbated by climate change. These are:

- *Phytophthora ramorum*, which affects trees and other plants, although the disease is a particular problem for in the UK for larch grown for timber;
- *Chalara fraxinea*, a fungus that affects ash trees and leads to dieback;
- *Dothistroma* needle blight of pine, which causes premature needle defoliation and reduces timber yield (and in severe cases causes tree mortality); and
- Yellow rust and *septoria* on winter wheat, which leads to yield loss.

These pathogens have been selected due to their potentially significant economic impact and/or the ecological value of the ecosystems that are affected. Due to the absence of a specific 25YEP target on the levels of reduction in (i.e. on whether to manage to acceptable levels, to optimal levels as defined by costs and benefits, or as low as reasonably possible) we have defined a goal. The assumed baseline objective (and outcome) is that the risks from all four of these pathogens would be reduced compared to current levels.

How does climate change affect the outcome, in a 2 vs 4°C pathway?

Changes in the climate can affect the suitability and geographical range for pests and diseases and may also, in combination with changes in extremes, affect the prevalence and intensity of pest and disease outbreaks. The economic costs of these outbreaks can be very high, once established. However, making precise projections of the changes in specific pathogens, and the subsequent impact, is much harder. There is no robust evidence on how climate change will affect each of the pathogens above, and certainly no information to distinguish between 2 and 4°C scenarios. Phytophthora ramorum and Yellow rust/Septoria generally favour warmer and wetter conditions over autumn/winter/spring: they might therefore become more prevalent as these conditions are projected by UKCP18 (Sturrock et al., 2011). However, for septoria, the increase in warmer drier summers (also projected by UKCP18) could potentially offset these increases (Gouache et al., 2013). Ash die-back is projected to decline under climate scenarios that project warmer, drier, summers (Goberville et al., 2016)) whilst red band needle blight is projected to increase to 2050 as a result of the higher projected winter rainfall (Ray et al., 2017)).

Importantly, this outcome also involves potential lock-in and threshold risks, because once diseases are established (endemic), they are difficult and costly to eradicate, and can cause large economic costs.

What are the economic costs of climate change, i.e. the effect on the outcome?

While the evidence on the likely changes are difficult to project, it is possible to explore the potential economic costs of climate change through some indicative 'what-if' analysis. In the table below we summarise the assumptions made on disease spread under climate scenarios, and the associated cost estimates.

Disease type	**Disease spread assumptions**	**Additional Costs from Climate change from now to 2050** (£m; 2018 constant prices; discounted)
Phytophthora ramorum	Current extent of spread (2010-2018) to be maintained to 2050 Upper-bound, what-if scenario	67.5
Chalara fraxinea	Range of 15% to 50% increase in spread to 2050	178 to 596
Dothistroma	23% increase in spread to 2050	300
Septoria	2-6% reduction in spread to 2050	- 83 to -245

What are the potential additional adaptations options to address climate impacts on the outcome?

There are a number of existing actions set out in NAP2 to address pest and disease risks (Defra, 2018). However, these are not extensive, and in some cases, they rely on others (industry, volunteers) to provide monitoring and surveillance. There is very little on how to address future climate challenges – although it does highlight these will be covered in a subsequent Forestry Sector Climate Change Action Plan. However, analysis of the latter Plan (Defra, 2018c) shows it does not have a strong focus on pests and diseases, i.e. there appears to be a gap.

The specific options currently recommended for each of the four pathogens has also been reviewed (Defra, 2014b; GB DNB; HGCA, 2012). On the basis that climate change will make the outcome of managing and reducing pests and diseases probably more challenging, an uplift in adaptation is considered to be warranted to maintain the level of impact from these four diseases at today's levels, or reduce it further. To investigate this, the study has looked at additional adaptation options that could be introduced. We focus on early adaptation priorities– that might be used to make sure that Government outcomes are put back on track - using three key building blocks that comprise a high-level adaptation pathway.

These are:

- Early low- and no-regret options that address current risks and build resilience;
- 'Climate-smart' decisions including decision making under uncertainty (for early decisions with a long life-time / risk of lock-in);
- Early planning / iterative adaptive management, in cases where there are benefits from early activities / or adaptation that involves long lead times.

What are the benefits and potential costs of adaptation?

The case study has examined the possible costs and benefits of adaptation. The analysis has looked at the existing costs and benefits of current adaptation actions to tackle the four pathogens above (Brown and Webber, 2008: Forestry Commission, 2011; Fones and Gurr, 2017), and the potential increased costs and benefits under climate change. For Phytophthora ramorum, comparison of the costs and benefits of identification, felling and replacement of infected larch trees gave a benefit-cost ration of 1:1. Whilst lack of data on adaptation options preclude the possibility of a quantitative cost-benefit analysis (CBA) for ash die-back, it is likely that investment in monitoring and surveillance would be a no-regret option as it is for many other diseases. For red band needle blight, thinning undergrowth is found to be a cost-efficient option, (i.e. the benefit-cost ratio (BCR) > 1), as long as a certain level of effectiveness is achieved, whilst Septoria on winter wheat can be reduced cost-efficiently using fungicides.

The analysis therefore indicates that it is possible to manage changing pathogen risks, at least to some extent, using existing adaptation options. However, there would be a large resource cost associated with higher management effort and it is possible that public intervention is needed, either in the efficient provision of data and information relating to the pathogen spread, or in the local economic transition away from a reliance on the affected agricultural or forestry-based activity.

More generally, this indicates that once established, managing pathogens and pests is costly. Given that a wide range of pathogens and pests may spread or be introduced as a result of climate change, and given the need for co-ordinated provision of information, there would seem to be a case for an expanded role for Government intervention to provide enhanced monitoring and surveillance and early response. Evidence on the economic justification for such a scale up (SRUC, 2013) suggests this would be highly beneficial, with a benefit to cost ratio of up to 10:1.

What is the objective and outcome?

This case study is focused on the biosecurity theme in the 25 year Environment Plan (25YEP; HMG, 2018), in the section on Managing Environmental Pressures. The goal and target focusses on managing and reducing the impact of existing plant and animal diseases, lowering the risk of new ones, and tackling invasive non-native species.

The 25 YEP highlights that such disease outbreaks affect communities and the ability to trade with other countries, as well as harming animal welfare. By strengthening biosecurity, the 25 YEP sets out the aim to better protect the nation's animals, cultivated crops, wild plants, trees and forests from pests and diseases. This includes invasive non-native species. Threats from pests and diseases can lead to the threat of extinction, costly and lasting damage to the character of rare natural habitats. The plan uses the example of Ash dieback (a fungal disease) across Europe, and the proliferation of Quagga and Zebra mussels, to highlight the potential risk. The 25 YEP highlights the benefits of early and effective intervention, in reducing subsequent costs, and in reducing impacts on the environment from breaches in bio-security. Again, it uses an example, the early eradication of the invasive water primrose in Great Britain as an example of cost saving (of approximately £240 million compared to late stage eradication in this case). The 25 YEP states that Government will continue to take early, pre-emptive action based on evidence of a threat to stop pests and disease arriving here, and presents the following actions:

- Developing plans to reduce the risk from all high priority pathways for invasive non-native species introduction into England.
- Working with partners to raise awareness of invasive non-native species and the need for strong biosecurity.
- Maintaining an alert system to detect high priority invasive non-native species and implement contingency plans to rapidly eradicate them where feasible.
- Publishing a Tree Health Resilience Plan later in 2018 to protect against tree pest and diseases and improve resilience of trees to withstand threats.
- Working with industry to place biosecurity at the centre of buying practices – including encouraging the development of a bio-secure supply chain for woodland creation.

The 25 YEP also has a related action on reaching the detailed goals to be set out in the Tree Health Resilience Plan of 2018 (Defra, 2018a). It also sets out an action to appoint a National Tree Champion, who will look to advance integrated thinking including the management of the impact of pests and diseases, and that a revised Plant Health Biosecurity Strategy in 2020 will set out the strategic framework to protect plant health. It also includes an action to continue to deliver the GB Invasive Non-native Species Strategy (2015) in order to protect natural capital in England from invasive non-native species

The goal is also transferred through into the second National Adaptation Programme (Defra, 2018b), which sets out actions that will be taken to:

- Manage existing plant and animal diseases and lower the risk of new ones; and
- Tackle invasive non-native species.

In response to the first of these, NAP2 sets out that there is already a robust system of horizon scanning and international monitoring for animal disease threats, which provides an early warning system that enables targeted active surveillance for high impact diseases (to supplement the system of passive and scanning surveillance for new and emerging diseases). It also sets out the creation and deployment of the UK Plant Health Risk Register (UKPHRR), which allows for the characterisation of risk and also prioritisation, to decide on the key actions to be taken to reduce risks, such as research and contingency planning. Pest-specific contingency plans are being drafted for high priority plant health pests. It highlights that industry and private veterinarians also have a role to play in scanning surveillance for new and emerging threats, including those resulting from climate change, and sets out working across the industry to better utilise data held by business, private labs, veterinarians and animal keepers, which will enable a more comprehensive surveillance system in the future.

In relation to invasive species, NAP2 sets out the following:

- The continuation of the programme of invasive non-native species surveillance and risk analysis across Great Britain, coordinated by the GB non-native species secretariat. This aims to prevent the establishment of novel, and the spread of established, invasive species by building on contingency planning and rapid response action, working across Government to contain outbreaks and prevent species gaining a foothold in the UK. NAP2 cites the example of the dedicated alert system for the Asian hornet. Volunteers play a key role in supporting Government to implement the GB invasive non-native species strategy, providing grants (albeit only a total of £1.5 million between 2011 and 2015) to help establish Local Action Groups (LAGs) to tackle aquatic and riparian invasive non-native species in England.
- Government will seek to eradicate high priority invasive non-native species identified by risk analysis, establishing contingency plans for high priority new arrivals, and implementing management plans for priority established species where eradication is not feasible. This involves pathway action plans to reduce the risk of invasive species introduction into England from all high priority pathways.
- Defra will continue to support initiatives that compile and analyse species data so that we can track trends in species distributions.
- It also highlights the linkages to the Action Plan set out in the 2018 Tree Health Resilience Strategy.

The Tree Health Resilience Strategy - Building the resilience of our trees, woods and forests to pests and diseases (Defra, 2018a) sets out plans to protect England's tree population from pest and disease threats. The strategy focuses on delivering three outcomes to build resilience (1) resistance, (2) response and recovery and, (3) adaptation. The strategy sets out a number of goals, as well as a planned National Action Plan. The tree health resilience strategy has its own vision, which is 'to build the resilience of England's trees, woods and forests', and 'to enhance the benefits that trees provide, by mitigating and minimising the impact of pests and diseases and improving the capacity of our trees to adapt to changing pressures'. It also sets out the need for the strategy in the context of the annual economic value of ecosystem services (economic, social and environmental) that trees in England provide, estimated at £4.9bn per year. The strategy does highlight the potential role of climate change, but it does not assess how this will affect the strategy's objectives.

Finally, the Forestry Climate Change Working Group, (FCCWG), has published a detailed list of climate change adaptation-specific actions, disaggregated in terms of policy, research and practice, with lead actors identified and a target date for the action to be undertaken by.

Focus of the case study

There are an extremely large number of possible plant and animal diseases. To try and make this outcome manageable, the case study has focused on four plant-based pathogens that are currently established in England, and that might be exacerbated by climate change. These are:

- *Phytophthora ramorum;*
- *Chalara fraxinea;*
- *Dothistroma* needle blight of pine;
- Yellow rust and *septoria* on winter wheat.

These have been selected due to their potentially significant adverse economic impact and/or their ecological value. In this section, each is described.

It is highlighted that the 25 YEP – and NAP2 – are not specific on the goal of managing and reducing the impact of existing plant and animal diseases. This could be, for example, managing down to acceptable levels (e.g. based on the balance of costs and benefits). Or it could be to reduce down to levels that involve no economic damage (or as close as possible to this). For this case study, we assume that the objective (and outcome) of current policy would be to manage and reduce the impact of existing plant and animal diseases; lower the risk of new ones and tackle invasive non-native species.

Phytophthora ramorum

Phytophthora ramorum (Pr) is a fungus-like pathogen that has spread rapidly in recent years. It causes damage and mortality to trees and other plants. Although the disease can infect around 150 plant and tree species, in Britain, commercially grown larches (Japanese, European and Hybrid – of which there are 16,000 hectares in England) have been found to be particularly susceptible and can die within one to two seasons after infection. Its significance arises from the fact that larches are important timber species for Scotland and account for around 10% of conifer growing stock in Great Britain (35.6 million m^3).

Chalara fraxinea (ash dieback)

Ash is a widespread species and makes a substantial contribution to many landscapes. Ash trees - in woodlands of 0.5 hectares or more in size - cover 141,600 hectares in Great Britain (5.4% of the total woodland) and 110,400 hectares in England (9.2% of total woodland). In addition, there is a further 38,500 hectares of ash in Great Britain's smaller sized woodland (less than 0.5 hectares) and 32,100 hectares in England. Ash is estimated to be 15% or 22 million tonnes of the standing UK hardwood.

Ash trees are affected by ash dieback, a disease caused by a fungus, *Chalara fraxinea*. The disease causes leaf loss and crown dieback in affected trees and often leads to tree death. Common ash (*Fraxinus excelsior*) is the most severely affected species and is the only native species of ash in the UK. Young trees are particularly vulnerable to *Chalara fraxinea* and succumb to disease rapidly. Chalara ash dieback has the potential to cause significant damage to the UK's ash population, with implications for woodland biodiversity and ecology, and for the hardwood industries.

Dothistroma (Red band) Needle Blight.

Needle blight is an economically important disease affecting a number of coniferous trees, in particular pines (Brown and Webber, 2008). Red band needle blight causes premature needle defoliation which results in the loss of timber yield and, in severe cases, tree mortality. Since the late 1990s the incidence of the disease has increased dramatically in Britain, particularly on Corsican pine (*Pinus nigra* ssp. *laricio*), and due to the extent and severity of the disease on this species, there is now a five-year planting moratorium of it on the Forestry Commission estate. More recently there have been reports of the disease causing damage to lodgepole pine in Scotland and it has also been reported on Scots pine – although it rarely appears to be causing significant damage to this species.

Yellow Rust and Septoria on Winter Wheat

Septoria tritici, caused by the fungus *Mycosphaerella graminicola*, is the most important wheat disease in the UK. In the UK, wheat is the largest arable crop (by area) with an annual planting of approx. 1.9 million hectares. Production is centred towards the Eastern parts of England with the East Anglian, South-Eastern and East Midland regions together accounting for more than 58% of the crop grown. Yield loss occurs as a consequence of reduction in green leaf area for photosynthesis. Coastal regions stretching up the East coast of England are most at risk of yellow rust, with early sown crops in the region around the Wash being most likely to develop the first early disease outbreaks.

How does climate change affect the outcome, in a 2 vs 4°C pathway?

The next step is to assess the potential impacts of climate change on the goal of managing and reducing the impact of existing plant and animal diseases; lowering the risk of new ones and tackling invasive non-native species.

There are many factors that affect the spread of indigenous and invasive pests and disease. The focus in this case study is on the driver of climate change involved.

Most pests and diseases have some degree of climate sensitivity, related to the optimal range and tolerable range for their survival, although this can be highly complex, relating to particular parts/timing of their development, maturation and reproductive cycle. Changes in the climate can therefore affect the suitability and geographical range for pests and diseases (Porter et al, 2014). It may also, in combination with changes in extremes, affect the prevalence and intensity of pest and disease outbreaks. As a simple example for England, climate change could lead to a northward migration of existing pests and disease (for those pests and diseases that are currently temperature limited, in relation to survival from over wintering), as well potentially enhanced suitability for invasive species, e.g. from warmer parts of Europe. However, it may also have benefits, if it reduces the climatic suitability of current pests and diseases.

In practice, the combination of climate variables that determined the bio-climatic range, and the parameters that affect outbreaks, are often very complicated and species specific: temperature alone is not a good guide to the likely effects, and rainfall, humidity, and extreme variables are all important. It is stressed that while there is a general perception that climate change will increase the impact of pests and diseases, there is no reason why this should automatically be the case.

The case study has assessed the available evidence on the potential influence of climate change on the four plant-based pathogens above, and how this might affect the outcome of reducing them. It is stressed that the evidence base on what these potential changes could be is low, and there is a lack of information on how much they might differ between 2 and 4°C pathways. It is also highlighted that not all of the possible changes are negative, i.e. that pest prevalence/range and outbreak intensity will increase.

Nevertheless, the overall conclusion is that climate change could make the outcome – of managing and reducing these pathogens – more challenging.

Phytophthora ramorum (Pr)

Phytophthora ramorum is sensitive to climate conditions. It has optimal growth between 18 and 22°C. Moisture is essential for survival and sporulation, and the duration, frequency, and timing of rain events during the winter and spring play a key role in inoculum production. Sturrock et al. (2011) - the only authors who give an indication of likely changes in incidence under climate change - report that in the forests of central coastal California, winter rains are critical to the persistence of the pathogen, whereas in coastal evergreen forests rain must fall in March, April and May. The authors state that increases in precipitation will probably produce optimal conditions for the pathogen in some areas, resulting in an increase in rates of infection. They conclude that if conditions become warmer and drier, the pathogen will decline whilst if conditions are warmer and wetter it will increase.

The latest UK projections UKCP18 (Lowe et al., 2018; Murphy et al., 2018) report an increased chance of milder, wetter winters and hotter, drier summers along with an increase in the frequency and intensity of extreme weather events. The projections of rainfall are more uncertain than for temperature, and vary on a seasonal and regional scale. However, the majority of projections suggest winter precipitation to increase significantly and summer rainfall to decrease significantly. The effect of these changes on *Phytophthora ramorum* in England are therefore complex: the increase in wetter and warmer winters is likely to increase survival and sporulation, however, this could be offset by warmer and drier summers.

Chalara fraxinea (ash dieback).

Pautasso et al. (2013) report that the current spatial distribution of common ash is constrained by aversion to cold winters and hot dry summers, thus, the temperate climate of England is understood to be well-suited to the species. The *Chalara fraxinea* fungus is most productive in temperatures of 20–22 °C and no fungal growth takes place above 28 °C. Goberville et al. (2016) ran simulations of the productivity of both ash trees and *chalara fraxinea* and their interactions, at the European scale. They found that by 2050 the productivity of ash – taking account of *chalara fraxinea* – may rise by between 15% and 50% under RCP2.6 and 8.5 scenarios, respectively. This is a consequence of the fact that the higher mean temperatures encourage ash growth whilst the projected increased dryness of the summers constrains fungal growth. The paper suggests that this effect is likely to be exacerbated in western parts of Europe such as the UK.

Dothistroma (Red band) Needle Blight

Brown and Webber (2008) report that the critical period for infection in Britain is spring and early summer when the fruiting bodies are formed on the needles. Furthermore, Archibald and Brown, (2007) identify that severe episodes of the disease appear to be associated with higher than average rainfall at the time of infection. Ray et al. (2017) model this and other factors under alternative climate change and forest management scenarios to 2100 for four forestry estates in Scotland in order to quantify the effects on biomass, timber production and biodiversity. An RCP 4.5 climate scenario was used. Management regimes were found to significantly dictate the size and direction of change. Thus, against a composite indicator of biodiversity, a continuous cover management option where there is no change in species composition results in an improvement of biodiversity, whilst a short rotation management model whereby the species is felled after 25 years leads to a decline. A similar pattern results for biomass under these management regimes. Under the RCP4.5 climate scenario and a continuous cover management option, the impact on timber production of needle blight is a decrease of 5m^3/hectare, whilst under the short rotation management model, there is little effect until 2050 after which there is a decrease of 50m^3/hectare.

Yellow Rust and Septoria tritici on Winter Wheat

Fones and Gurr (2015) report that because *Septoria tritici* requires a moist leaf surface for successful infection, and is spread throughout the crop canopy via rain splash, the frequency of either very wet days (>10 mm rainfall) or consecutive wet days (three days with at least 1 mm rain) during the early growth of the wheat crop are of major importance in predicting outbreaks. Similarly, the frequency of weather fluctuations is important, with temperatures below -2°C in the early stages of growth reducing the risk of *septoria tritici* for winter wheat in the UK. The projections from UKCP18, with wetter and warmer winters, might therefore provide the conditions for increased outbreak.

Seedlings from early autumn planted seeds will endure temperatures more conducive to the establishment of infection and be exposed to sufficient rainfall to facilitate spread of the disease. Imposing A1B (medium – 2.6° - 4.2°C by 2100 for the UK) climate scenarios on the pathogen, using four GCM models, down-scaled, and generating daily data for maximum and minimum temperatures, incoming radiation and precipitation, Gouache et al. (2013) projected that *septoria tritici* incidence could be reduced by 2-6% at three sites across France by 2071-2100 – though the climate projection uncertainties ensure that the direction of change is unstable. It is also not known how transferable these results are likely to be to England, though given the uncertainties involved and geographical proximity it is likely that these range of estimates can be used initially. An analysis of UKCP18 would validate this assumption.

Lock-in and thresholds
All of the pathogens above are climate sensitive, and thus there will be bio-climatic thresholds for their suitability, and potential threshold levels associated with more extreme outbreaks. There is not good evidence to identify thresholds, and thus whether exceedances (of these) will be more of a risk in 2 or 4°C futures. Importantly, there are also potential lock-in and threshold risks associated with these pathogens, because once established, pathogens can spread rapidly and can be difficult to control. This is a particular issue also for invasive species. These lock-in risks can apply to baseline investment decisions, notably for forestry where life-times are long, i.e. changing patterns of pests could affect the financial viability of commercial forests, if there is the future potential for pest outbreaks.

What are the economic costs of climate change, i.e. the effect on the outcome?

As highlighted by the review above, there is no clear evidence on the likely changes from climate change on pathogen prevalence and outbreak, and therefore on how climate change will affect the achievability of the target to reduce and manage these specific risks. The case study has, however, looked at the potential costs of not achieving the outcome (due to climate change) using some 'what if' analysis. Throughout the case study, in order to derive values for the natural assets affected by the climate risks of concern here, we adopt the principles of natural accounting outlined in ONS, (2017).

Phytophthora ramorum (Pr)

The primary cost of inaction from *Phytophthora ramorum* is the loss of revenue resulting from the decline in larch wood production and sales. The cost of managing and slowing the spread of *Phytophthora ramorum* in the UK was £23 million between 2009 and 2014 (Defra, 2018a). For this analysis, we try and unpick the costs and use this to project the possible extent of impacts under future climate change. Based on its average height, we assume that the average mature larch tree produces the equivalent of 20 cubic metres of wood. The current price of coniferous wood per cubic metre is £29.02 (2016 constant prices).[1] On average, over the last eight years, the annual average volume of infected wood – estimated from data on the stands being given SPHNs – is estimated to be 77,500 cubic metres. There is no evidence that these recent infections have been associated with climate change; the reason for the spread of the disease from California to Europe fifteen years ago and its subsequent spread around Western Europe is not known. If, however, it was assumed that a change in climatic conditions had facilitated this spread so that all this recent loss was attributed to climate change, the current annual cost would be £2,250,000.

This cost, in future years, will be affected by the patterns of pathogen spread and the stock of living larch trees across the country. Given that England is expected to experience more warm days of 18-22°C under all climate change scenarios, and that wetter winters are also expected, climate change could enhance the spread of the pathogen (although this might be somewhat reduced by drier summers). In the absence of detailed evidence, a "what if" scenario could be to assume that the current annual average cost continues to be borne until 2050. This may be plausible given that - combined with the fact that climate change is projected to result in growing conditions more conducive to larch[2] - the pathogen is likely to be more challenging to manage under a changing climate (i.e. the goal of reducing risks is not achieved). The total cost of inaction would then be £67,500,000. However, this value may be judged to be somewhat of an upper bound estimate as infected wood can still be sold at the market price, and the trees that are felled can – after a fallow period of three years - be replaced with alternative tree species that produce commercially valuable wood. It is also unlikely that current costs can solely be attributed to climate variability. The range of alternative tree species are suggested by the Forestry Commission in a recent guidance note.[3]

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[1] https://www.forestry.gov.uk/forestry/infd-6czjyb

[2] Forest Research (2015) *Adapting Scotland's forests to climate change - changes in tree species suitability*.

[3] https://scotland.forestry.gov.uk/images/corporate/pdf/FCReplantingrecommendations.pdf

Chalara fraxinea (ash dieback).

The costs of *chalara fraxinea* on the ash tree population can be estimated on the basis that the disease has been detected in 36% of the 10km squares in England and the UK. Vulnerability to the disease differs depending on the age of the tree, with more mature trees being more resistant to the disease whilst younger trees being are more at risk. The total annual value of the Ash population in the UK has been estimated to be £150 million (Defra, 2013), of which £22 million is commercial value of wood. In the absence of more specific modelling, we have used the anticipated spread of the disease across Europe (a 15% to 50% increase) and applied this to the English stock through to 2050. Again, we assume that in the absence of climate change, the disease might be manageable. The annual costs are estimated at £22.5 million to £75 million, reflecting the 15%-50% increase in spread. Total discounted costs then range between £178m - £596m.

Dothistroma (Red band) Needle Blight (DNB)

The Forestry Commission (2012) judge that there is a risk of a significant reduction in Great Britain's forest resource due to this disease – particularly Scots pine, Lodge-pole pine and Corsican pine. In order to generate quantitative estimates of the costs of climate change on DNB, we focus on the impacts on timber production. We use the results of the Ray et al. (2017) study that estimated changes in pine timber production under a climate change scenario as a result of DNB. This projects approximately a 2m^3/ha (0.7%) annual loss in pine trees to 2050. Since there are approximately 320,000 hectares of coniferous production in England – equivalent to 87 million cubic metres – this rate of loss would lead to a total of 211,400 hectares by 2050. At £29.02/m^3, the current market price for coniferous wood, which we estimate equates to a total, discounted cost of £300 million.

Yellow Rust and Septoria on Winter Wheat

HGCA (2012) state that yield losses of 30-50% have been reported and susceptible varieties can average a yield loss of 20% in untreated trials. This equates to a cost of up to £250 per hectare, based on a grain price of £150/tonne and an average treated yield of 8.5 ton/hectare. Adopting a figure of 15 million tonnes for total winter wheat production in England, (Cho et al. (2012)), and assuming the yield loss of 20%, this gives rise to a total annual cost of £450 million and a total discounted cost to 2050 of £8,276 million, equivalent to a 20% loss in overall production. Under climate change, we project this cost to be reduced by £83m - £245m, to £8,196 million - £8,131 million.

In the table below we summarise the assumptions made on disease spread under climate scenarios, and the associated cost estimates.

Disease type	**Disease spread assumptions**	**Additional Costs from CC from now to 2050 (£m; 2018 constant prices; discounted)**
Phytophthora ramorum	Current extent of spread (2010-2018) to be maintained to 2050. Upper-bound, what-if scenario	67.5
Chalara fraxinea	Range of 15% to 50% increase in spread to 2050	178 to 596
Dothistroma	23% increase in spread to 2050	300
Septoria	2-6% increase in spread to 2050	-83 to -245

What are the additional adaptations options to address climate impacts on the outcome?

As highlighted above, there are a number of existing actions set out in NAP2 to address pest and disease risks. The UK Plant Health Risk Register tracks plant health risks and prioritises them for action. However, the actions set out in NAP2 on monitoring are not that extensive, and in some cases, they appear to rely heavily on others (industry, volunteers) to provide monitoring and surveillance.

For trees, the Defra Tree Health Resilience Plan sets out the following on the three pillars of resistance, response and recovery and, adaptation:

- ‘Resistance is the first line of defence and focuses on actions that should be taken to reduce the risk of the threat occurring. In the context of increasing threats, we will continue to assess our approach and take opportunities to strengthen biosecurity, including through the development of a new Plant Biosecurity Strategy in 2020.
- Response and Recovery, facilitating a suitable response when threats do occur, to allow our existing trees to recover wherever possible.
- Adaptation is about driving long-term change to strengthen our trees, woods and forests to be more resilient to future threats. It is about improving the baseline diversity, health and condition of our tree-scape to equip our trees to be better able to withstand future pest and disease if they arrive. The priority areas for focus about implementing measures and taking action to increase the extent, connectivity, diversity and condition of our trees.
- Adaptation is about supporting the tree-scape to adapt if a pest or disease has established. If it is not possible for the tree population to recover as the pest or disease is established, then it may be appropriate to manage trees in a way that helps transform the tree-scape to a new desirable state. This may require changes such as breeding new resistant genotypes of threatened species, targeted management of individual trees with naturally higher resistance, or planning of replacement tree species. Tree species are genetically diverse and have substantial potential to adapt if the conditions allow – i.e. that frequent regeneration is occurring or a managed breeding programme is being implemented’.

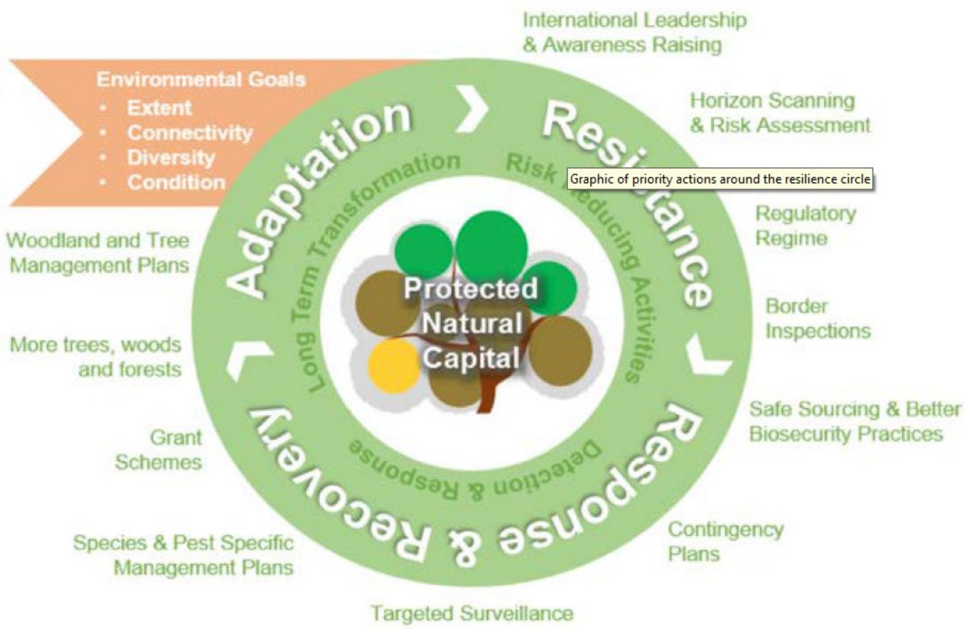

Figure 1 Priority actions around the resilience circle Tree Health Resilience Strategy Defra 2018a

Nonetheless, on the basis that climate change will make the outcome of managing and reducing pests and diseases more challenging, an uplift in adaptation is considered – especially as the actions in the Strategy (the tables of action) do not seem to match its ambitions. This is particularly the case for the adaptation actions, and there is very little in the Strategy on how to address future climate challenges – although it does highlight these will be covered in a subsequent Forestry Sector Climate Change Action Plan. However, analysis of this document shows it does not have a strong focus on pests and diseases.

It is also noted that for forests, the Economics of Climate Resilience study (Frontier et al., 2013) outlined that for pest and disease outbreaks, while adaptation measures are available and are being applied, given the uncertainty over future pest and disease outbreaks, even if current adaptation measures are implemented, the residual impact could be high. The case study has first looked at some of the proposed adaptation options for each pathogen.

Phytophthora ramorum (Pr)

The principal method currently used to control this pathogen is to identify the infected trees and then issue Statutory Plant Health Notices that oblige the owner to fell them. As identified previously, the owner can then sell the felled wood and re-plant with an alternative species. Depending on the financial viability of alternative species, other longer-term adaptation options may include the development of pathogen-resistant larch species or a change in the land use.

Chalara fraxinea (ash dieback).

A number of possible adaptation options are listed in Defra (2014). These include:

- Improved understanding of the pathogen's biology in order to improve models of pathogen spread and severity and develop sustainable and practical management strategies.
- Research to produce genetic maps of the pathogen and ash trees. The maps will allow identification and breeding of resistant or tolerant ash trees and, where appropriate, improve detection techniques.
- For ash saplings that have been planted in areas with a high risk of infection, to identify trees with resistance or tolerance to the disease. Ash seeds have been collected from a number of locations across the UK to be used in future screening and breeding programmes.
- Standardised techniques for producing infection in the laboratory are being developed. This will allow disease development to be assessed under controlled conditions. This will be essential for identifying genetic markers for host resistance for use in breeding programmes.

Dothistroma (Red band) Needle Blight

As set out in the GB DNB strategy, adaptation measures include:

- Surveillance and monitoring to understand the extent, severity, progression and evolution of the pathogen in pinewoods;
- undertake competent and consistent inspections/sampling procedures for forest tree nurseries
- maintain moratoria on affected pine species;
- respacing, thinning, brashing/pruning, herbicides, fertiliser and fungicide application, where DNB is already established;
- species diversification at the stand and/or landscape level;
- increase awareness raising and encourage early action e.g. removal or treatment of infected trees.

Yellow Rust and Septoria on Winter Wheat

HGCA (2012) identify the following principal adaptation options:

- Select wheat varieties with the best available septoria resistance;
- Use a fungicide programme focusing on septoria in the spring phase of growth;
- Monitor all crops regularly for rust symptoms, focusing on early sown crops in high-risk regions;
- Grow resistant varieties alongside susceptible varieties to limit the spread of disease;

Currently, fungicides are understood to be the most common option adopted.

What are the benefits and potential costs of adaptation?

The final step has been to consider potential benefits and potential costs of adaptation. First, we have considered the potential current options and their costs and benefits.

Phytophthora ramorum (Pr)

We assume that as with current practice, adaptation consists of the identification, felling and replacement of infected larch trees. We estimate the approximate costs for each of these stages. We assume that the identification process by an accredited expert from the Forestry Commission and takes one day per tree at a cost of £500/day, including wage, travel and administration costs (note this will be an over-estimate if there are a large number of trees in a stand that are collectively issued with a SPHN). Depending on the size and accessibility, the costs of felling trees are estimated to range between £80 and £600, with a typical cost of £300[4][5]. Replanting costs are notionally estimated to be £50 per tree, based on an allowance for time spent on the replanting and the purchase price which is understood to be negligible.[6] The costs of £850 per tree are offset by the benefits from the wood from the felled tree plus the value of the wood from the replacement tree. Adopting the values derived above, the felled tree may be sold at an equivalent of £600 whilst the replacement would be assumed to be sold at the same price, £600, in 30 years' time. If the Government social discount rate of 3.5% is adopted, the replacement tree value is £214. Aggregating these costs and benefit over 130 trees and over the next 30 years, total discounted benefits of tree replacement are £2.05 million whilst total discounted costs are £2.14 million. This is approximately a benefit to cost ratio of 1:1. It is clear that there are a large number of assumptions made throughout the derivation of these total adaptation costs and benefits, but this provides an initial indication of the possible extent of current activities.

Chalara fraxinea (ash dieback).

At present, it is not expected that ash die-back management techniques (today) will be effective in preventing the spread of the disease in the near future. The investments in research identified above are, however, expected to impact upon disease spread over time, though it has not been possible to quantify the costs of this research in monetary terms. Effectiveness is likely to vary from site to site. Independent of this research, Government-supported precautionary policy is to destroy ash that is or has a high likelihood of being infected, and to replace with an alternative species. We do not have costs for this for this study.

Dothistroma (Red band) Needle Blight

In the absence of the licensing of appropriate chemical treatment options, Brown and Webber (2008) highlight the effectiveness of thinning as an option. Forestry Commission England (2011) give a series of typical unit costs associated with different aspects of woodland maintenance. Whilst it does not give

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[4] https://www.rawtreecare.co.uk/tree_surgery/cost-remove-tree/

[5] https://www.forestry.gov.uk/pdf/ewgs-on009-standard-costs.pdf/$FILE/ewgs-on009-standard-costs.pdf

[6] http://www.albatrees.co.uk/availability/?category=&keyword=&in_stock=&hedging=&productive=&ppage=all

an explicit cost for thinning in this context, it does give a cost of £600/hectare for thinning of small woodlands where the wood is small or non-marketable. If we assume that thinning would be undertaken once in the 30-year period to 2050 for the hectarage that would otherwise be lost, the discounted cost equates to £22.75 million. If the thinning was all undertaken in the current period, the total cost equates to £36.5 million. It is not known how effective thinning would be; as seen from the costs of inaction above, 100% effectiveness would equate to benefits of £300 million (and thus a high benefit to cost ratio). This option would be cost-efficient as long as the effectiveness of thinning on needle blight reduction was above 12%.

Yellow Rust and Septoria on Winter Wheat

Fones and Gurr (2017) calculate that – adopting an annual cost of applying a fungicide of £85 per hectare – the total cost of adapting to current risk levels equates to £138 million. As identified above, the results from Gouache imply the possibility that climate change may lead to a small reduction of 2-6% in the incidence of *septoria tritici* by the end of this century. On the basis of linearity, we may assume 1 – 3% by 2050. If we assume the measure is completely effective, this generates total, discounted, savings of £83 million - 245 million. On this basis, there is a benefit-cost ratio of 2.5 – a ratio that would remain constant under alternative climate scenarios since both benefits and costs are determined by the volume of wheat production.

Additional adaptation

Across the pathogens considered here – as highlighted above – the economic case for further uptake of existing adaptation measures is strong. However, this additional uptake of measures has an associated resource cost that would need to be financed. Whilst most of the costs may be borne by private land-owners, public support might be needed where there are local concentrations of economic activity that are threatened by the rapid spread of one of these pathogens in an area. Additionally, there may be a role for public co-ordination of information about these pathogens – their spread, likely impacts, and treatment methods – if this information flow would not otherwise occur. More generally, there are a range of other potential pathogens and pests that threaten to expand in England under more benign climatic conditions associated with climate change, where the economic argument for Government intervention appears to lie in the research, monitoring and co-ordination of reactive response toward these threats. This economic argument is exacerbated under climate change since the future nature of the threats cannot be so easily understood on the basis of private actors' past experience. Therefore, as a consequence of the complexities of pathogen and climate science, there is very likely to be a strong economic case for significant investment in this science and communication (awareness). A manifestation of this is the investment by the UK Government in CropMonitor – one of a range of services provided by FERA Science – which gives up-to-date information needed to make well-informed crop-treatment decisions. It is a free, interactive tool that plots the current geographic distribution of pathogens and pests, and outlines how they spread. This could effectively be developed further to provide a more dynamic predictive tool that would allow producers to make better strategic choices with regard to what is produced, and in what manner. Previous analysis by SRUC (2013) identifies that investment in monitoring of Septoria on winter wheat has a benefit-cost ratio of around 10:1 – a not untypical ratio for a range of investments into better climate scenario data.[7]

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[7] For example, see the literature reviewed in: https://publications.europa.eu/en/publication-detail/-/publication/8a4bd368-094f-471c-b26f-966e3a56b644/language-en

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