Assessing long-term resilience of Scottish spruce forests to climate change and novel pests: *Ips typographus* as a case study

Project Final Report

Photograph 1: Larval feeding galleries in Norway spruce bark caused by European spruce bark beetle (Ips typographus). Crown copyright © Forest Research.

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Research Team: Kleczkowski led the project, designed the model, carried out simulations and provided the final write-up. Rodrigues organised the workshop and carried out the literature review on economics. Blake and Steinke provided insight into *Ips typographus* phenology and its impact on Sitka and Norway spruce.

Content

1 Summary

Sitka Spruce, *Picea sitchensis*, is a vital tree species for Scottish forestry in the current climate with few current pest or disease problems. However, it is unclear how Scottish forests might respond to further increases in pressure from climate change and pests. One potential threat is *Ips typographus* which has caused significant mortality of Norway spruce (*Picea abies*) in Europe. However, the co-interaction of a different spruce species (Sitka vs. Norway) and a substantially different climate (maritime Scotland vs. continental Europe) leaves a significant evidence gap.

In this project, we have combined an extensive literature review with data analysis and modelling to evaluate risk factors associated with the potential introduction of *Ips typographus* to Scotland under past, current and different future climate change scenarios. Climate and distribution data have been analysed, and the results have been compared to extensive case studies across Europe with a range of existing models tested and verified. Models were used to examine different aspects of the beetle life cycle (flights, emergence, overwintering potential) and the potential for drought conditions affecting spruce. The modelling was subsequently used to examine the risk of outbreaks in the current and future climate for the period from 1960 to 2100.

We have concluded that according to the best evidence, the potential for *Ips typographus* to be established in Scotland is currently moderate, with the risk of outbreaks currently low, but rising to moderate, then high within the next Sitka rotation of 30-50 years. Throughout the report, we associate low risk with sporadically occurring droughts, flights starting in July and occurring for less than 100 days, as well as one or no generation. Medium risk is associated with sporadic moderate to severe droughts, flights shifting to June and possibly for more than 100 days, as well as occasional years with 2 generations. When the number of generations increases from one to two or three, and combines with frequent prolonged and severe droughts, we associate it with a high risk.

In particular, we found that parts of South Scotland already have temperatures that support *Ips typographus* flights, and with the temperature rise predicted over the next period until the end of century, the conditions are likely to be even more conducive. Under the most optimistic climate change scenario, North Scotland's temperature range appears well below what is seen in Europe in areas conducive to beetle flights, and under the worst-case scenario, it will only reach this range around 2070. Further, we see that the climatic conditions in southern Scotland are already conducive to *Ips typographus* swarms, with the phenology model predicting conditions for one generation in most years. Sustained conditions for the establishment and main and sister generations are predicted for the late 2020s, with two generations possible from 2040-50s, depending on the climate change scenarios. As this coincides with the increased likelihood of drought events, there is an increased likelihood of large-scale outbreaks. In contrast, the model predicts that North Scotland will only become severely affected in the last decades of the 21st century and only under extreme climate change scenarios. Finally, if the beetle becomes established in Scotland but stays in the "endemic" range of conditions, average annual damage is estimated to be at least 2% of the area. The current risk of "epidemic" outbreaks is low, but rising to medium over the next rotation and eventually to high in the second half of the century. This points to a possibility that in the "epidemic" phase, the scale of the impact might be beyond normal sustainable felling

programmes, causing large-scale losses as seen in some parts of Europe since the early 2000s. North Scotland appears to be relatively protected by low summer temperatures and high rainfall, at least for the duration of the next rotation.

We have carried out an extensive literature review on the economic impact of bark beetles. Several approaches have been used to capture the costs, although we did not find examples of a systematic approach directly transferable to Scotland. We broadly divided the impacts as direct – associated primarily with consequences of forest loss and effort for removing damage, pest detection and control – and indirect – productivity and forest health loss, shifts in species, and environmental and social costs. With further information or scenario development, the methods identified here could be used to explore the potential economic costs of *Ips typographus* outbreaks. Several studies indicate significant impacts at the regional and national scale, highlighting the importance of continuing surveillance, detection, and eradication actions as well as increased diversification of forests.

We have also identified several knowledge gaps that the project could not address within its scope and duration, but with the ongoing research, there is potential for future project extension. In particular, more work is needed to understand how windthrow, drought and other extreme events can affect the likelihood of establishment and potential impact of *Ips typographus* on Sitka spruce forests in Scotland.

2 Introduction

Sitka Spruce, *Picea sitchensis*, is currently one of the most widely planted timber forest trees in the UK since its introduction in 1831 from North America [1]. Accounting for about 50% of commercial planting, Sitka is perceived as a "resilient" tree known to grow and survive in nutrient-poor soils and exposed ground, with height growing at the rate of 1.5m/year and a potential lifespan of 600 years [2], even though the typical rotation is much shorter. Scotland's forest sectors contribute 1.1 billion GVA per year to Scotland's economy [3]. In Scotland, Sitka accounts for 515,000 hectares of tree species and has been a key species of afforestation in the UK for much of the past century.

Sitka spruce is favoured for its rapid growth, suitability for Scotland's current climate and soils, and for its contribution to timber production (for construction grade timber C16) and carbon sequestration, and so is a mainstay of the timber processing sector.

Photograph 2: Looking across Blaen-Y-Glyn restock Area. Birch and p73 Sitka spruce. Coed Y Mynydd Fd. Crown copyright © Forest Research.

One of the major challenges of the 21st century is the understanding of the impacts of climate change on ecosystems and, in our case, specifically forest ecosystems. Several studies have been documenting and studying forest mortality across the globe due to warmer temperatures and climatic stress. For example, Allen et al provided a global overview of drought on tree mortality, concluding that regions that are not typically water-limited (like Scotland) are not invulnerable to climate change [4]. These changes can, in turn, cause pathogens and herbivores to weaken tree defences against insects [5]. An increase in the frequency and size of extreme events, causing windthrow and prolonged drought, is also likely to decrease the resilience of spruce forests.

Photograph 3: Larger eight-toothed spruce bark beetle galleries in Norway spruce bark. Location: Alice Holt, Hampshire, England. Crown copyright © Forest Research.

Bark beetles, particularly the European spruce bark beetle (*Ips typographus*), have a significant impact on spruce populations, often leading to tree mortality and altering forest dynamics. The beetles' behaviour, such as mate choice and attack dynamics, is influenced by various factors, including the search for suitable entry points on the bark and the conditions of the trees they infest [6]. Large-scale disturbances, such as windthrows, can exacerbate beetle populations from endemic to epidemic levels, resulting in the death of Norway spruce trees over several years [7].

The ability of the beetle to produce multiple generations in a year is enhanced by warmer climates, potentially leading to more severe forest damage. Extreme weather events, such as windstorms, provide fallen trees which serve as ideal breeding grounds for beetle populations. Drier conditions and lower precipitation at the southern margins of spruce distribution favour beetle infestations, exacerbating the impact on forests [8,9].

Despite forests, both globally and locally in the UK, being under an increased threat from climate change and pests and diseases, Sitka spruce has so far exhibited high levels of resilience. However, there is growing apprehension about the potential consequences of overreliance on a single species. It is unclear how Scottish Sitka spruce forests might respond to further increase in pressure from climate change and existing and new pests and their potential synergistic effects. Although *Ips typographus* has not yet been found to be established in Scotland, concerns are growing over its incursions into South-East England [10]. The key question is whether the resilience will continue to hold and how likely it is that Scotland is going to experience a "perfect storm" of climate change causing large outbreaks.

While progress has recently been made in understanding the dynamics of the tree and the pest, different strands of knowledge (epidemiology, phenology, land use) have yet to be incorporated into a modelling framework [11,12]. Further, the economic analysis of the impact of different scenarios is often missing, and policymakers have rarely been involved from the beginning in the risk modelling [13].

In this project, we have used a combination of literature review, expert solicitation, interactive workshop, climate and epidemiological modelling, and economics to address Sitka spruce risk from potential *Ips typographus* infestation. In particular, we have asked, how does climate change under different scenarios affect the potential for *Ips typographus* to become established in Scotland and what impact that would have on the Sitka spruce forests over the period up to 2100, were the current *I. typographus* monitoring and eradication measures to be unsuccessful at some point in the future?

3 Methods

The aim of the project is to establish the potential for *Ips typographus* establishment and development and to assess the potential damage to Sitka and Norway spruce in Scotland under the current and future climate. In order to achieve this critical assessment, we deployed a combination of literature review, expert workshop, data analysis and model development, Figure 1.

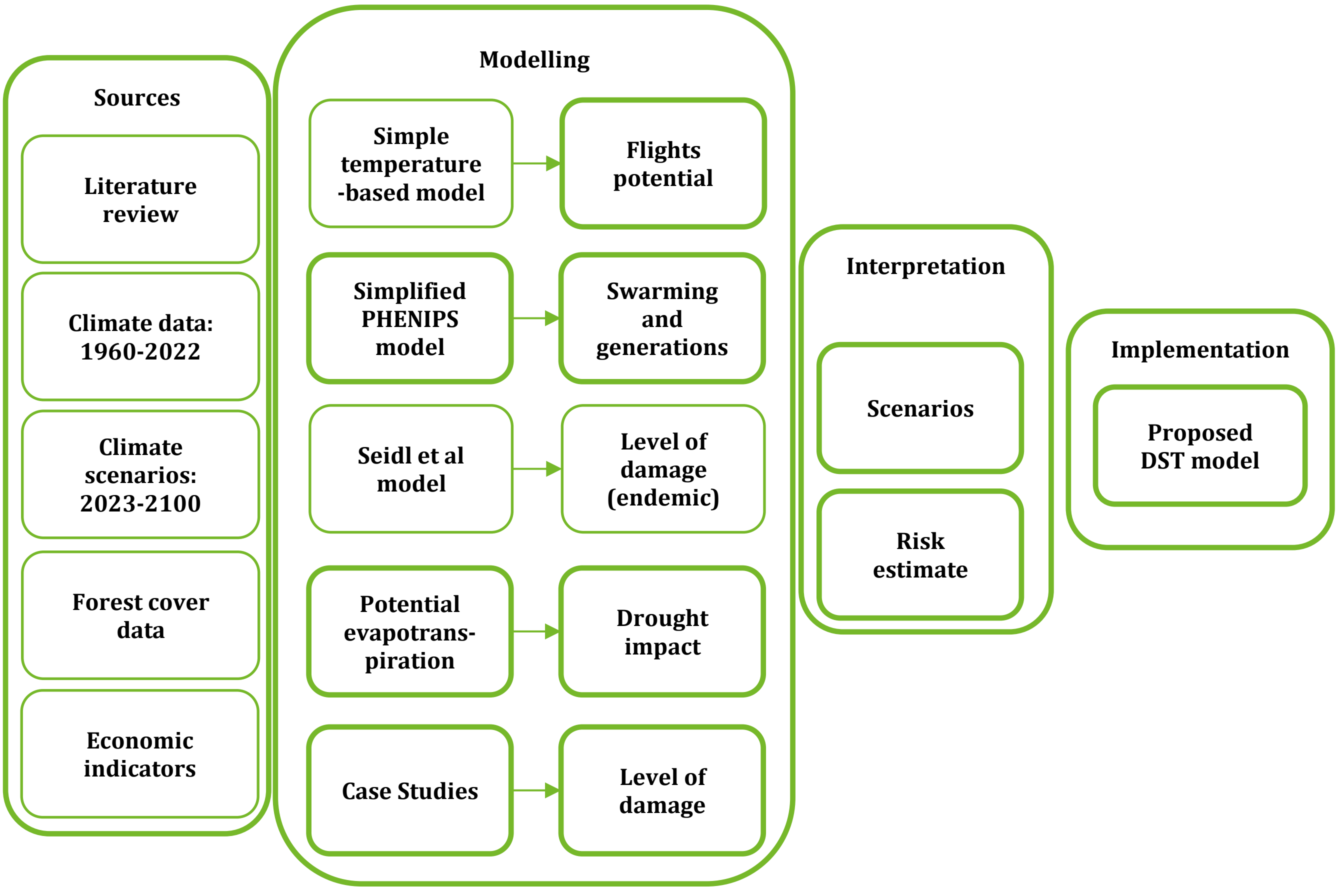

Figure 1 – Schematic representation of the approach taken in the project. Symbols, acronyms and model details are explained in the report below.

3.1 Data sources

The basic unit of analysis is a Met Office region, dividing the UK into 13 regions, with Scotland divided into three: East Scotland, West Scotland and North Scotland. We chose the regional scale as it provides a balance between enough spatial resolution to differentiate climatic and geographical conditions and the amount of data to process.

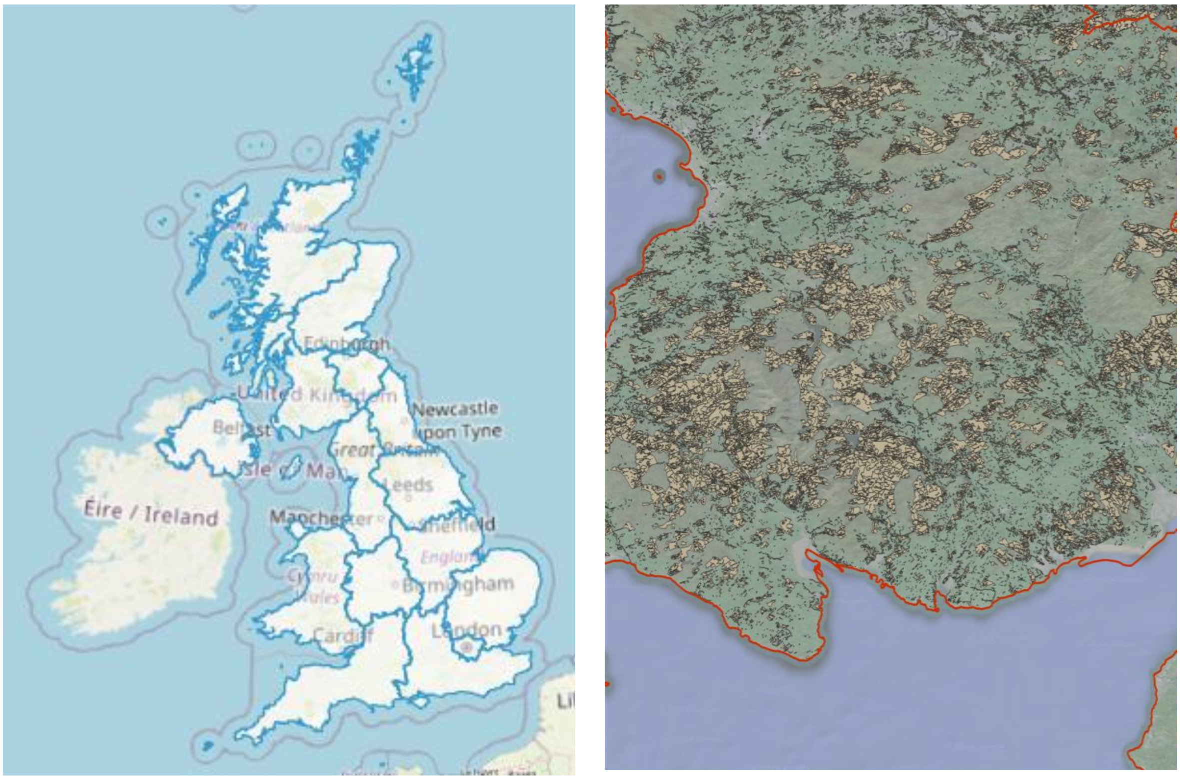

Figure 2 – UK Regions used in the analysis and a sample of the distribution of trees in Scotland (forest/woodland areas classified as "conifers" are shown in yellow).

Forest cover was estimated from the National Forest Inventory Scotland (2021) [14], with further validation using Forest Research National Statistics [15]. We also used Forestry Commission Forest Yield: A handbook on forest growth and yield tables for British forestry [16].

Average volume and age were obtained from [17]. Areas, age and volume were analysed in QGIS 3.10.2 [18].

We used publicly available data to quantify Sitka spruce hectarage, stand age, and volume[1].

[1] The estimates can be improved if more detailed data are available.

Table 1 – Sitka spruce areas and volumes at risk for three Scottish regions based on the National Forest Inventory 2020 [14] and the Forest Research Report on Forestry Statistics 2024 [15].

	All GB	All Scotland	East Scotland	West Scotland	North Scotland
Stocked area [1,000 ha]	668	515	157	186	172
Volume [1,000,000 m^3]	215.8	170.2	51.9	61.4	56.9
Volume per ha (Moreno et al, 2017)		236	238	247	223
Volume per ha (Forest Research)	330				

The data for Great Britain were taken from the Forest Research report; see table 1.8c in [15]. The area and volume in all of Scotland were then calculated using the distribution of Sitka spruce across the nations, see Table 1.10c in [15]. The further division into three Scottish regions was based on calculating the proportion of conifer forests in each area using GIS data from the National Forest Inventory [14].

The typical volume for Sitka spruce is 200-400 m^3/ha depending on the yield class, with the average volume, as reported by Moreno et al, 2017 [17], pointing towards the lower values (but averaged over all trees). 84% of all conifer species has age between 0 and 60 years, with the distribution skewed towards younger trees due to the recent woodland creation programmes [14,15]. 32% of conifer trees are between 0 and 20 years and 26% are between 20 and 40 and 40 and 60, each. This stands in contrast to Norway spruce plantations in Europe, with a typical rotation length of 80 years and more; only 4% of the UK conifers are in that age bracket.

3.2 Climate variables and predictions

In this project, we have used both the existing data (1960-2022) and the climate projections (2023-2100). The predictions were based on the Representative Concentration Pathways (RCPs) which are scenarios used by climate scientists to project future changes in atmospheric greenhouse gas concentrations based on different socio-economic assumptions. These pathways range from the more optimistic RCP 2.6, which assumes significant mitigation efforts and aims to keep global warming well below 2°C, to the worst-case RCP 8.5, which assumes continued high emissions and could result in global warming exceeding 4°C by the end of the century.

At a required temporal and spatial resolution, the Met Office only provides results for RCP 2.6 and 8.5. However, based on current estimates and trajectories, the world is not strictly on a path to either RCP 8.5 or RCP 2.6 [19,20]. The extreme scenario of RCP 8.5 remains a critical risk scenario for evaluating potential outcomes and resilience planning.

Key climatic variables, minimum and maximum daily temperatures and daily rainfall were obtained from the following sources:

- UK: regional data from HadUK-Grid gridded and regional average climate observations for the UK. HadUK-Grid is a collection of gridded climate variables derived from the network of UK land surface observations;
- UK: predictions were based on RCP scenarios 8.5 (worst-case) and 2.6 (best-case) and obtained from the UKCP18 datasets. We have used the 12 members of the Hadley Centre PPE [21], although the results are shown for the model 6;
- Poland: Local datasets (A. Wypych, pers. communication, and [22])
- Other European data [22]: www.ecad.eu

3.3 Expert elicitation

The key to our approach was to closely involve experts and policy-makers. A two-day workshop was organised in Glasgow in May 2023, and presentations and discussions were used to establish the state-of-art of *Ips typographus* knowledge and to construct a baseline for the modelling.

The dialogue with policy-makers continued throughout the project, and guided the selection of approaches. In particular, it was decided that the project should concentrate on *Ips typographus,* given the timeliness and importance in light of the 2023 findings of the beetle in Scotland. The interaction also helped to identify key knowledge gaps, particularly as related to the impact of *Ips typographus* on Sitka rather than Norway spruce and the introduction vector and dispersal. Given the ongoing research at Forest Research aimed at filling in the gaps, it was decided not to proceed with the full implementation of the Decision Support Tool, see section 3.7.

3.4 Data analysis and modelling approaches

The existing *Ips typographus* models focus on (i) the number of generations [23,24], (ii) beetle trapping, for example, in pheromone traps [25], and (iii) the probability of outbreak and its impact [26]. Exceptions include [27,28] using data from Scandinavia, [26] which although primarily designed for Austria, has been tested in the Czech Republic and other locations, and [23].

Seidl et al model has recently been used to estimate the probability of *Ips typographus* outbreak across Europe [11]. In this report, we use a range of modelling approaches to estimate the likelihood of *Ips typographus* establishment in Scotland and its impact on Sitka spruce also drawing on case studies in South East England and in Europe.

We have used four approaches to establish whether and when climatic conditions will allow *Ips typographus* to be established and to cause damage to the spruce forests in Scotland.

Firstly, we use the flight criteria summarised in [29] to establish the *Ips typographus* invasion potential. Secondly, we implemented a simplified version of the PHENIPS model [23] to establish under which conditions breeding can occur and to estimate the number of generations.

Thirdly, following [11,26] we have used a simplified version of the model of [26] to estimate the potential losses. However, the Seidl et al model does not fully incorporate the effect of drought [11] and so an alternative approach is needed.

Finally, relatively less attention is given to the host side of the bark beetle impact on trees, and yet tree mortality depends on both factors [8]. Drought has often been identified as one of the key abiotic factors [30], and we used the Standardized Precipitation Evapotranspiration Index (SPEI) to establish the potential level of stress in trees [31].

3.4.1 Basic flight potential

Wermelinger provided a general overview of phenological and epidemiological conditions for *Ips typographus* establishment and spread [29]. Throughout the project, we used these characteristics to validate our model results. Specifically, we quantified the potential for the beetle establishment by analysing the first day in the year the air temperature reaches the threshold for flight, 16.5C.

Table 2 - Selected data from research on Ips typographus *published between 1990 and 2002, after [29] where the references can be found.*

Feature	Data
Biology	
Minimum temperature for development	6-8.3C
Minimum temperature for oviposition	11.4C
Optimum temperature for development and oviposition	29-30C
Fecundity	Up to 80 eggs/female
Sex ratio (% females)	50% (retrogradation) ≫50% (progradation)
Overwintering mortality	~50%
Optimum breeding density	~500 maternal galleries m^2
Optimum harem size	Three females
Minimum temperature for flight (threshold)	16.5C
Optimum flight temperature	22-26C
Main flight time	Noon, early afternoon

Minimally required number of days with temperatures > flight threshold for successful attack on living trees	3-4 days in a row
Active flight distance	> 500m
Natural enemies	
Most important insect groups	Clerid beetles, dolichopodid flies, pteromalid wasps, braconid wasps
Prey consumption	
Clerid larvae	Approximately 50 scolytid larvae
Clerid adults	Approximately 100 scolytids
Dolichopodid larvae	5-10 scolytid larvae
Mode of host/prey finding	
Parasitoids	Volatiles
Clerids	Bark beetle pheromones
Host susceptibility	
Host defence mechanisms	Stored resin, toxins, deteriorated food quality, wound reaction
Trees at high risk	South, west exposition, sunlit, >70-100 years old, trees with heart rot
Radius of higher risk of attack around infestation	100m
Outbreaks	
Causes of outbreaks/prolongation of outbreaks	Windthrow, drought, high temperatures, snow/ice break
Peak abundance of *I. typographus* in windthrow areas	2nd to 3rd summer after storm
Management	
Optimum period for salvage harvesting of windthrown logs	Between infestation and emergence of first generation
Estimated catch rates of pheromone traps	3-10% of population

Optimum exposition of pheromone traps	South
Catch efficiency of baited trap trees relative to pheromone traps	Up to 30x
Size of phytosanitary buffer zone around reserves	500m (100-1500m)
Bark beetle mortality with machined debarking	93%

3.4.2 Phenology: PHENIPS model

Baier et al (2007) constructed a model, PHENIPS, that incorporates factors such as air and bark temperature and light availability to predict in detail the breeding pattern for *Ips typographus* [23]. The model is based on maximum daily temperature and was parameterised based on the beetle outbreaks in Austria in 1990-96 and 2000-2002. The model was recently used to assess the impact of the UK current and future climate on *Ips typographus* phenology [32].

Here, we further simplify the PHENIPS model to assess:

- The day of the year in which the first early spring swarm can occur (air growing degree days (GDD) with the baseline of 16.5C exceeding 60.5).
- The day of the year in which the first main swarm can occur (air GDD with the baseline of 16.5C exceeding 140).
- The day of the year when the first sister generation swarms (bark GDD based on thermal temperature – nonlinear relationship to the air temperature with lower cut off of 8.3C - exceeding 278).
- The day of the year when the first filial generation swarms (bark GDD based on thermal temperature – nonlinear relationship to the air temperature with lower cut off of 8.3C - exceeding 557).
- The day length cut-off occurs on 10th August with the day length in Scotland (Glasgow) shorter than 14.5 hours.
- Development for overwintering is conditioned on the bark GDD based on thermal temperature exceeding 557 plus 334. This is ignored if it is later than 31st October.

The main structure of the model is shown in Figure 3.

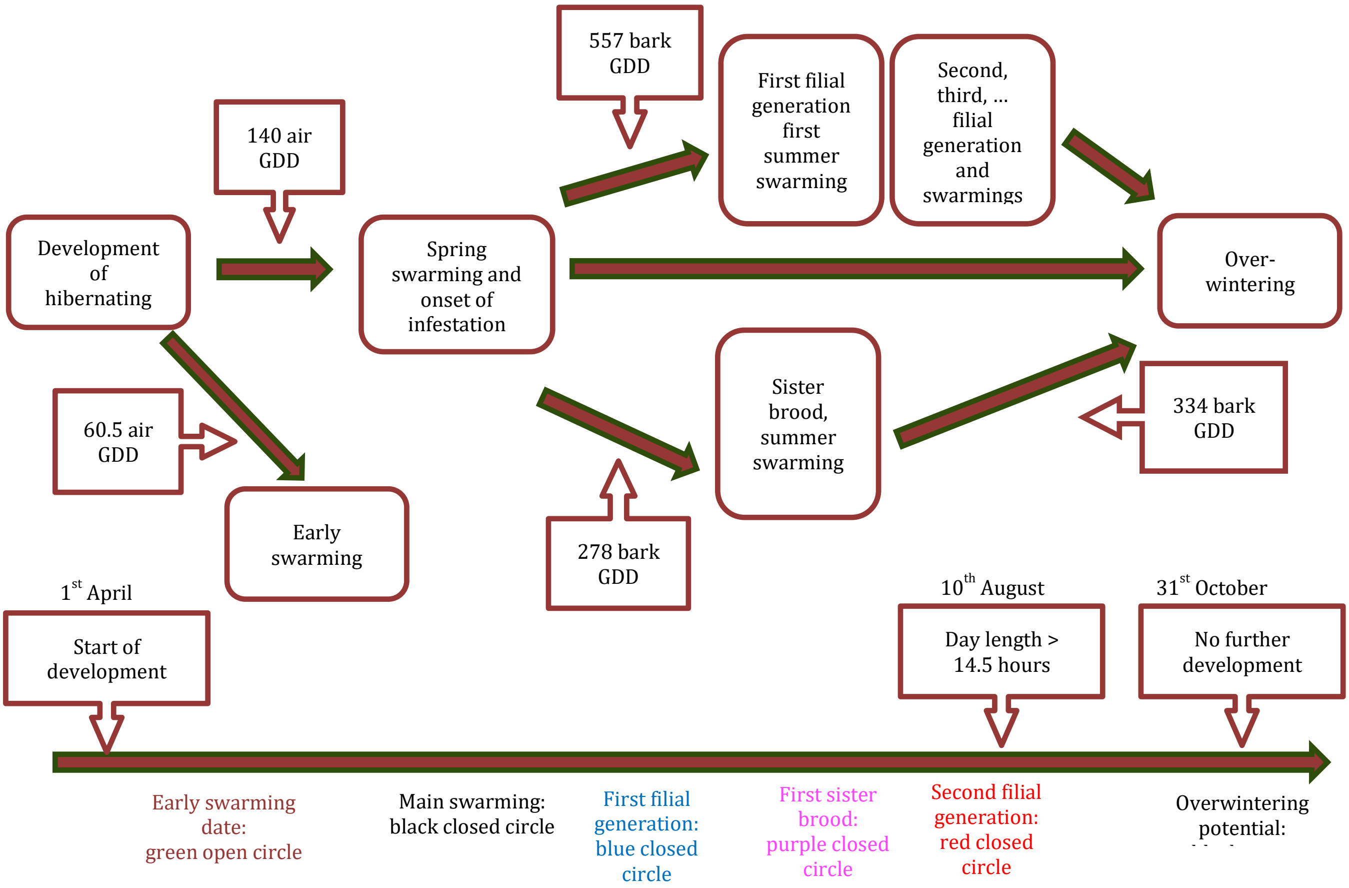

Figure 3 – The simplified PHENIPS model structure as used in this project. Rounded boxes correspond to development stages, whereas boxes with arrows specify the environmental conditions determining the timing of stages. The colour and symbol codes at the bottom refer to those used in Figures 10-14.

The number of generations is calculated based on the swarming and survival.

3.4.3 Impact on trees

Seidl et al model was constructed to provide input into PICUS and EFISCEN, spatially-extended and detailed models of forest dynamics [26].

Hlásny et al (2021) used Seidl's model to evaluate the probability of *bark beetle damage, pBB*, across Europe [11], and explored the impact of increased annual temperatures. While PHENIPS model focuses on the bark beetle phenology, the Seidl et al model incorporates the age of trees, stand density and composition, as well as soil moisture indicators, and so can be used to predict damage to trees.

3.4.3.1 Model structure

The probability of *Ips typographus*-caused damage (averaged over a 5 year period) is given by:

$$pBB = \frac{e^{z_{ijklm}}}{1 + e^{z_{ijklm}}}$$

$$z_{ijklm} = \mu + a_i + b_j + c_k + d_l + e_m + (a_i \cdot b_j) + (a_i \cdot c_k) + (a_i \cdot d_l) + (a_i \cdot e_m) + (b_j \cdot c_k) + (b_j \cdot d_l) + (b_j \cdot e_m) + \varepsilon_{ijklm}$$

where

pBB probability of bark beetle damage

z_{ijklm} linear combination of predictor variables

μ intercept

a_i logarithm of mean annual temperature (2-15C)

b_j logarithm of mean/total annual precipitation (500-2000mm)

c_k stand age (40-120 years)

d_l stocking density (0.6-1.0)

e_m host tree share (10, 50 or 100%)

ε_{ijklm} error term.

Similarly, the annually damaged relative stem number is given by:

$$iBB = \frac{1}{1 + \exp(3.9725 - 2.9673\ SHI)}$$

$$SHI = e_m(\mu + a_i + b_j + (a_i \cdot b_j))$$

where

μ intercept

a_i mean annual temperature (2-15C)

b_j $(\text{mean/total precipitation})^{-2}$.

(note the values of parameters differ for *pBB* and *iBB* despite the same notation).

We used parameters from [11,24,26], and annual values for both past data and future predictions. Throughout simulations, we assumed high stocking density (1.0), 100% host share and the age of 60 years.

As pointed out by [11], the Seidl et al model does not incorporate effects of prolonged or severe droughts. Its application is therefore limited to the "endemic" phase of the outbreak, as discussed below.

3.4.4 Drought

It has long been recognised that large outbreaks of *Ips typographus* (and other similar pests) are associated with extreme events like windthrow [29]. There is also evidence that such extreme events are likely to be more frequent and stronger in the future due to climate change [33]. This, in turn, will affect storm damage and, consequently, pest outbreaks [34].

More recently, large-scale *Ips typographus* outbreaks appear to be linked to drought [11,35,36], the trend often interpreted as a switch from "endemic" to "epidemic" state. A low rainfall in a given year can cause weakening or even death of trees in the current or, more likely, subsequent years [37], particularly those with relatively shallow root system [38].

To assess the potential direct drought impact on trees, we used the Standardized Precipitation Evapotranspiration Index, SPEI [31]. An R package, SPEI, combined the maximum monthly temperature, total monthly rainfall and the location latitude (to estimate the solar radiation). First, the Thornthwaite method is used to estimate the Potential Evapo-Transpiration, PET [39]. PET is subsequently compared to the actual rainfall data to calculate the water balance, providing input into the SPEI calculation [31].

SPEI is a multiscale index and so the approach needs to be focused on the appropriate scale and variables [40–42].

1. Short-Term SPEI (1-3 months): This scale is particularly useful for analysing immediate responses to water stress, which can be crucial for understanding impacts on young trees or seedlings with shallow root systems. Short-term SPEI is also relevant for assessing risks related to forest fires and immediate vegetative responses.
2. Medium-Term SPEI (3-12 months): Medium-term scales capture seasonal variations and cumulative effects over a growing season. This makes them suitable for studies focused on forest health, growth, and productivity. For example, research has shown that this scale aligns well with the annual cycles and health assessments of deciduous forests and coniferous forests with relatively deeper root systems.
3. Long-Term SPEI (12 months and beyond): Long-term scales are essential for analysing prolonged drought effects and multi-year climatic variations, which influence long-term resilience, species composition, tree mortality, and forest structure. Studies indicate that these scales are particularly important for understanding the broader ecological impacts and adaptation strategies of forests.

We have used two drought-related indices for estimating the increased risk of *Ips typographus*-related damage. Following [37] and [41] we used the September to June SPEI value in both the current and the previous year, as an indicator for the tree mortality. [41] has identified the SPEI threshold of -1.63, but to simplify the analysis we have used a widely-accepted value of -1.5 as an indicator of severe drought [31], and used 12 months rather than 11 months (SPEI12).

Additionally, we have used the number of months in a year for which SPEI12 is below -1.5. Although this index uses a calendar year rather than a growing season, it is a general indication of the level of water stress.

3.5 Interpretation and implementation

The range of indices, as discussed above, has been combined to assess the risk of establishment of *Ips typographus* and the resulting damage to spruce forests across Scotland. We broadly follow [36,37] by combining PHENIPS and forest water balance models and particularly concentrate on periods when two or more *Ips typographus* generations are likely to occur in a year characterised by severe drought in the last 12 months.

For example, Faccoli (2009) found that "…damage caused by I. typographus was inversely correlated with March-July precipitation from the previous year but not correlated with temperature. Increases in spring temperature did not affect the development timing of the first generation, but only changed its onset. Earlier swarming of both overwintering beetles and first-generation offspring (approximately 20 days sooner over 10 years), and the early start of the second generation permitted more complete development of the second brood." [37]

We use the following indices:

- Beetle:
  - Number of days in a calendar year for which flights are possible. The more such days, the higher the risk of establishment, dispersal and development of generations.
  - First day in the year when flights are possible [29]. The earlier the beetles can fly, the more time there is for future development.
  - First day in the year when early or main spring swarming occurs [23]. As in [37], the earlier these events occur, the more complete the development of the second and subsequent generations.
  - Timing of the first and second filial and the first sister generations.
  - An indicator of whether the original generation reaches the developmental stage, allowing it to overwinter [23].
  - The number of generations (we exclude the sister generations).
- Trees:
  - The value of SPEI12 in June, with the readings below -1.5, signifies severe drought.
  - The number of months in a calendar year with SPEI12 below -1.5. We also indicate when flooding and water-logging are likely to occur by calculating the number of months in a calendar year with SPEI12 above 1.5.

3.6 Endemic and epidemic phases

Following [11] we also distinguish between the "endemic" phase characterised by the constant presence of *Ips typographus*, but a relatively limited and localised damage, mainly caused by windfall. The beetle mostly affects trees that are damaged by wind and other pests and diseases. However, in areas with a large availability of windthrow and with appropriate conditions, healthy trees can also be attacked.

The “epidemic” phase, in contrast, is characterised by large and wide-spread outbreak, such as seen in Czech Republic [43] and elsewhere across Europe (particularly 1990-95 and after 2002).

3.7 Case studies

In addition to the extensive literature review on modelling of and evidence from *Ips typographus* outbreaks outside Scotland, we used data from South East England and six European locations, to illustrate the range of *Ips typographus* response to climatic drivers.

South East England was chosen because of the location of the recent findings of *Ips typographus* and hence, the availability of evidence of the climatic suitability in the specific context of the UK [25].

Figure 4 shows a map of the locations for the European case studies. A full exposition of the results for each location is outside the scope of this report, but we will use the results to compare with the locations in Scotland. Although some of them are not directly linked to outbreaks of *Ips typographus*, there is evidence of its presence in all locations considered here. Location in France was chosen because it is most likely the source of *Ips typographus* current incursions into South East England. Denmark and Sweden were chosen as close climatic analogues for Scotland, with evidence of *Ips typographus* presence and outbreaks in both countries. The location in Austria represents the area for which both PHENIPS and the Seidl et al model were developed. Finally, the two locations in Poland have been studied by Kleczkowski et al (private communication), with outbreaks related to both wind damage and droughts.

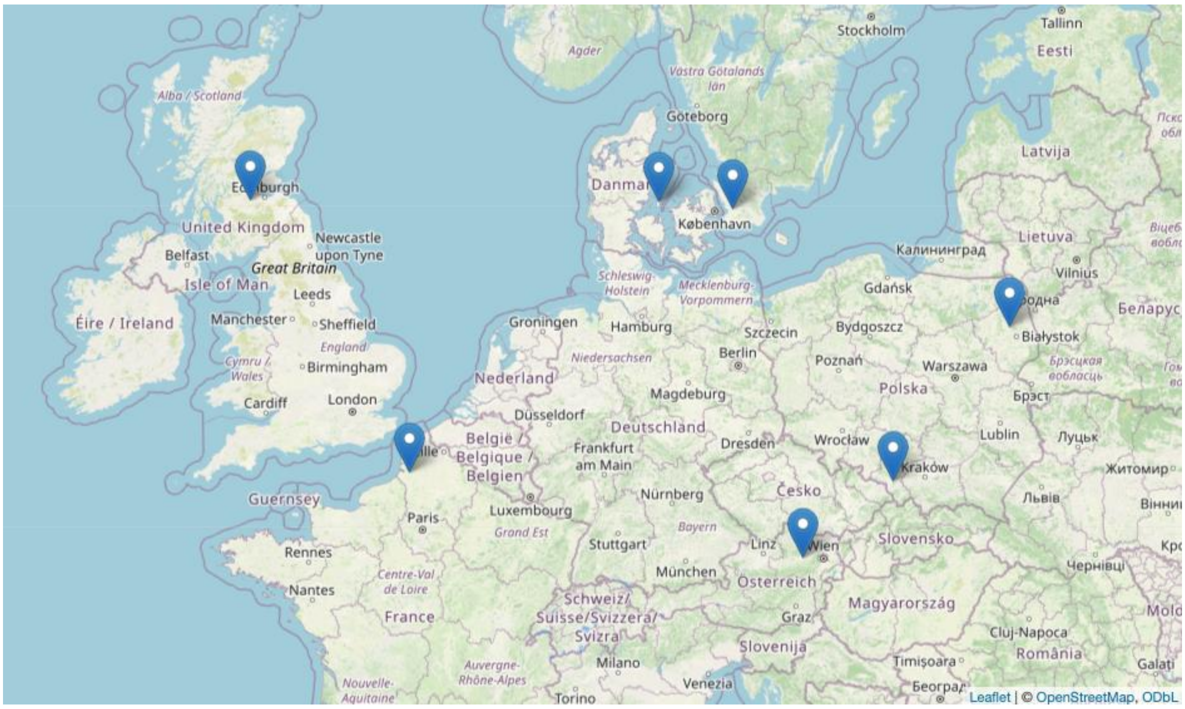

Figure 4 – A map showing the locations for six European case studies.

3.8 Decision Support Tool

Kleczkowski et al [44] have developed a simplified model for assessing the potential for *Ips typographus* to spread in the UK, and implemented it in an online Decision Support Tool. The key assumptions of this model and the current approach are briefly compared in Table 3.

One of the objectives of the project was to modify the Decision Support Tool. As shown in Table 3, the current project addressed several oversimplifications of the 2020 DST model. However, it also identified further knowledge gaps which could not be addressed within the time frame or resources available. Thus, a full implementation of the DST is not plausible at this stage as any quantitative prediction would be characterised by too much uncertainty.

Table 3 – Comparison of key assumptions of the 2020 DST model and the current approach.

Processes and parameters	2020 DST	Current approach
Area under consideration	UK-wide	Division of the UK into 13 regions, with 3 in Scotland. Significant regional variation observed.
Ips typographus phenology and climate dependence	No spread below 16°C and above 30°C, with significant increase above 20°C	Phenology significantly improved by PHENIPS
Susceptibility	40-60% based on age	Age included in Seidl et al model, but no quantitative data for Sitka spruce (vs. Norway spruce)
Long-term climate dependence	Initially only 50% area available, increasing to 100% to represent climate change effect	Detailed climatic model with both beetle phenology and tree phenology affected
Incursions	Fixed intensity per year	Noted lack of evidence for vector and mode of arrival, as well as risk of a successful incursion
Dispersal	6 months doubling time (probably unrealistic given the evidence of wind transport)	Noted lack of data on dispersal potential to improve the estimate
Impact on trees and timber	All affected areas contribute to annual loss	Seidl et al model used for endemic phase; risk of potential large-scale outbreaks estimated. Although there is evidence of *Ips typographus* affecting Sitka spruce in a similar way to Norway spruce, it is unclear how it would perform on a tree and landscape scale. As this is area of active research at FR, we felt it would be too early to include it in the model.

3.9 Other models

In a study of 2011-14 outbreak in North-West Russia, June temperature and previous years' average yearly temperature were found to be predictors of the outbreak size and impact on trees, respectively [45].

March-July precipitation *in the previous year* was found to be inversely correlated with damage caused by *Ips typographus* [37]. Increases in spring temperature were found not to affect the development timing of the first generation, but only changed its onset. They also found that the swarming of both overwintering beetles and first-generation offspring occurred ~20 d sooner over 10 years. The early start of the second generation permitted more complete development of the second brood. These results broadly agree with PHENIPS analysis shown above.

Jönsson et al (2007, 2011) developed an alternative model to PHENIPS to predict the number of generations, and used it to predict the impact of climate change [27,28]. The model is based on thermal sums above 5C and a combination of Growing Degree Days and daily maximum temperature. Emergence from winter hibernation occurs at 120 GDD, and swarming when daily maximum temperature exceeds a threshold (16, 18 and 20C). Egg development starts 7 days after swarming, and it takes 625/750 GDD to complete development. Second-generation swarming starts on the first day with a maximum temperature above the threshold and follows the same rules.

Other models predicting tree mortality include [7,45,46].

4 Results

4.1 Climate variables

Although the full analysis of the past and future climate data exceeds the scope of this report, we point out some key features in figure 5.

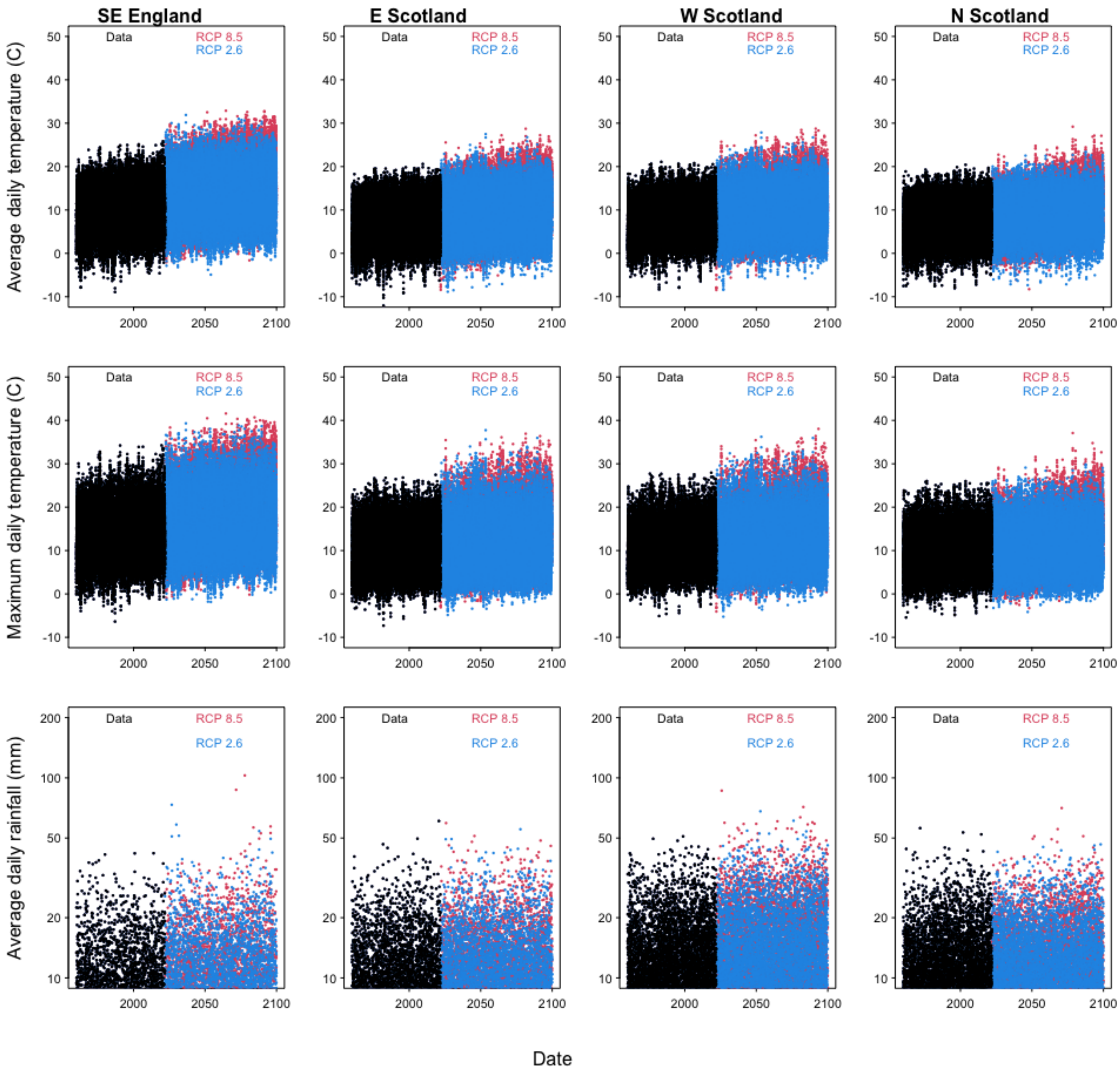

Figure 5 – Daily data for the UK regions considered in the report. Black points: data; red points: predictions based on RCP 8.5; blue points: predictions based on RCP 2.6. Note that only part of the rainfall range is shown and the plot uses a logarithmic scale.

There is a clear difference in the overall temperature and rainfall levels along the South-North gradient, with South-East England (SE England) showing the highest average and maximum temperatures and the lowest rainfall, and North Scotland (N Scotland) being coldest, and West Scotland (W Scotland) having the largest rainfall.

The temperatures have been increasing since the start of the records in 1961 and will continue to increase under both RCP scenarios, with the fastest growth in SE England and slowest in

N Scotland. The rainfall is also expected to grow across the UK, but there is no significant increase predicted for the wind speed, figure 6, although extreme events are predicted to be more frequent and more intense (not shown).

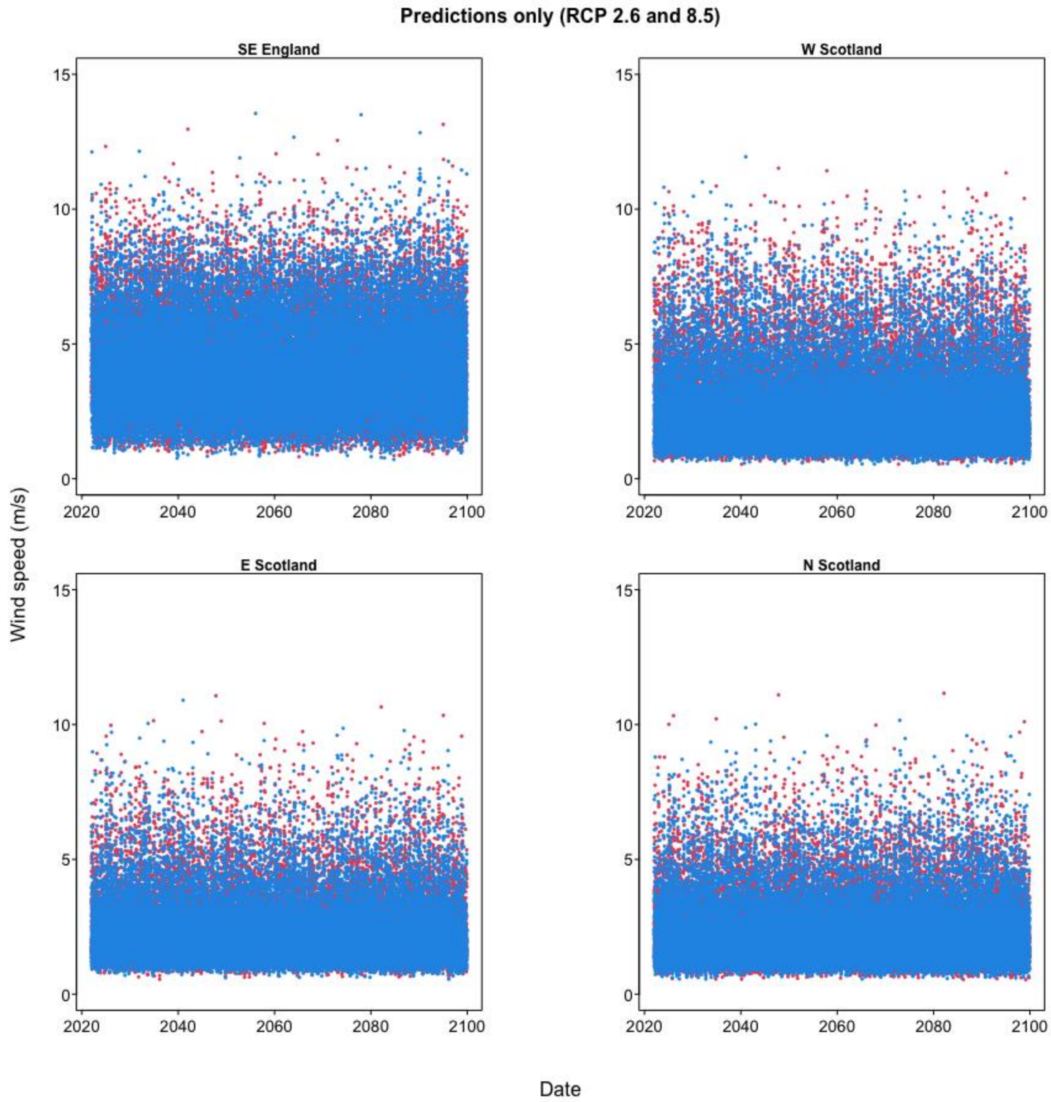

Figure 6 – Daily wind speed at 10m; predictions only 2023-2100, as no comparable data are available for 1960-2022.

As discussed in the Methods section, we use the Standard Precipitation-Evaporation Index (SPEI) to assess the drought potential. Figure 7 shows the value of SPEI averaged over the period of 12 months for each month in the year between 1960 and 2100 and in each location. In the period 2016-2020 the periods with excess floods and droughts alternate, but overall there are more wet periods (SPEI12>0) than dry; the late 1970s drought period is clearly visible in the data from Scotland. This picture changes with the increase in temperature and all regions are likely to move to much drier conditions, with sustained dry conditions in SE England and E Scotland, particularly under the "worst case" scenario RCP 8.5. Spruce forests are likely to be affected by the drought conditions, especially if they span multiple years.

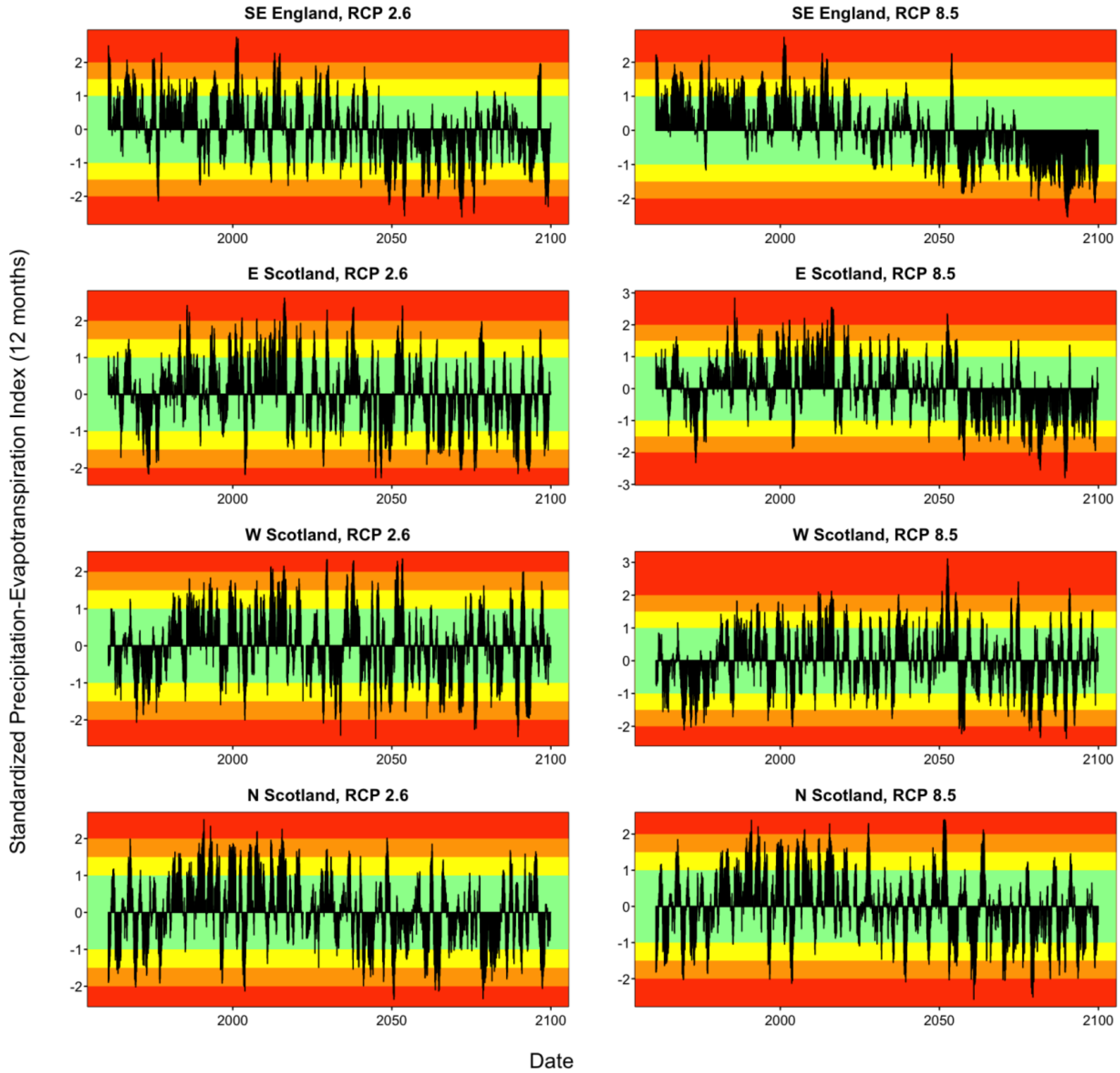

Figure 7 – Monthly Standardised Precipitation-Evapotranspiration Index, SPEI12 for different UK locations and climate change scenarios. Green bands correspond to "normal" conditions, yellow to "moderately" wet or dry, orange to "severely" wet or dry, and red to "extremely" wet or dry. Positive y-axis: wetter; negative y-axis: drier.

4.2 Establishment and flights

As mentioned above, there is evidence that *Ips typographus* is only able to fly if the air temperature exceeds 16.5C. In this section, we analyse the number of days in a calendar year for which the maximum temperature exceeds 16.5C as well as the first day in the calendar year when the maximum temperature exceeds 16.5C. We also compare the records with the range seen in the case studies.

The conditions in SE England are well within the range for the case studies, Figure 8, each of which has documented evidence of *Ips typographus* infestation. Both E Scotland and W Scotland are currently within the lower range of what is observed in the case studies, while temperatures in N Scotland are likely to remain less conducive for the beetle flights, except later in the century and under the worst-case scenario.

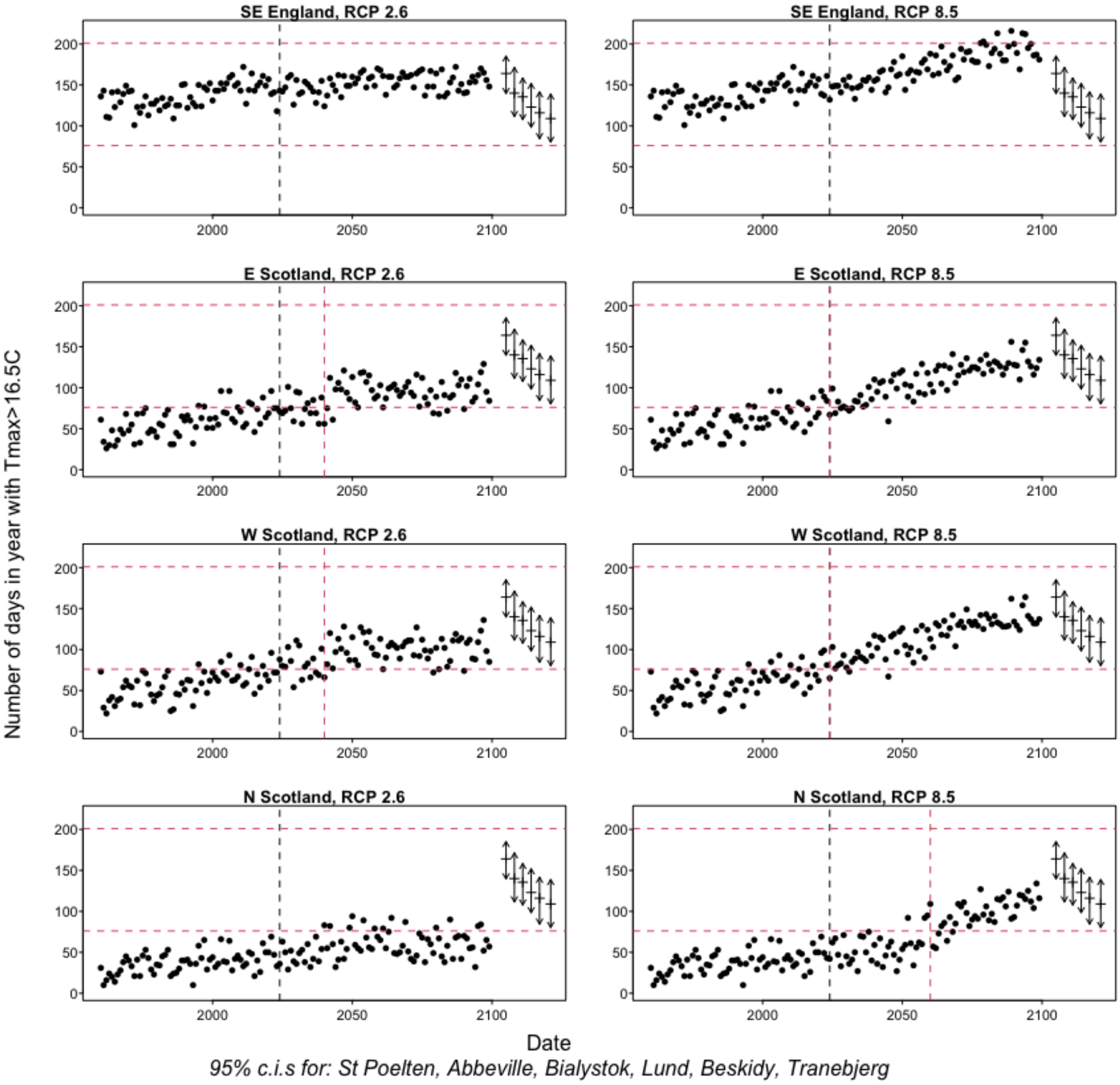

Figure 8 – The number of days for which the maximum daily temperature exceeds 16.5C (flight threshold). The left column shows the results for RCP 2.6 (best case) and the right column for RCP 8.5 (worst case). Arrows on the right show the median and the 95% c.i.s for the 1960-2023 data, whereas the red horizontal dashed lines show the maximum and minimum values for the 6 case studies. Black vertical dashed line marks 2024, and the red line is a date after which the predictions are mostly within the range observed in the case studies.

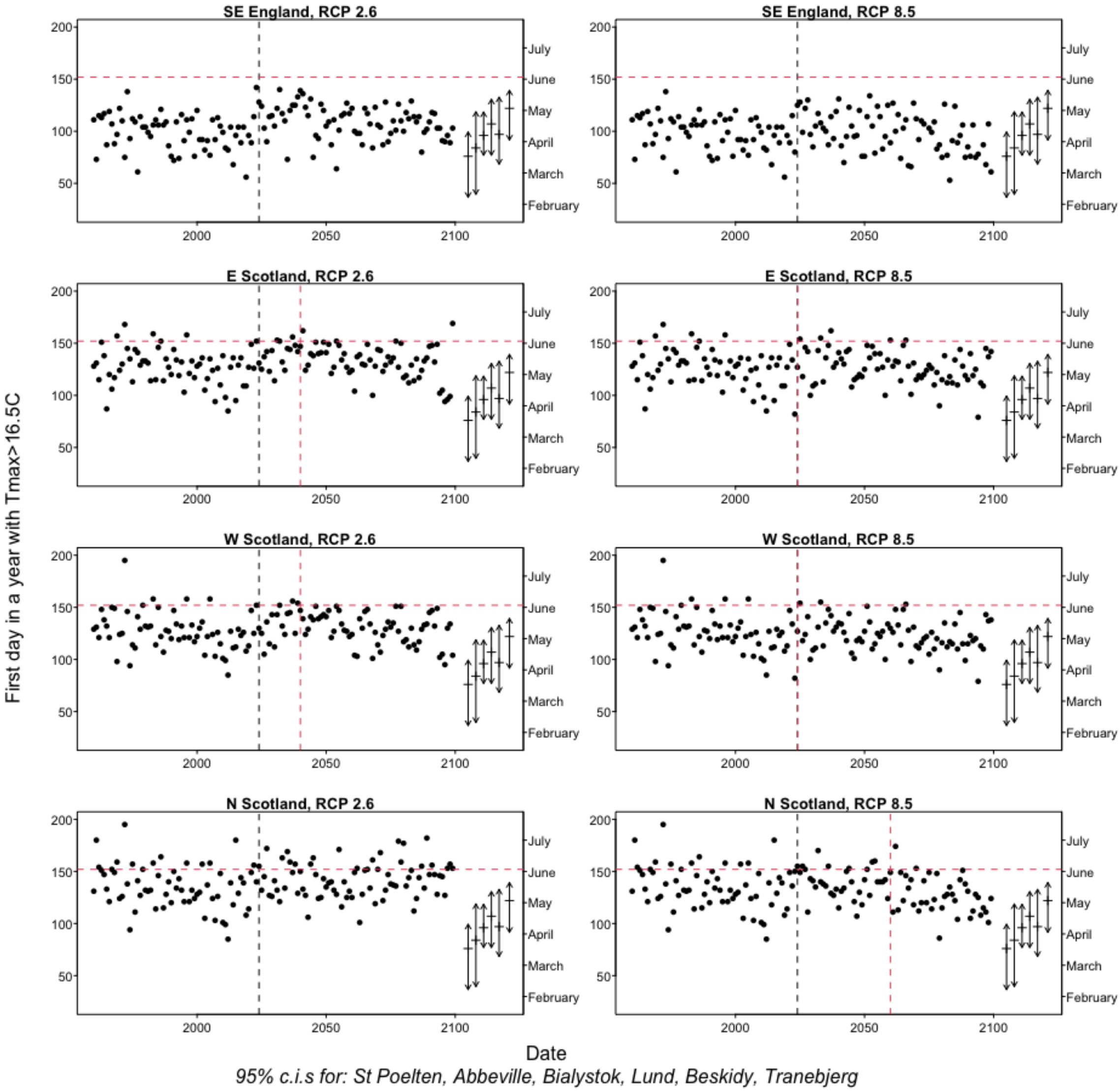

Figure 9 – The first day in a year for which the maximum daily temperature exceeds 16.5C (flight threshold). Details as in Figure 8.

4.2.1.1 Interpretation of flight modelling

This indicator captures the length of time that the beetles can fly each year. South parts of Scotland already have temperatures that support *Ips typographus* flights (up to 100 days per year above the threshold of 16.5C), and with the temperature rise predicted over the next period, the conditions are likely to be even more conducive (rising to close to 150 days per year by 2100). Under the most optimistic climate change scenario, North Scotland's temperature range (corresponding to ca. 50 days per year above 16.5C) appears well below what is seen in Europe in areas conducive to flights, and under the worst-case scenario, it will only reach this range around 2070.

4.2.1.2 Caveats and extensions

The ability to fly does not necessarily mean the beetles will survive or cause damage to trees. The analysis is based on the average temperature in the whole region; parts of the region will experience higher temperatures earlier in the year and hence will support the flight longer during the year, enabling the beetles to explore larger areas.

4.3 Beetle and host tree phenology

In this section, we combine the phenology results for the beetle and for the effect of drought on trees. A typical combined output from the model is shown in Figure 10, combining all the results into a timeline from 1960 to 2022 (data) and 2023 to 2100 (prediction). Note that due to the details of the computation, the SPEI results for the 1960-2022 (data) period will slightly differ in graphs where different scenarios for 2023-2100 (prediction) period are used. The results for South East England are used here to illustrate the general behaviour, before considering all areas.

The figure is composed of three areas which illustrate different aspects of the phenology of *Ips typographus* and host trees. The bottom panel captures the risk associated with increased drought frequency and severity. It shows either the number of months in a calendar year that are characterised by extreme weather, or the SPEI12 value for the month of June. The colour code represents either severely wet weather (SPEI>1.5; blue) or moderately (SPEI< -1; yellow), severely (SPEI< -1.5; orange) and extremely dry weather (SPEI< -2; red). The particularly dry periods are associated with an increased risk of damage to spruce trees. The example shown here (SE England with the "worst case" scenario RCP 8.5) illustrates the transition towards more frequent, prolonged and severe droughts as the temperatures increase causing higher levels of evapotranspiration.

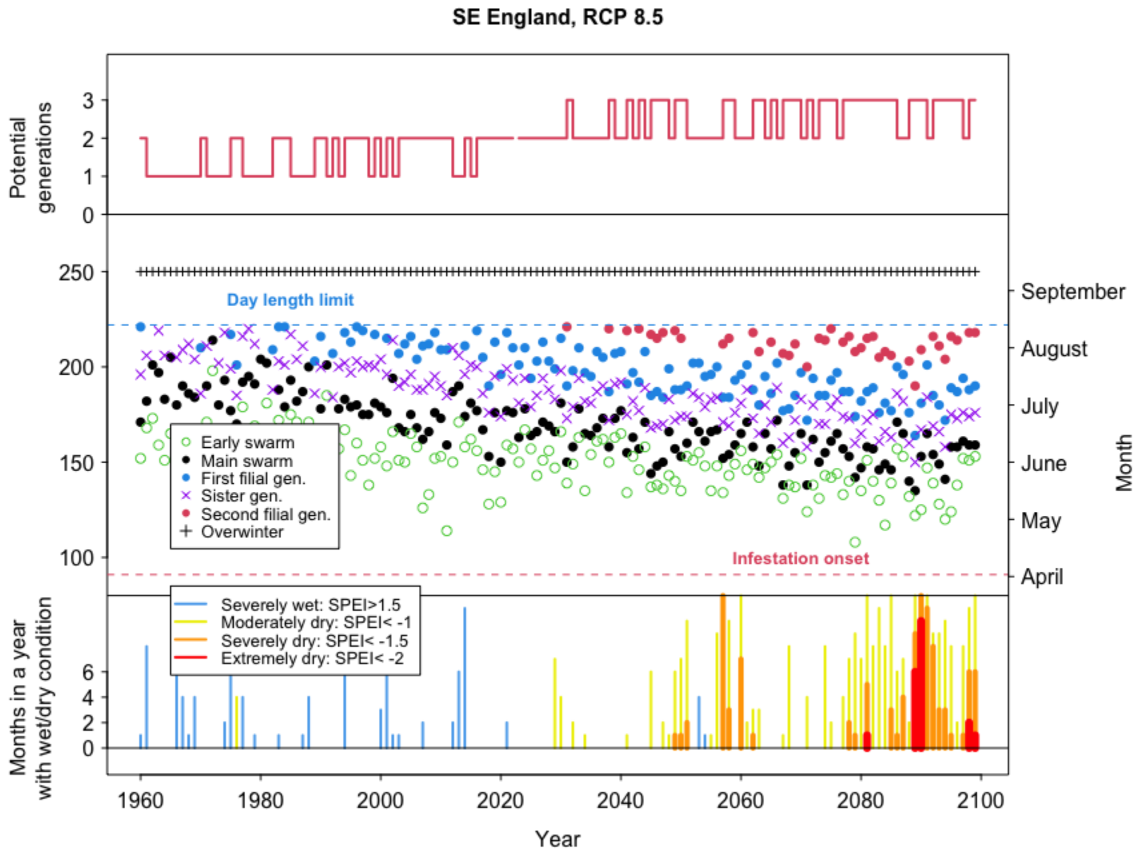

Figure 10 – A combined output of the models, shown here for South East England and the RCP 8.5 scenario. Bottom graph: the number of months in a calendar year for which SPEI12 is in a certain range, indicating severe or extreme drought or flood. The middle graph shows the first day of the year with the early and main swarm, first, second filial generation, first sister generation and potential for overwintering. The top graph shows the potential number of generations. Symbols colour and code are the same as in Figure 3.

The middle panel shows the timings of the key events in *Ips typographus* phenology: (i) the early swarm (green circles), (ii) the main swarm (first generation; black dots); (iii) first sister brood (purple crosses); (iv) first filial generation swarming (second generation; blue dots); (v) second filial generation swarming (third generation; red dots); and (vi) indicator whether the first generation will be developed by the cut-off point of 31st October (crosses). Two horizontal lines are also shown, marking the infestation onset on 1st April, and the day length limit.

The example shown here demonstrates the general shift towards earlier times at which generations are initiated; the transition having already started in 1980s. During 1960-70s, the early and main swarms occurred in June and July but have now moved to late May and June. Under the extreme climate change scenario, they are predicted to be in early May and early June, respectively. The PHENIPS model predicts that this shift allows more generations to develop, with the potential for 2 generations since 1990s and 3 generations starting in 2030s. It should be stressed that these are results based on the model not observations.

The top panel summarises these results by plotting the potential number of generations in a given year. While there is a lot of variation and uncertainty associated with *Ips typographus* development, the larger the number of generations, the more severe the impact is on trees.

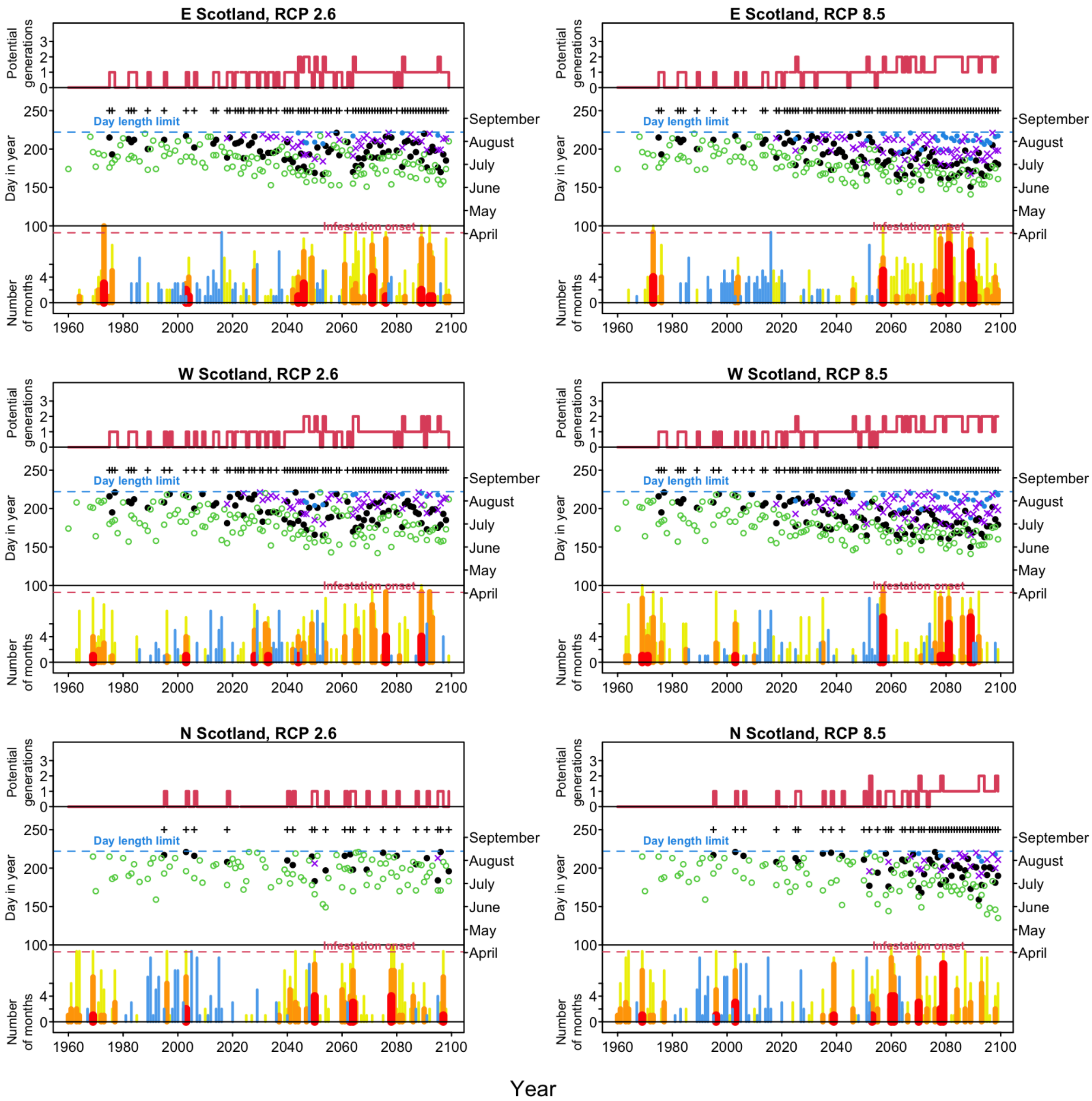

Figure 11 – A combined output of the phenology and drought models for Scotland, under RCP 2.6 and 8.5. In each panel, the bottom graph: the number of months in a calendar year for which SPEI12 is in a certain range, indicating severe or extreme drought or flood. The middle graph shows the first day of the year with the early and main swarm, first, second filial generation, first sister generation and potential for overwintering. The top graph shows the potential number of generations.

There are clear differences both in the location (W and E Scotland, N Scotland) and in the different climate change scenarios ("best case" RCP 2.6 and "worst case" RCP 8.5).

The current drought stress is surprisingly similar in all locations, reflecting relatively high rainfall and moderate temperatures. Noteworthy is the late 1970s drought seen in all locations.

Beyond the current (2022/23) time, there is again evidence for increase in frequency, duration and severity of droughts across the country, with some regional variation. East Scotland appears to be more affected than West, and North is only likely to be affected sporadically. There is less difference between RCP 2.6 and 8.5 than expected, with the increase in temperature and hence evaporation is balanced by a (small) increase in the rainfall.

For the timing of generations, the pattern seen in SE England, figure 9, is also repeated in Scotland, although lower summer temperatures delay the transition to an increased number of generations, according to the PHENIPS model. In East and West Scotland regions (with the north boundary broadly marked by Cairngorms) the PHENIPS model currently (2022/23) predicts early swarm in late June and the main swarm in July or August, with just enough time for the beetle development to prepare it for overwintering, and potential for sister brood development. The model predicts that the conditions for the second generation will start around 2040. Under the "worst case" scenario, RCP 8.5, the shift towards earlier swarming events will continue, with longer periods when two generations can be climatically sustained according to the model.

Predictions for North Scotland differ due to lower summer temperatures, whereby the model predicts only occasional years when the first generation can be raised from the invading stock. Under the "worst case" scenario, the establishment becomes possible only in the middle of the century, and sister and eventually filial generations start appearing from 2080s. It should be noted that the model predictions are here based on the whole region, so there is likely to be significant local variation.

4.3.1.1 Interpretation of phenological modelling

The climatic conditions in southern Scotland are already conducive to *Ips typographus* swarms, with the phenology model predicting conditions for one generation in most years. Sustained conditions for the establishment and main and sister generations are predicted for the late 2020s, with two generations possible from 2040-50s, depending on the climate change scenarios. As this coincides with the increased likelihood of drought events, there is an increased likelihood of large-scale outbreaks. In contrast, the model predicts that North Scotland will only become severely affected in the last decades of the 21st century and only under extreme climate change scenarios.

4.3.1.2 Caveats and extensions

The analysis is based on the average temperature in the whole region; parts of the region will experience higher temperatures earlier in the year and hence will support the flight longer. Swarming is strongly dependent on site conditions - so it may occur earlier than indicated above in sheltered and sun-exposed locations - and may begin as early as April in central and southern Europe or as late as June in northern Europe; cf. [47,48].

Although PHENIPS concentrates on beetle physiology, it has been developed for and parameterised based on its outbreaks in Norway spruce, based on data collected in Austria. It remains to be tested how transferable its results are for Sitka spruce with faster development, different bark width and resin pressure.

The tree phenology approach used here is based on a study [41] based on data for *Pinus edulis* and *Pinus ponderosa* in the Southwestern United States, with additional evidence from [4,37] and other sources, and may not be applicable to the Sitka spruce growing in a maritime (warm winters, cold summers) climate of Scotland.

4.4 Comparison with the case studies

How do the scenarios compare to the current data for other locations in Europe where *Ips typographus* is already present and causing significant damage? In this, highly preliminary, study we used the same approach as for the UK to analyse climatic conditions in six case studies.

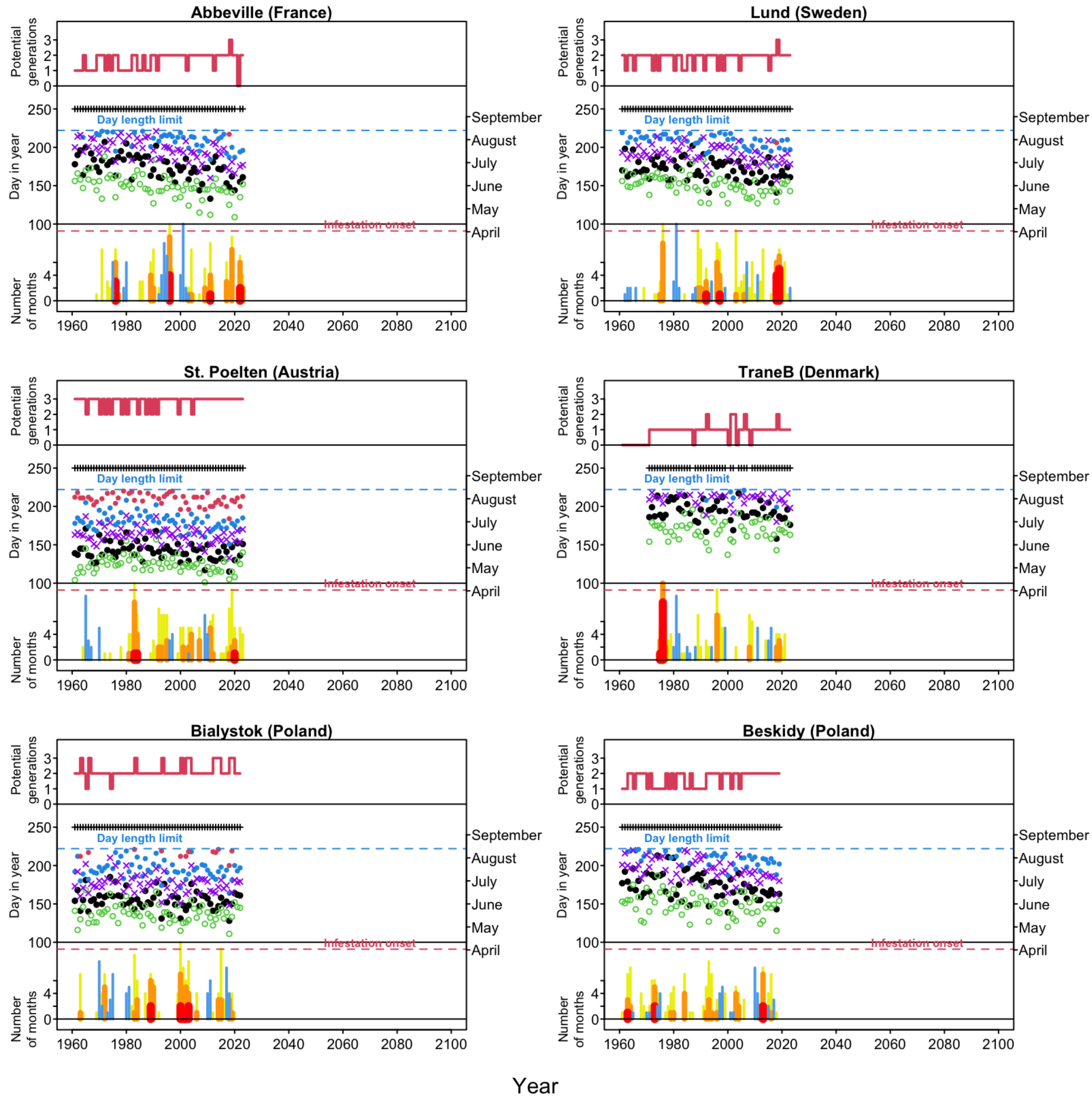

Figure 12 – A combined output of the phenology and drought models for the case studies. In each panel, the bottom graph: the number of months in a calendar year for which SPEI12 is in a certain range, indicating severe or extreme drought or flood. The middle graph shows the first day of the year with the early and main swarm, first, second filial generation, first sister generation and potential for overwintering. The top graph shows the potential number of generations.

The locations in Austria (for which PHENIPS was developed) and Poland show frequent and prolonged droughts, interspersed with flooding, and climatic conditions conducive to 2-3 generations. The outbreaks in Austria, the Czech Republic and Białowieża Forest in Poland demonstrate the potential for a highly damaging impact on Norway spruce forests. The location in Denmark, in this respect, is more similar to the southern locations in Scotland (E and W Scotland), with some potential for first and sister broods. South Sweden and Northern France are more representative of Scotland's conditions predicted for the mid-century, with the condition for two generations and the potential for large-scale outbreaks.

Note that this is only an initial study, and more analysis and data collection are needed.

4.5 Impact on forests

In this section we consider two approaches to predicting the impact of potential establishment of *Ips typographus* in Scotland. The "endemic" phase is captured by Seidl et al model, whereas we combine the PHENIPS prediction of the number of generations with the SPEI calculation for the drought intensity to assess the likelihood of large-scale damage.

4.5.1 "Endemic phase"

Seidl et al model is relatively insensitive to variation in temperature and rainfall when they are in the range exhibited in the UK, figure 12, although the broad picture agrees with other models presented here. For SE England, the current probability is 0.4 and rising to 0.5-0.7 by 2100, with the % area affected rising only steadily from 3% to 5-6%. These relatively high values are driven by the combination of low rainfall and high temperatures.

In contrast, under the "endemic phase" scenario, Scotland's results show the probability currently at 0.1-0.2, rising to 0.2-0.3 by 2100, while the % area affected is at 2% and not changing with climate change. This is primarily the result of relatively high average rainfall which does not change according to the current RCP predictions. These results are in line with what has been observed in other countries in their "endemic phase" [11], barring the windthrow- and drought-linked large-scale outbreaks.

4.5.1.1 Interpretation with respect to outbreaks: The "endemic phase"

Although the results need to be interpreted with caution, the expectation is for Scotland to experience a climate-driven outbreak every 3-5 years, with average annual damage of about 2% of the area/volume. The relatively low impact is due to high rainfall, and does not differ between East, West and North Scotland, or increase with changed climate.

For comparison, the average windfall area is ca. 1.4% of the total area (conifers, broadleaves and mixed), see Table 1, but possibly higher in conifers. At the impact scale expected in the "endemic" phase, there is likely potential for the industry to adapt and adjust the programme to fell and clear up the infestation caused by *Ips typographus*.

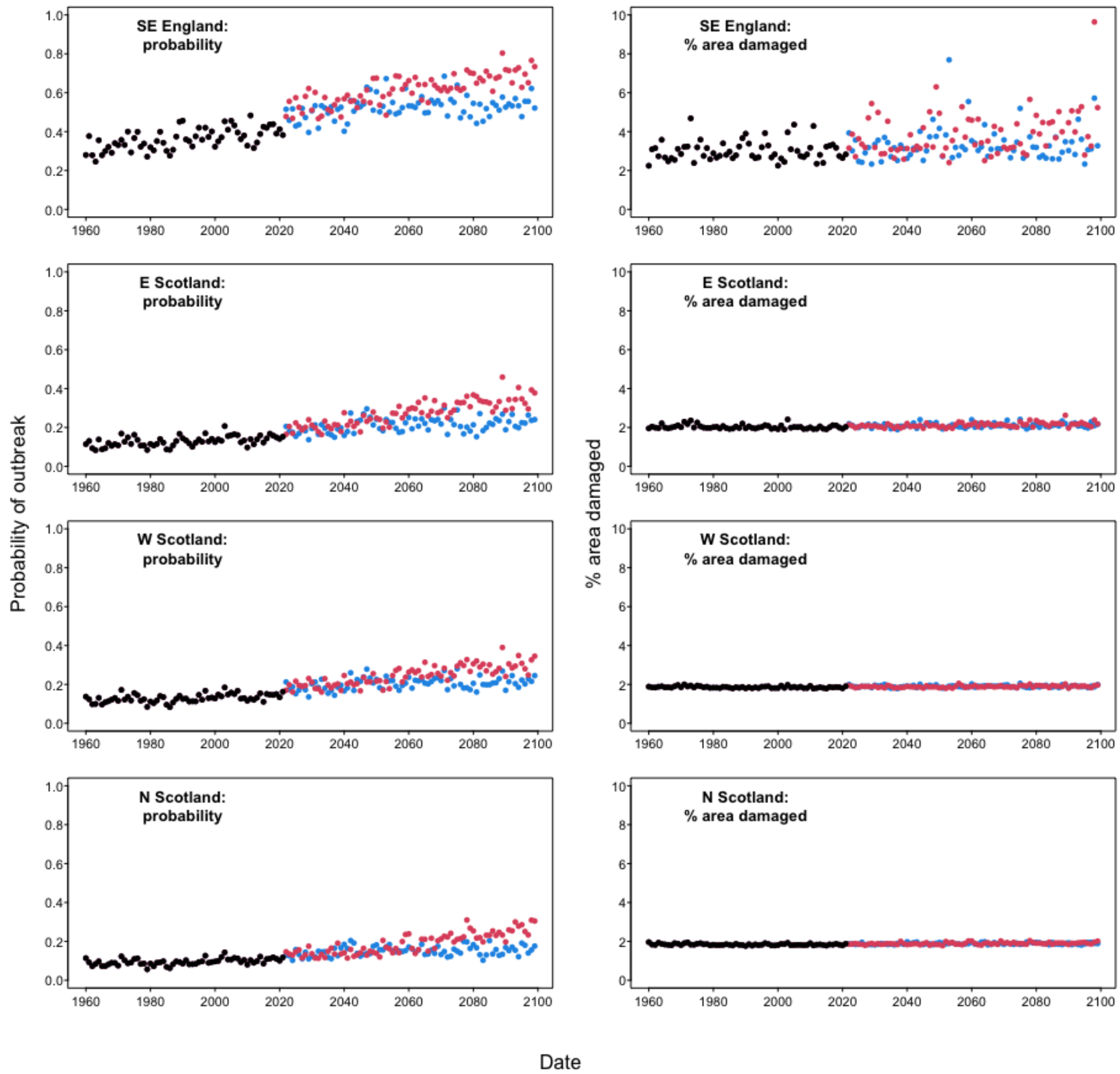

Figure 12 – Seidl et al model results. The left column shows the probability of an outbreak causing damage per year, averaged over 5 year period. The right column shows the % area damaged per year. Black dots: past climate; blue dots: RCP 2.6; red dots: RCP 8.5.

4.5.1.2 Caveats and extensions

Predictions for the impact of *Ips typographus* on trees and the level of tree loss are made based on the Seidl et al model, which in turn is based on Norway spruce. There are currently no studies that provide similar evidence for Sitka spruce, although research is under way in FR.

In particular, the effect of stand age might be very different for Sitka spruce than for Norway spruce, depending on the bark depth, resin pressure, and general health of the tree (including the presence or absence of primary pests like parasitic fungi and abiotic stresses).

It is well evidenced that mortality due to *Ips typographus* is strongest for Norway spruce with age 70+ or even 100+ [49,50], with a typical rotation length of 100-120 years. At the moment, there is no scientific evidence for how age of Sitka spruce affects its mortality due to *Ips typographus*. Thus, it is not possible to validate the Seidl et al model for Sitka spruce, and so the results presented need to be treated with caution. While for Norway spruce, the mortality is strongest in old trees, Sitka spruce, as a faster-growing tree, is more likely to be affected at a lower age. More work needs to be done to assess the impact of *Ips typographus* on trees grown in Scotland.

4.5.2 "Epidemic" phase

To our knowledge, there is currently no quantitative framework combining drought risk with beetle phenology and representing the "epidemic" phase as defined in [11]. The approach taken in this report is to combine the two strands of evidence presented in this report, the potential for drought affecting – as represented by SPEI12 in June – and the potential number of generations as predicted by PHENIPS.

Following [11,37], we assume that the combination of sustained and severe droughts with conditions supporting the development of 2 or more generations creates a scenario in which the outbreaks of *Ips typographus* can become widespread.

As seen in Figure 13, the likelihood of such a combination is relatively low at present across Scotland. We henceforth conjecture that if *Ips typographus* becomes established in Scotland, it will enter the "endemic" phase with the associated damage limited to the south part (here represented by E Scotland and W Scotland regions) and associated primarily with trees damaged by abiotic or biotic agents, for example, windthrow. This likelihood is estimated to be low for N Scotland, although locally, the damage might be higher.

However, climate change is likely to lead to an increased likelihood of the combined impact of increased drought and *Ips typographus* development shifting earlier in the year. Such a combination becomes more frequent in the period after 2040 in E and W Scotland, with E Scotland more affected under the RCP 8.5 scenario than W Scotland. Such a transition is only expected in N Scotland towards the end of the century (2070-80).

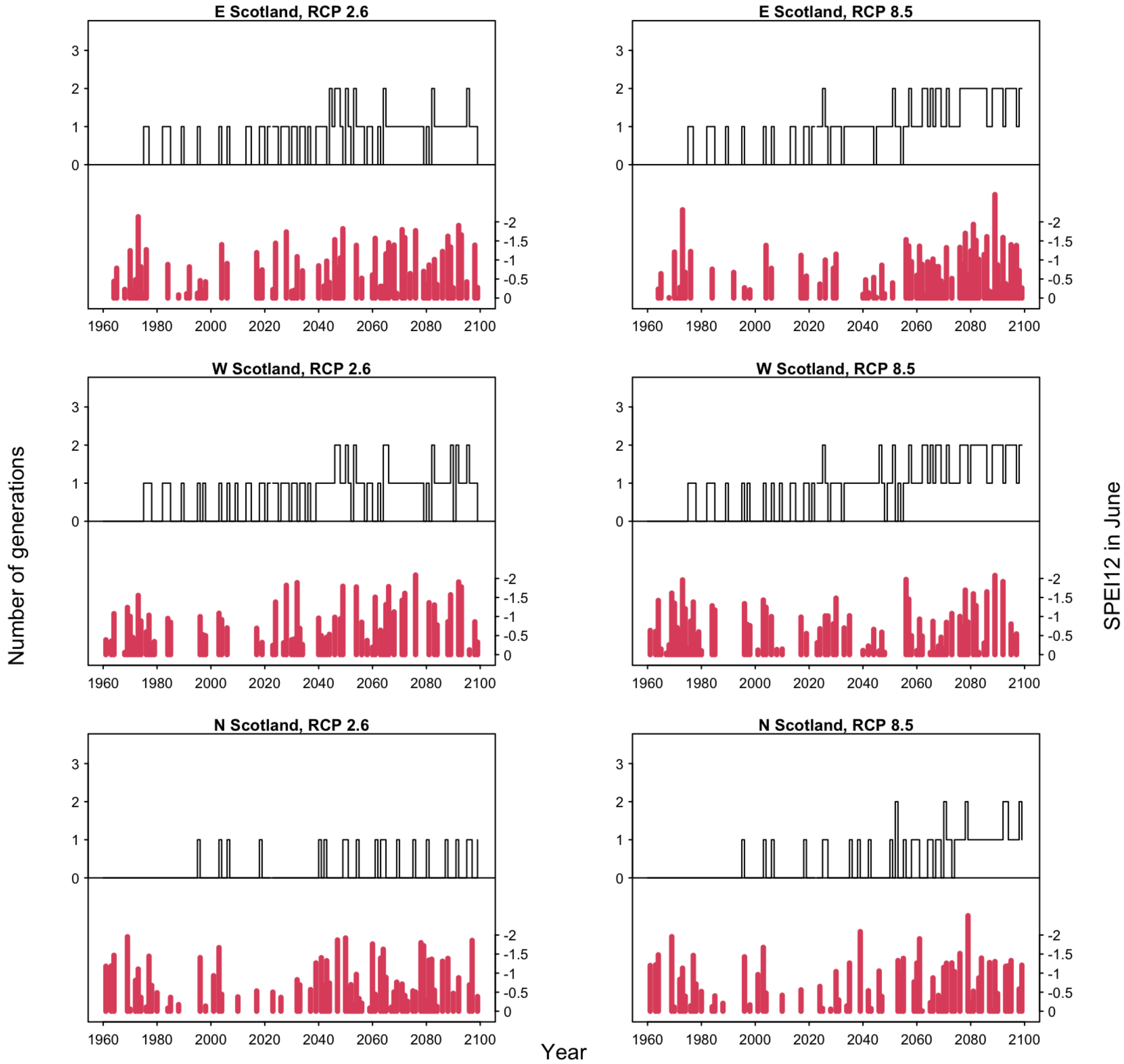

Figure 13 – Combined SPEI12 (June) and number of generations for different locations and climate change scenarios.

4.5.2.1 Interpretation with respect to outbreaks: The "Epidemic phase"

We estimate that if *Ips typographus* becomes established in Scotland, the current risk of a large-scale outbreak will be low but rising to medium over the period of the next rotation and become high in the second half of the century. However, at present, it is not possible to provide a firm quantification of the risk due to significant knowledge gaps as outlined elsewhere in the report. North Scotland appears to be relatively protected by low summer temperatures and high rainfall, at least for the duration of the next rotation (until 2060-70). There is a risk that in the "epidemic" phase, the scale of the impact might be beyond normal sustainable felling programmes, causing large-scale losses as seen in some parts of Europe since the early 2000s [11].

4.5.2.2 Caveats and extensions

The analysis presented here has not been peer-reviewed and is based on a range of simplifying assumptions, as discussed in the previous sections.

4.6 Sensitivity analysis

In the project we carried out an extensive sensitivity analysis, by performing multiple simulations with different assumptions. In this section we show how the results change if a different RCP model is used.

The UK Met Office data used in this project are based on the HadGEM3 (Hadley Centre Global Environment Model version 3) family of models, which comprises a range of specific model configurations incorporating different levels of complexity but with a common physical framework [21]. The family consists of 12 models each with different results for future climate predictions. The results presented above use one of the models, HadGEM3.GC3.05.r001i1p01935.

Figure 14 shows the results for E Scotland based on eight different models in the same family. Although the results show differences in the timing and severity of droughts and the timing of *Ips typographus* development, the results are consistent. The results for the remaining four models are not shown due to problems with the SPEI algorithm.

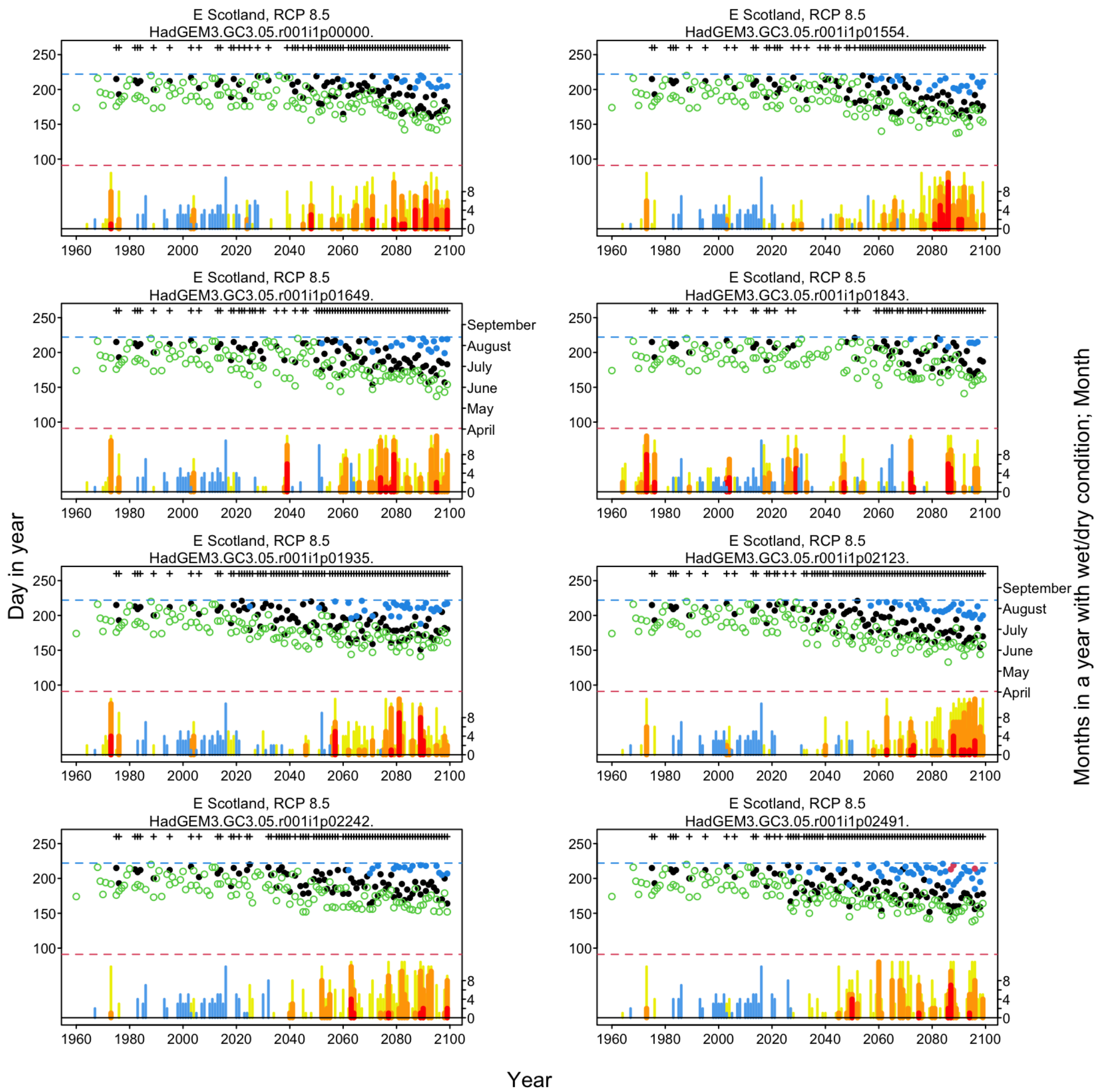

Figure 14 – Combined SPEI12 (number of months) and PHENIPS timings for E Scotland under RCP 8.5 scenario but different HadGEM3 models. Symbols as in Figure 11.

4.6.1.1 Interpretation of the sensitivity analysis for the effect of climate projections

The trends are broadly independent of the details of climate prediction models. Although details vary, in all presented scenarios, the bark beetle starts flights earlier, produces more generations, and reaches the overwintering capacity. At the same time, the frequency and severity of droughts will increase after 2050, again in all presented scenarios.

4.6.1.2 Caveats and extensions

The analysis presented here has not been peer-reviewed and is based on a range of simplifying assumptions, as discussed in the previous sections.

5 Economic impact – a review

In this section, we provide a discussion of economic consequences of the potential establishment of *Ips typographus* in Scotland. Given the severe uncertainties associated with the vector and timing of the introduction and with the impact on Sitka spruce, we do not carry out a full economic modelling. Instead, a literature review is presented here to illustrate what can be learned from other systems about the consequences of bark beetle outbreaks.

In the last 70 years, bark beetle outbreaks have consistently ranked in the top 5 major forest disturbances across the globe [51–53]. Although there has been significant progress in the efforts to understand the economic and environmental consequences of bark beetle damage, there is still much that needs to be explored. The implications of bark beetle outbreaks can be diverse and widespread. We will discuss the direct and indirect economic implications to forest managers as well as wider implications to the economy. We identify potential consequences drawn from studies where this major forest disturbance has manifested. The report aims to provide a comprehensive review of evidence to inform decision-makers and help them devise damage control or prevention strategies.

Direct costs or losses are typically associated with a loss of timber due to windfall or fire as well as the expenses incurred for detection and control. On the other hand, indirect costs are much harder to quantify and may vary based on multiple factors such as the socio-economic scenario, the severity, duration and nature of the outbreak, the number of trees affected, mitigation measures and others. Numerous approaches can be used to measure costs associated with forestry management. In this section, we review some of the main costs as well as set-out the limitations that make measuring these costs challenging. Given the heavy reliance of the Scottish industry on Sitka spruce, economic losses from an outbreak could be significant, with far-reaching implications for both forestry industries, the rural economy, and the broader UK economy.

Surprisingly, there is very limited literature providing quantitative evidence for the economic loss associated with bark beetle damage. Hlásny et al (2021) provide an overview of current literature [11], and the book by Vega and Hofstetter (2015) provide a chapter on the economic and social impact [54].

5.1.1 Market value and timber loss

Direct costs due to the loss of timber can be estimated by assessing the market value of the timber that is damaged or destroyed. Bark beetles predominantly attack the inner bark of the trees, hampering the transportation of nutrients and ultimately causing tree mortality. In severe cases, trees may become unfit for harvesting or perish. The quality of wood produced by infested trees may decrease the value for industrial uses such as sawmilling and wood processing. Hence, the affected timber may produce only lower-value products such as bio-fuel or pulp-wood or decrease the market prices. As shown by Chow and Obermajer (2007), bark beetle infestations of lodgepole wood often result in blue-stained wood that considerably reduces the value of timber [55]. In the early stages of the infestation, the effect on the structural integrity of the wood is negligible; however, the visual effect lowers consumer demand. In their study of infestations in British Columbia, they estimated the projected loss of sales to be approximately US$400 million in the following ten years. Patriquin et al (2007) relied on a computable general equilibrium model to study the short and long-run economic consequences of pine beetle infestation regarding timber supply in British Columbia [56]. They found that in the long run, the decline in timber supply would have adverse, long-lasting consequences for the local economy. The main concern was that this infestation could cause "sustainable resource-based economies" to experience high fluctuations in employment turning them into essentially boom-bust mining economies. This result is also in line with Flint et al (2009) who report high volatility in persistent employment impacting the communities of Alaska that heavily relied on timber harvesting from 1989 – until their collapse in 2004 [57,58].

Hence, in the absence of the infestation, we observe a sustainable industry built around the timber industry (i.e. a resource economy). However, because of the infestation there is a lot of labour reallocation and not necessarily to the right sector. In economics, there is a large body of literature that studies the labour reallocation response to shocks [59–61]. Uncertainty is important for sector mobility, however, the duration of this uncertainty cannot be predicted or whether it will attract or repel occupational switching. Allowing a sustainable resource-based economy to change into a boom-bust economy can create severe long-term economic consequences since it can potentially create structural unemployment (see, for example, the Australian mining boom). This structural unemployment tends to create long-lasting unemployment spells with significant costs for the taxpayer. Structural unemployment occurs when there is a shift in the economy that makes the existing skills of a part of the population obsolete. Hence, it results in longer unemployment whilst dealing with it requires substantial government expenditure to re-train and re-allocate displaced workers.

However, as mentioned above, this simple measure accounts for only immediate direct costs. As such, the main limitation of this measure is that it assumes that we can plant Sitka spruce and pine interchangeably and does not account for duration between the initial investment and the first returns. In reality, Sitka spruce is a much more resilient species, and a pine species may not be a perfect substitute for it.

5.1.2 Measuring Direct Costs

We define direct costs as closely associated with and resulting from bark beetle infestation.

5.1.2.1 Market value of timber

In order to calculate the direct costs from loss of timber, in the first instance we need to ascertain the market value of the damaged timber. This involves evaluating the volume and quality of lost timber and thus determining its current market price. According to Hlásny et al (2021), following the 2018 outbreak of bark beetle in the Czech Republic, the timber price per cubic meter fell [43] from the region of 56– 64 euro, calculated as an average for the period of 2011 to 2017, to 14- 16 euro per m^3. Similarly, the SFA (2010) report finds that the bark beetle attack that followed the storm Gudrun in 2005 caused Swedish timber prices to drop from 40 to 25 euros per cubic meter, with the timber prices recovering in subsequent years [62].

There are two main factors that determine the loss of market value of timber.

5.1.2.2 Revenue loss

Aside from the immediate expenses, we can estimate the foregone income from timber that could have been harvested, which is another direct cost. These costs are directly linked to timber degradation and quality loss. Naturally, as the outbreak progresses, timber continues to degrade, and the wood structure weakens. As such, the volume of suitable lumber is reduced.

Loeffler and Anderson (2017) proposed that in a standard lodgepole pine stand, "the volume suitable for lumber declined by 15% between the green and red stages and declined by another 50% between the red and grey stages" [63].

The study found that overall, the total cost of logging, loading, hauling and sawmilling increased by around 45% for each activity due to timber defects along the transition to different stages of the outbreak.

Additionally, from the early work of Valatin and Coull (2008) to Pohjola et al (2018), we expect that in subsequent years, forest owners may also receive compensation for ecosystem services that their forests provide [64,65]. As such, a bark beetle outbreak will negatively affect their compensation whilst also leading to decrease in property values. For instance, according to Hlásny et al (2021) "tree mortality caused by the mountain pine beetle in Colorado, USA induced a loss in home values of between 5.1% and 22% depending on the county, timing and severity of the outbreak" [11,43].

5.1.2.3 Insurance Claims

There may be insurance claims made by forest owners for any losses covered by insurance. These costs could be used to calculate some of the direct costs.

Although we do not have access to quantitative measures, it is well- established in the literature that how the government approaches the outbreak influences the behaviour of forest owners. However, the response of public policy to bark- beetle attacks has been quite diverse. For example, Brunette and Couture (2008) found that the government response tends to deter private forest owners from seeking insurance coverage for natural disturbances and encourages them to adopt a proactive stance on prevention instead [66]. Their evidence was based on the way that many European state compensated forest owners for windstorm damage.

Similarly, Sims et al (2010) built a bioeconomic model addressing tree harvesting following mountain pine beetle damage [67–69]. Their objective was to evaluate alternative public management strategies. Their analysis indicates that conventional practices tend to exacerbate mountain pine beetle cycles. In contrast, a more centralized management approach could potentially eliminate these cycles and mitigate their impacts, with minimal long-term reductions in timber reserves.

5.1.2.4 Management costs of detection and control

Another crucial aspect of a bark beetle infestation are the management costs. Forest owners may face considerable expenses for controlling and managing an infestation. These could include costs associated with detection, monitoring, salvaging and implementing biological control measures such as applying insecticides, pesticides, manual interventions, sanitation thinning or use of pheromone traps. In the first instance, forest managers would incur direct costs from implementing control measures to reduce damage and prevent any further spread. There will be costs involved in employing traps, mechanical interventions and monitoring systems. Direct costs can be measured by calculating the costs associated with personnel, technology utilised for surveillance operations and any equipment used.

Once detected, arrangements for the removal of trees that are affected as well as mitigation strategies will also incur further costs. Followed by the removal, clean-up and salvage operations will incur further direct costs. These are expenses associated with cleaning and salvaging timber such as felling, processing and removal of any damaged trees. Subsequently, forest managers will conduct surveys and inventories to determine the level of damage and evaluate the value of timber lost.

5.1.3 Measuring Indirect Costs

As can be expected with an industry dependent on healthy forests, a bark beetle outbreak can have a knock-on effect on tourism, timber processing and importantly on the local economy. As discussed above economic losses can be exacerbated by job losses, and decrease in revenue. However, with these losses come indirect costs with many being difficult to quantify. Let us consider some of these potential impacts particularly, if bark beetle infestation becomes endemic.

The long- term effects of an insect disturbance are unambiguous and negative, see [70]. Long after the disturbance is realised and forests begin to regenerate, it is anticipated that timber reserves and exports will diminish, causing timber prices to increase due to the decrease in timber supply. However, shortly after the bark beetle outbreak is realised, the short-term economic results are ambiguous. According to Hlásny et al (2021), substantial surges of salvaged timber may present problems for the local sawmill industry [43]. Such influxes of timber generated by bark beetle outbreaks could potentially exceed their processing capabilities, resulting in increased expenses associated with safety hazards and timber storage. This excess supply of timber might affect prices in both local and distant markets. As a result, timber producers are faced with reduced timber prices as well as increased costs associated with logging, sanitation and regeneration.

Overall, the literature finds the net effect on the forestry economy to be negative, with substantial spill-over effects. For example, Pye et al (2011) found that following the southern pine beetle outbreak (1977–2004) in the Southern United States, the short-term estimated net economic loss to be approximately $375 million (in 2004 constant dollars) [71]. Timber producers reported an estimated loss of about $1.2 billion, whilst timber-processing companies earned approximately $837 million due to the lower timber prices.

The economic repercussion of bark beetle disturbance extends well beyond their effect on timber prices. A large-scale outbreak, like seen in some parts of Europe [11], will likely lead to a reduction of the carbon pools in forests [72]. For example, in the case of the European Union, if the forest carbon sink of a member is reduced relative to its ‘forest reference level’, other measures must be implemented to offset this, albeit at an economic cost.

5.1.3.1 Productivity and forest health

Once we consider the immediate consequences of an outbreak, the long-term implications can be far-reaching. Unlike traditional financial assets, trees are tangible assets possessing unique characteristics such as growth value appreciation over time, illiquidity, and logistical challenges. Thus, an outbreak may imply years of recovery and the requirement to replace with possibly less valuable species if there is a loss of confidence in spruce. As such, this may affect the long-term economic potential of the forestry industry as well as forest health, making it less resilient to other risks, including wildfires and windstorms. Afflicted or dead trees pose an additional danger due to their vulnerability to windstorms, causing further damage and additional costs. Similarly, there may be an increased susceptibility to forest fires presenting both immediate and long-term damage [73].

Schowalter (2012) demonstrated that for a public forest where the manager wishes to optimise multi-criteria objective functions, this might not be the case [74]. These forests often house older and/or more vulnerable trees. They are sites with high cultural value, often populated with endangered species whose protection often requires expensive management options.

In the past, bark beetle outbreaks were infrequent and typically primarily localised in landscape patches with dense or ageing pine hosts [75]. In such conditions, bark beetles served as natural thinning agents, targeting injured hosts, especially in areas where pine trees grew close together and faced competitive stress. This process helped maintain wide spacing among host trees and encouraged diversity in associated hardwoods, shrubs, and grasses. Outbreaks were naturally contained as host mortality reduced resource availability across forested areas [76].

However, due to changes in land use and the preference for faster-growing pine species, these plantations often feature closely- spaced trees, making stressed hosts easily accessible to bark beetles [77]. Consequently, there are fewer barriers to the spread of bark beetle populations across landscapes, resulting in widespread tree mortality during outbreak years. Hence, growing concern for forest health and the multi-use management of public lands has increased the public’s attention to the issue of bark beetle infestations.

Schowalter (2012) also highlighted that “Although bark beetles often are blamed for forest health problems, healthy trees are capable of defence against bark beetles. Therefore, outbreaks of bark beetles are less a threat to forest health than a symptom of abundant trees in poor health.” [74]

5.1.3.2 Shifts in species preference

A loss of confidence in planting spruce can trigger a chain-reaction of challenges for the forest management and all associated industries. Forest managers may prefer selecting tree species that are less susceptible to bark beetle infestations.

However, switching species involves costs from sourcing seedlings, replanting, and potentially adapting forest management practices and infrastructure to accommodate the needs of the new species. The new species (or varieties) might also not be as well acclimatised in Scotland, potentially resulting in lower growth rates, yields, and/or timber quality. Further, to date, Sitka has been remarkably resilient, while other species have suffered (e.g. larch). All species, not just Sitka, will be up against significant pressures of climate change and pests and disease, a factor that needs to be taken into account when searching for alternative species.

5.1.3.3 Environmental and social costs

Lastly, bark beetle infestation can be associated with the environmental and social costs. Large-scale outbreaks may impact biodiversity, carbon emissions, forest ecosystem services, and risks of fire due to afflicted or dead trees, adding challenges for forest management. Furthermore, an infestation may exacerbate the already challenging situation by adding negative social and cultural impacts on communities that depend on the forestry sector, in some cases even causing a loss in livelihood. We may see negative impacts on recreational facilities and a decline in leisure activities. A shift in unique landscape features may affect the aesthetic appeal and, hence, its value, deterring tourism revenue. We could measure the change in contributions to the local economy by evaluating, for example, the number of visits and spending patterns of tourists.

Although we lack numerical values, we know that bark beetle outbreaks can negatively affect recreation benefits. However, the results reported in the literature remain somewhat ambiguous, particularly as spruce commercial forests may not attract as much recreation as other forest types.

The dynamics of bark beetle outbreaks within social contexts are anticipated to evolve in tandem with shifting forest landscapes and disturbance risks.

Rosenberger et al (2013) found that depending on the intensity a mountain pine beetle attack in the Rocky Mountain National Park, USA would cause important losses in total recreation value [78]. Yet, for the case of the Canadian National parks, Dhar et al (2016) reported that overall visitation and revenue earnings were not affected by beetle outbreaks [79]. However, we must point out that main objective of national parks pertains to the effects on biodiversity rather than recreation value.

Despite the severity and scale of bark beetle disturbances, there is still very little research on their socioeconomic consequences. Two rare exceptions are Müller (2011) and Qin et al (2017) who study responses to bark beetle outbreaks Europe and North America, respectively [80,81]. They find that the demographic characteristics, the communities' perception of the outbreak as well as their past experiences with bark beetle outbreaks shape their perceptions regarding forest risks.

Additionally, the social dimensions of forest disturbance by beetles vary between places experiencing different stages of beetle outbreaks.

5.1.3.4 Environmental consequences.

Qin et al (2017) investigated the spruce beetle outbreak in the Kenai Peninsula (Alaska) [81]. Their study revealed that while the significance of the disturbance's aftermath tends to diminish over time, apprehensions regarding immediate threats to personal property and safety, such as forest or grass fires, persisted. This suggests a nuanced and evolving process that is more complex than typically presumed.

5.2 Interpretation of economic impact.

In this literature review of the economic consequences of bark beetle outbreaks, we have identified a number of direct and indirect impacts. Several approaches have been used to capture the costs, although we did not find examples of a systematic approach directly transferable to Scotland. With further information or scenario development, the methods identified here could be used to explore the potential economic costs of *Ips typographus* outbreaks. Several studies indicate significant impacts at the regional and national scale, highlighting the importance of continuing surveillance, detection, and eradication actions as well as increased diversification of forests.

6 Research gaps and future work

The project has collated the most recent developments in data analysis and modelling and has made significant progress in applying those to the UK and particularly Scotland conditions, bringing together different strands of evidence. However, it also identified a range of research gaps which it could not address, either due to time or scope limitations, or – more likely – because the evidence is simply not there.

1. Most of the evidence currently comes from Norway spruce and climates unlike the maritime one in Scotland. The beetle will encounter a different host and ecosystem, including other insects and pathogens.
2. Both Sitka and Norway spruce have a shorter rotation in the UK, because they tend to grow faster. It is not clear how that affects the resin pressure and hence their resilience to *Ips typographus* attacks. Work is currently underway at Forest Research and once the results are known, the approach taken in this project can be updated.
3. The quantitative evidence is missing for the interaction of abiotic (flooding and drought) and biotic factors in the "epidemic phase".
4. It is not clear when and how *Ips typographus* can arrive in Scotland and hence parameterising the arrival module of the Decision Support Tool was not possible.
5. In the project, we had to balance the feasibility of the modelling approach with the temporal and particularly spatial resolution, and we decided to use the regional scale in the analysis (West, East and North Scotland). As a result, the finer climatic resolution is lost and yet addressing it might be essential to understand the potential for establishment and survival of *Ips typographus* and the impact on particular areas. Spruce is not equally distributed and hence there is a need to consider a higher spatial resolution.
6. Some processes are highly dependent on location, slope and height above sea level, but this level of heterogeneity is missing from the analysis.
7. The economic impact, particularly the indirect part, is not well understood. Most evidence comes from the Pine Mountain Beetle outbreak in the US, and the transferability of it to Scotland is doubtful. However, there is potential for transferability of economic approaches to windthrow, with its focus on spruce.

7 Conclusions

In this report, we have addressed the question of what the impact would be if *Ips typographus* were to become established in Scotland. We have combined literature review, expert solicitation, data analysis and modelling, to capture different aspects of the pest and tree physiology, climate change and economic and social impact.

We also identified a range of knowledge gaps, solution of which exceeded the scope and timing of this project. It is only if the bark beetle actually becomes established, we can reliably start answering the question of how it will perform in the new conditions. However, significant progress has already been made, see e.g. [25] and relevant research is ongoing in Forest Research.

Nevertheless, several broad patterns emerge from different lines of analysis, and we summarise them in Tables 4 and 5, on both near (2020-2040), medium (2040-2060), and far (2060-2100) horizons, while keeping in mind that any rotation planted in 2024 will most likely be harvested around 2054 (30 years) or 2074 (50 years).

7.1 Combined risk estimation

As discussed throughout the report and established in consultation with the experts, we use the following classification:

- **Low overall risk** is associated with sporadically occurring droughts, flights starting in July and occurring for less than 100 days, the beetle capable of producing at most one generation. Under such conditions, *Ips typographus* can become established but is only likely to affect trees at high risk (otherwise damaged) and sporadically.
- **Medium overall risk** is associated with sporadic moderate to severe droughts, flights shifting to June and possible for more than 100 days, as well as occasional years with 2 generations. We associate this condition with the “endemic” state, with local outbreaks, limited to windfall or otherwise affected areas.
- When the number of generations increases from one to two or three, and combines with frequent prolonged and severe droughts, we associate it with **High overall risk**. There is an increased probability of large, spatially extended outbreaks in areas and in years of drought, affecting otherwise healthy trees.

For the purpose of this summary, East and West Scotland regions are treated together, although the results are presented separately in the rest of the report.

Table 4 – Risk estimates for East and West Scotland

East and West Scotland	2020-2040	2040-2060 (30 years rotation ends in 2054)	2060-2100 (50 years rotation ends in 2074)
Estimated risk of establishment[2]	Medium	High	
Estimated risk of outbreaks (endemic)	Low raising to medium	Medium to high	High
Estimated risk of large-scale outbreaks (epidemic)	Low to medium		Medium to high
Possibility of flights and number of days above 16.5C	Earliest flights in May-June, with 50-100 days	~75-125 days	Earliest flights in April-May; up to 150 days
Main swarm	August	July	June
Number of generations	Mostly 1	Occasionally 2	Mostly 2
Overwinter[3]	Sporadically	Most years	
Drought potential (June SPEI12 < -1.5) [4]	Sporadically	Some severe	Frequent prolonged and severe

Table 5 – Risk estimates for North Scotland

North Scotland	2020-2040	2040-2060 (30 years rotation ends in 2054)	2060-2100 (50 years rotation ends in 2074)
Estimated risk of establishment[5]	Low, raising to medium		Medium to high
Estimated risk of outbreaks (endemic)	Low to medium		Medium
Estimated risk of large-scale outbreaks (epidemic)	Low		Medium
Possibility of flights and number of days above 16.5C	Earliest flights in May-June; up to 50 days	May-June, but raising to 100 days	Earliest flights in June; up to 150 days
Main swarm	Late August if possible	August	Mostly July
Number of generations	Occasionally 1	Occasionally 1, possible 2	1, occasionally 2
Overwinter[6]	Rarely	Sporadically	Most years
Drought potential (June SPEI12 < -1.5)	Rarely	Sporadically but can be severe	

[2] Predictions in this table are based on the worst-case scenario of RCP 8.5.
[3] Note that the values here are based on the whole region; populations can survive locally much earlier.
[4] East Scotland is more likely to experience droughts than West Scotland.
[5] Predictions in this table are based on the worst-case scenario of RCP 8.5.
[6] Note that the values here are based on the whole region; populations can survive locally much earlier.

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