The evidence base for factors affecting woodland resilience against pests and pathogens: Systematic Map Protocol

Type of Review: Systematic Map

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Abstract

Background

Pathogens and herbivorous arthropod pests are amongst the most widespread threats to trees and forests. Because these impacts are projected to become more severe and frequent, policy responses increasingly emphasise the need to build and maintain resilience. However, many factors could influence resilience and the effect of these factors on the impacts from pests and pathogens could be assessed in many ways (e.g. damage, mortality, pest/pathogen spread). We therefore propose a systematic map to collate evidence on the factors affecting resilience in the context of tree health. Our primary question is: *'What evidence exists on factors that may affect the spread of tree pests and pathogens, and the damage caused by tree pests and pathogens?*

Methods

Based on stakeholder consultation, initial scoping, and theoretical expectations, we first identified a series of factors that may affect resilience. We will search multiple databases and websites of organisations for primary research and review articles that consider whether one or more of these factors affect the spread/abundance of tree pests and pathogens, or the impacts. Consistent information will be extracted from all relevant articles to describe ***(i)*** study region, design, and question, ***(ii)*** tree species and pest(s)/pathogen(s) considered, ***(iii)*** the factors affecting resilience that were investigated, and ***(iv)*** the metrics used to assess the impacts of the pest(s)/pathogen(s). This information will be used to identify topics suitable for more targeted synthesis and to highlight gaps in the literature that may require new primary research. In addition, a searchable database will be produced, allowing policymakers to quickly locate relevant evidence examining if and how particular factors affect resilience.

Background

Trees are exposed to a wide range of biotic and abiotic pressures, which shape the structure and functioning of forest ecosystems. Amongst the most important and widespread influences are those caused by pathogens and invertebrate herbivores. Although these organisms are an integral part of natural systems, a subset can have major detrimental effects from an anthropocentric perspective (Boyd et al. 2013), particularly if moved outside the native range. For example, following accidental introduction in the early 20th century, chestnut blight killed billions of trees across North America (Jacobs et al. 2013). This fundamentally altered forest structure and composition with cascading effects on biodiversity and ecosystem functioning, and continues to prevent the use of a potentially valuable timber species. Some invertebrate herbivores ('pests' from an anthropocentric view) and pathogens can also cause major economic losses in production forests and pose additional risks if affecting trees in urban areas or near infrastructure. Furthermore, these threats are predicted to escalate in severity and frequency as increasingly globalised trade networks allow organisms to reach regions where they may have far greater impacts (e.g. due to the lack of co-evolved tree defences), whilst changing climatic conditions may lead to more severe outbreaks of both native and non-native tree pests and pathogens (Boyd et al. 2013). Policy responses increasingly emphasise the need to build and maintain resilience against these threats. For example, the UK Department for Environment, Food and Rural Affairs (Defra) recently published the Tree Health Resilience Strategy aiming *'To build the resilience of England's trees, woods and forests'* (Defra 2018).

Resilience is a prominent theme across environmental management and policy, from organisations responsible for specific systems and countries through to global strategies such as the Aichi Biodiversity Targets. This emphasis probably partly reflects the interpretation that in a resilient system, major detrimental change is unlikely or can be quickly recovered from.

78 However, there is important ambiguity over definitions of resilience, which can cause problems

79 if a common interpretation amongst stakeholders is incorrectly assumed (Box 1; Newton 2016).

Box 1: Interpreting and Implementing Resilience

The concepts and considerations below have been explored in further depth by other authors (e.g. Brand & Jax 2007; Folke et al. 2010; Fuller & Quine 2016; Standish et al. 2014)

Prominent Resilience Concepts

Resistance: The extent to which a variable is altered by disturbance (e.g. maintaining leaf area, forest biomass etc. during outbreaks).

Recovery: The speed or completeness of return to the pre-disturbance state following an impact (e.g. recovery of leaf area, forest biomass etc. after disturbance).

Adaptation: Reorganising of a system in response to disturbances, to support the maintenance of similar functions in future (e.g. diversifying tree species to reduce the risk of impacts from species-specific threats).

Transformation: More fundamental change (either intentional or unintentional) to give a different type of system (e.g. transforming from timber plantation to multi-use forestry also emphasising recreation, biodiversity etc.).

Thresholds: Points at which further changes result in a fundamentally different state (e.g. climate-induced shifts from forest to grassland). Changes may be reversible but restoring initial conditions does not always recover the previous state. Thresholds assume multiple stable states rather than a single 'equilibrium' towards which the system returns. Multiple states occur in some systems but are disputed in others.

General vs. specific resilience:
'General' resilience refers to the system as a whole and all the threats it may face, whereas specific resilience relates to the resilience of defined properties against defined threats (i.e. the resilience 'of what, to what').

Important Considerations

Resistance, recovery or adaptation?
These concepts are not mutually exclusive but may require different properties to an extent (e.g. factors that improve resistance will not necessarily facilitate recovery etc.). Resistance, recovery or adaptation also lead to a system that is affected by disturbance in different ways, and so clarity on the aims of resilience-based policy with respect to these ideas is important.

General or specific resilience?
Building general resilience is often desirable but may be challenging and prone to ambiguity. Specifying the resilience 'of what, to what' can focus research and policy and reduce ambiguity but will exclude some properties and threats. Note that building resilience against specific threats does not necessarily confer general resilience (e.g. connectivity might enhance resilience to climate change but could increase the spread of disease).

The challenges of measuring resilience
Resilience can only truly be measured *after* disturbance. However, decision-makers often require information on resilience prior to potential impacts. These assessments can include (i) measuring characteristics that are assumed to influence resilience, (ii) identifying early warning signals that predict proximity to a threshold, (iii) following guidelines for describing the system qualitatively and in detail (e.g. stakeholders, threats, benefits etc.), and (iv) modelling impacts of disturbance on variables of interest. The predictive nature of these assessments should be appreciated by users, and needs to be grounded in evidence and validated.

What are the risks?

Important risks associated with resilience as a policy objective include:

i) Ambiguous definitions lead to actions that do not recognise concerns of some stakeholders
ii) Oversimplified assessments lead to generic interventions that are counter-productive
iii) Increasing resilience against pests and diseases may reduce resilience against other pressures.
iv) Increasing the resilience of one forest property could impair the resilience of another
v) Resilience assessments are interpreted and acted on with a certainty that is not warranted.

Furthermore, devising and implementing policy depends on understanding the factors that influence resilience. This information is potentially valuable for identifying interventions and for understanding risks and prioritising resources.

What Factors Affect Resilience Against Pests and Pathogens?

The breadth of potential impacts from tree pests and pathogens means there are many ways of exploring the resilience of trees and forests. These encompass the spread of pests and pathogens, tree damage and mortality, and the subsequent consequences for ecosystem services. We considered literature relevant to this topic with which the review team (which includes experts on forest ecology, management, and policy, and on tree pests and pathogens) were familiar, and we discussed scope internally and with representatives from the funding body. This suggested that investigating factors influencing pest/pathogen spread, abundance, damage and mortality would be tractable and would also inform an understanding of the resilience of ecosystem services (e.g. timber production, carbon stocks, biodiversity), since these are affected by tree damage and mortality. Examples of the types of questions that might be examined within this context include:

- What factors affect the spread and abundance of tree pests and pathogens?
- What factors affect the damage and mortality caused by tree pests and pathogens?

Although these questions avoid using the term resilience due to the ambiguity and potential breadth of definitions (Haines-Young & Potschin 2010), in practice the above questions

primarily relate to the resistance and recovery concepts. For example, the first question might consider whether forests with certain characteristics are more or less resistant to the spread of pests and pathogens. Similarly, the second question might examine what determines how effectively forests can resist pest and pathogen impacts, or recover from such impacts over time.

The above questions potentially encompass a range of factors and outcome metrics. As such, the foundations for these questions could be established through systematic mapping. Systematic maps collate and categorise a body of evidence on a broad question, but do not attempt to synthesise this evidence (CEE 2013; James et al. 2016). Instead, information extracted from the literature is stored in a searchable database, allowing users to identify and locate primary research on questions of interest (e.g. specific interventions or outcomes). Systematic maps also provide the basis for more targeted syntheses, by identifying specific questions in which there is substantial existing research. Similarly, evidence gaps detected during the mapping exercise may represent priorities for future primary research. The approach is therefore increasingly applied to broad topics for which an overview of the state of current evidence is valuable (e.g. Bernes et al 2015; Haddaway et al. 2016; Papathanasopoulou et al. 2016), and a similar method has also been used to explore climate change resilience (Haines-Young & Potschin 2010). Based on this reasoning, we chose to produce a systematic map encompassing the factors that influence the spread of tree pests and pathogens, and the factors that affect the damage and mortality caused (i.e. encompassing both of the bullet points above). Reflecting the priorities of the funding body for this work (Defra), we focused on temperate and boreal regions and in particular ensuring relevance to the UK. We began by identifying a series of potentially relevant factors in this respect, as displayed in Figure 1 (see Table 1 for rationale).

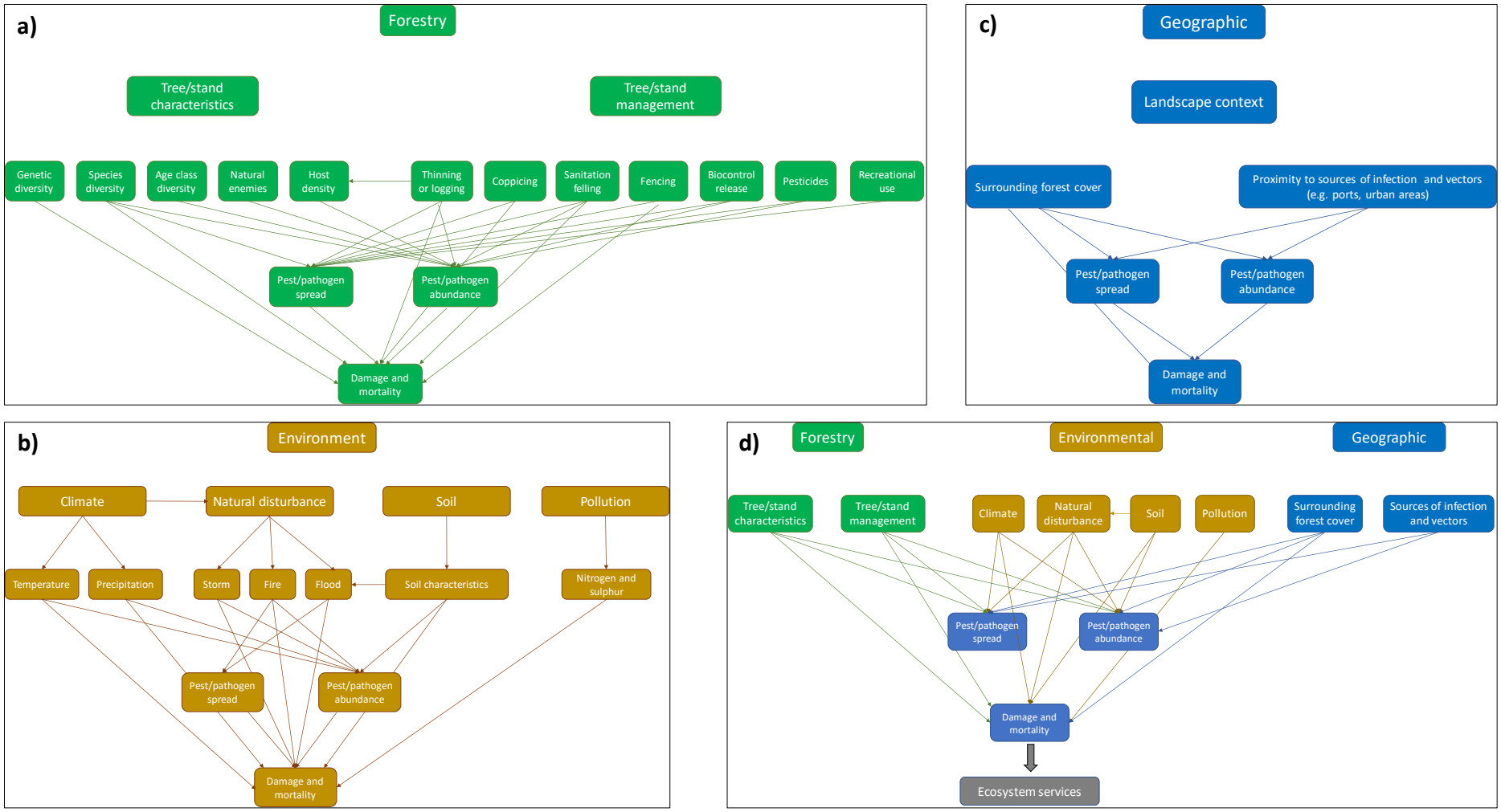

Figure 1: Logic network illustrating factors potentially affecting resilience to pests and pathogens. Factors (e.g. 'Genetic Diversity', 'Temperature', 'Surrounding Forest Cover') are linked to some or all of the resilience-related outcomes – 'Pest/pathogen Spread', 'Pest/pathogen abundance' and 'Damage and Mortality'. Factors are also grouped in Categories (e.g. 'Tree/Stand Characteristics', 'Climate', 'Landscape Context'), which are then placed within broader themes relating to **(a)** Forestry, **(b)** Environment, and **(c)** Geographic. Figure **(d)** displays each of the themes and categories, and the link between these topics and ecosystem services. For details and rationale for each factor, see Table 1.

Table 1: Factors potentially affecting the spread and abundance of pests and pathogens, and the damage/mortality caused. Related factors are grouped together into categories and then placed within a broader theme. Some factors could affect abundance and spread by influencing the movement or build-up of pest/pathogen populations (resistance). Similarly, factors could affect the magnitude of damage or mortality (resistance), the recovery from such impacts (recovery) or the capacity to reduce damage and mortality in future (adaptation). Brief rationale for each factor is provided, along with whether the effect on pest/pathogen spread, abundance or damage is likely to be positive (+), negative (-), or context dependent (+/-). It is assumed that any factor that could affect spread or abundance could also indirectly affect damage/mortality. **This table makes no judgment on the importance of each factor in practice**

Theme	Category	Factor	Potentially Affects	Rationale	Aspect of resilience
ENVIRONMENTAL	*Climate*	Temperature	Abundance	Pest/pathogen abundance greatest in an optimum temperature range	Resistance (+/-)
			Damage	Temperature may affect tree stress, and thereby capacity to prevent or recover from impacts	Recovery (+/-)
		Precipitation	Abundance	Pest/pathogen abundance greatest in an optimum precipitation range	Resistance (+/-)
			Damage	Precipitation may affect tree stress, and thereby capacity to prevent or recover from impacts	Recovery (+/-)
	Natural disturbances	Storms	Abundance	Damage caused by storms could create new habitat for pests/pathogens	Resistance (-)
			Damage	Damage caused by storms could affect tree stress, and thereby the capacity to prevent or recover from impacts	Resistance (-) Recovery (-)
		Fire	Spread	Fire could displace animals that are vectors of pests or pathogens	Resistance (-)
			Spread	Fire could restrict spread by reducing tree density or increasing distance between forest patches	Resistance (+)
			Abundance	Damage caused by fire could create new habitat for pests/pathogens	Resistance (-)
			Abundance	Fire could eradicate/reduce pest or pathogen sources	Resistance (+)
			Damage	Fire damaged trees and new growth could be susceptible to pests and pathogens	Resistance (-) Recovery (-)
		Flooding	Spread	Water may be a vector for some pests or pathogens	Resistance (-)
			Damage	Flooding may damage roots and change soil characteristics, reducing the capacity to prevent or recover from pests/pathogens	Resistance (-) Recovery (-)
	Soil	Soil characteristics (soil type, moisture, pH)	Abundance	Pathogen persistence may be affected by soil characteristics (e.g. soil type, moisture).	Resistance (+/-)
			Damage	Soil characteristics could affect tree stress and hence the capacity to prevent or recover from pest/pathogen impacts	Resistance (+/-) Recovery (+/-)
	Pollution	Nitrogen or sulphur pollution	Damage	May affect tree stress, and thereby the capacity to prevent or recover from damage	Resistance (-) Recovery (-)

Theme	Category	Factor	Potentially Affects	Rationale	Aspect of resilience
FORESTRY	*Stand characteristics*	Tree genetic diversity	Abundance	High genetic variation increases probability some trees will be resistant to the pest/pathogen, and the capacity to evolve to reduce future damage	Resistance (+) Adaptation (+)
		Tree species diversity	Spread	High tree diversity may reduce the ability of species-specific pests/pathogens to locate suitable hosts	Resistance (+)
			Abundance	High tree diversity reduces the potential for populations of species-specific pests/pathogen to build-up	Resistance (+)
			Abundance	High tree diversity may favour natural enemies that can control the abundance of arthropod pests	Resistance (-)
		Tree age class diversity	Abundance	High age class diversity makes build-up of organisms that target particular tree life stages less likely	Resistance (+)
		Host tree density	Abundance	High host density favours build-up of species-specific pests and pathogens	Resistance (-)
		Natural enemies	Abundance	May prevent populations of pests increasing, or reduce populations following outbreaks	Resistance (+)
	Tree/stand management[1]	Thinning, selective logging	Spread	Intervention may inadvertently spread the pest/pathogen	Resistance (-)
			Abundance	Reduces the number of potential host trees in the stand or landscape	Resistance (+)
			Damage	May cause additional stress that affects the capacity of trees to prevent or recover from damage	Resistance (-) Recovery (-)
		Clearfelling	Spread	Intervention may inadvertently spread the pest/pathogen	Resistance (-)
			Abundance	Reduces the number of potential host trees in the stand or landscape	Resistance (+)
			Damage	May cause stress that affects the capacity of trees to prevent or recover from damage	Resistance (-) Recovery (-)
		Sanitation felling (to control pest/pathogen)	Spread	Removing infected or potential hosts may contain pest/pathogen	Resistance (+)
			Abundance	Removing infected or potential hosts may restrict the build-up of pest/pathogen populations	Resistance (+)
			Damage	Healthy trees may be damaged/removed (some of which may have been resistant)	Recovery (-)
		Coppicing	Spread	Intervention may inadvertently spread the pest/pathogen	Resistance (-)
			Damage	May cause additional stress that affects the capacity of trees to prevent or recover from damage	Resistance (-) Recovery (-)
		Fencing	Spread	May prevent the movement of vectors including visitors	Resistance (+)
			Damage	May restrict access by mammals, which could inhibit recovery by browsing regeneration	Recovery (+)

Theme	Category	Factor	Potentially Affects	Rationale	Aspect of resilience
FORESTRY (contd.)	*Tree/stand management (contd.)*	Deliberate biocontrol release	Spread	Intervention could inadvertently spread pests and pathogens	Resistance (-)
			Abundance	May prevent populations of pests increasing, or reduce populations following outbreaks	Resistance (+) Recovery (+)
		Pesticide use	Spread	Intervention could inadvertently spread pests and pathogens	Resistance (-)
			Abundance	May prevent populations of pests increasing, or reduce populations following outbreaks	Resistance (+) Recovery (+)
		Recreational use	Spread	May inadvertently spread pests or pathogens	Resistance (-)
GEOGRAPHIC	*Landscape context*	Surrounding forest cover	Spread	Large areas of contiguous forest may favour the dispersal of tree pests and pathogens	Resistance (-)
			Damage	High landscape connectivity allows gene flow and dispersal between tree populations	Recovery (+) Adaptation (+)
		Proximity to sources of infection (e.g. ports) and vectors (e.g. urban)	Spread	Trees closer to sources of pests and pathogens may be more likely to be infected (e.g. urban areas/ports).	Resistance (-)
			Abundance	Trees closer to sources of infection may harbour a greater abundance of pests and pathogens.	Resistance (-) Recovery (-)

[1] We have not included continuous cover forestry as a management factor because it potentially encompasses several more specific practices (e.g. coppicing, selective logging), but will revisit the suitability of the tree/stand management factors when coding studies

Objectives of the Review

The review aims to collate and categorise research on the following questions

1) The factors affecting the spread and abundance of tree pests and pathogens
2) The factors affecting the damage and mortality caused by tree pests and pathogens

This information will be used to generate several outputs, including:

- A searchable database that can be used to assist policymakers in locating relevant evidence to (i) inform interventions that may increase resistance against pests and pathogens or recovery from impacts, and (ii) understand the risk from pests and pathogens, by identifying factors that may affect resistance and recovery.
- Identification of questions for which there is sufficient evidence and interest in more targeted syntheses (and provide the foundation for such work).
- Identification of priority gaps in the evidence base to target new research.

These objectives will be achieved by classifying all relevant studies according to a range of characteristics, including: which of the factors in Table 1 were investigated, what outcome metrics were determined (e.g. pest/pathogen abundance, damage etc.), and study characteristics (tree species, study type, region etc.).

Primary Question

We amalgamated the two questions above into a single primary question as follows:

'What evidence exists on the factors affecting the spread and abundance of tree pests and pathogens, and the damage and mortality caused by tree pests and pathogens?'

To components of the primary question will be:

Population: Trees and forests in temperate and boreal regions

Intervention/exposure: Any of the factors in Table 1, encompassing interventions (e.g. management) and exposures (e.g. climate, pollution)

Comparator: Trees or forests that differ in the Intervention/Exposure spatially and/or temporally.

Outcome metric: Measures of pest/pathogen occurrence, abundance, spread, damage or mortality.

Secondary Questions

Secondary questions will be adapted and added as the map develops, and could encompass:

- To what extent does evidence consider factors that are (in principle) amenable to management?
- To what extent does evidence consider resistance versus recovery from impacts?
- To what extent does evidence consider resilience against specific pests and pathogens vs. resilience against all pests and pathogens?

Methods

Search Strategy

Search String

Relevant primary literature often does not use the specific term resilience. For example, a study examining how landscape heterogeneity affects the spread of a pathogen might not expressly refer to resilience (especially in the title or abstract) but would still be informative. As such, search strings will not be restricted to resilience concepts. The search terms are designed to reflect the Population, the Pest/Pathogen, the Intervention/Exposure (i.e. factors potentially affecting spread, abundance or impacts), and the Outcome Metric (Table 2). The

159 ‘pest/pathogen’ component of the search string was established by expert consultation and
160 using recent literature to identify priority organisms. Reflecting the interest of the funding
161 body, we compiled a list using pests and pathogens of greatest concern in the UK (Forestry
162 Commission 2018; Freer-Smith & Webber 2017) and also consulted Dr Joan Webber (Principal
163 Pathologist, Forest Research). Terms include the Latin genus name and common name(s).
164 Because this search strategy may result in some level of UK bias in our results, we also used
165 several general terms such as ‘pathogen’, ‘arthropod’, as well as genus names (rather than
166 individual species names). As such, we are confident that non-UK studies will be returned
167 reliably.

Table 2: Search string and number of hits returned (Scopus, February 2019)

	Search String	Hits
Population	(Forest* OR woodland* OR tree OR trees OR woodland* OR woodlot*)	969,680
	AND	
Pest/pathogen	(insect OR insects OR arthropod* OR pest OR pests OR fungi OR fungus OR fungal OR nematod* OR pathogen* OR bacteri* OR *Adelges* OR *Agrilus* OR *Anoplophora OR Aproceros OR Armillaria OR Blumeriella OR Bursaphelenchus OR Brenneria OR Bursaphelenchus* OR *Candidatus* OR *Cameraria* OR *Cephalcia* OR *Ceratocystis* OR *Choristoneura* OR *Coryneum* OR *Cronartium* OR *Cryphonectria* OR *Cryptostoma* OR *Cylindrocladium* OR *Dendroctonus* OR *Dendrolimus* OR *Dothistroma* OR *Dryocosmus* OR *Ellatobium* OR *Erisyphe* OR *Erwinia* OR *Fusarium* OR *Gilpinia* OR *Gremmeniella* OR *Guignardia* OR *Heterobasidion* OR *Hylobius* OR *Hymenoscyphus* OR *Ips* OR *Lymantria* OR *Megastigmus* OR *Neonectria* OR *Ophiostoma* OR *Phaeocryptopus* OR *Phellinus* OR *Phomopsis* OR *Phytophthora* OR *Pissodes* OR *Platypus* OR *Polygraphus* OR *Pseudomonas* OR *Pulvinaria* OR *Pristiphora* OR *Rhabdocline* OR *Rhamicloridium* OR *Seiridium* OR *Sirococus* OR *Splanchnonema* OR *Thaumetopoea* OR *Xylella* OR *Xylosandrus* OR *Zeiraphera* OR {oak decline} OR {ash dieback} OR (beetle* AND bark OR buprestid OR {Asian longhorn*} OR {Asian long-horn*} OR wood-boring OR {wood boring} OR Ambrosia) OR (blight* AND box OR chestnut* OR fire OR holly OR needle*) OR {blister rust*} OR {budworm*} OR (canker* AND coryneum OR juniper OR bleeding OR Phomopsis OR pitch) OR Chalara OR {cherry leaf spot} OR {Cricket bat willow disease} OR {Dutch elm disease} OR {Emerald ash borer*} OR {gypsy moth} OR {gypsy moths} OR {larch budmoth*} OR {leaf miner*} OR {Massaria disease} OR (mildew* AND plane OR oak OR {Indian bean tree} OR {Horse chestnut powdery}) OR (moth* AND lappet OR processionary OR {Siberi an coniferous silk}) OR (needle cast* AND Swiss OR Rhabdocline) OR {Oak decline} OR {Oak pinhole borer} OR {Oak wilt} OR {Pinewood nematode*} OR {pine weevil*} OR {root rot*} OR {Elm yellows} OR (sawfl* AND larch OR {Elm zig-zag} OR {European spruce}) OR {sooty bark} OR {sudden oak death} OR (wasp* AND gall* OR {Douglas fir seed}) OR {woolly aphid})	100,701
	AND	
Intervention or exposure	({forest age} OR {woodland age} OR {stand age} OR {tree age} OR {forest cover} OR {forest area} OR {woodland area} OR {forest size} OR {woodland size} OR {species diversity} OR {tree diversity} OR {host density} OR {tree density} OR manage* OR silvic* OR felling OR felled OR {sanitation felling} OR coppice OR coppiced OR coppicing OR thinning OR thinned OR	53,178

	logging OR logged OR harvest* OR {selective harvesting} OR {biological control*} OR biocontrol* OR {natural enem*} OR predat* OR parasitoid* OR pesticide* OR insecticid* OR fungicid* OR nematicid* OR herbicid* OR antimicrob* OR molluscocid* OR climat* OR temperature* OR rainfall* OR precipitation OR drought* OR {water stress*} OR recreation* OR connect* OR fragment* OR {landscape heterogeneity} OR {landscape structure} OR {habitat heterogeneity} OR {habitat structure} OR {habitat configuration} OR {species richness} OR {species composition} OR {species abundance} OR {host abundance} OR {genetic diversity} OR {genetic richness} OR {genetic variation} OR {canopy cover} OR {canopy density} OR {sulphur deposition} OR {sulphur pollution} OR acidification OR {nitrogen deposition} OR {nitrogen pollution} OR {air pollution} OR {water pollution} OR fire OR fires OR storm* OR flood* OR wind* OR (soil* AND clay OR peat* OR sandy OR silt* OR loam* OR waterlogged OR nutrient* OR pH) OR {soil chemist*} OR {soil moisture} OR {soil type*} OR {soil condition} OR {soil health})	
	AND	
Outcome metric	(spread* OR outbreak* OR distribut* OR disturb* OR disease* OR infest* OR epidem* OR abundance* OR incidence* OR damage* OR mortalit* OR resist* OR recover* OR resilien* OR adapt* OR transform* OR herbiv* OR {dieback} OR {die-back} OR {crown die-back} OR {crown dieback}))	36,471

Bibliographic Databases

The following publication databases will be searched for relevant literature (University of Exeter subscription). All searches will be conducted with English search terms and only English-language results will be included. Although this approach may omit some relevant literature, we did not have sufficient resources to search in other languages and so the search emphasises the areas of greatest relevance for our stakeholders.

1. Scopus (http://www.scopus.com/)
2. Web of Science Core Collections (http://wok.mimas.ac.uk/)

Specialist Websites

The following specialist websites will be searched for relevant literature

1. Canadian Environmental Assessment Agency (https://www.canada.ca/en/environmental-assessment-agency.html)
2. Euroforest Portal (http://forestportal.efi.int/)
3. European Commission Joint Research Centre (http://ec.europa.eu/jrc/)
4. European Environment Agency (http://www.eea.europa.eu)
5. Finnish Forest Research Institute (http://www.metla.fi/index-en.html)
6. Finland's Ministry of Environment (http://www.ym.fi/en-US)
7. Forestry Commission (https://www.forestry.gov.uk/)
8. Joint Website for Finland's Environmental Administration (http://www.ym.fi/en-US)
9. Ministry of Natural Resources and Forestry (Ontario, Canada); https://www.ontario.ca/page/ministry-natural-resources-and-forestry)
10. Natural England (http://publications.naturalengland.org.uk)
11. Natural Resources Canada (http://www.nrcan.gc.ca)
12. Natural Resources Wales (http://libcat.naturalresources.wales)
13. Norwegian Environment Agency (http://www.miljodirektoratet.no/en/)
14. Oregon Forest Resources Institute (https://www.oregonforests.org/)
15. Saint Petersburg Forestry Institute (http://spb-niilh.ru/en)
16. Scottish Natural Heritage (http://www.snh.gov.uk)
17. Swedish Environmental Protection Agency (http://www.swedishepa.se/)

18. The Swedish Forestry Agency (https://www.skogsstyrelsen.se/en/)
19. UK Centre for Ecology and Hydrology (http://www.ceh.ac.uk)
20. UK Department for Environment, Food & Rural Affairs (Defra) (http://randd.defra.gov.uk)
21. UK Environment Agency (http://www.environmentagency.gov.uk)
22. UK Forest Research (http://www.forestry.gov.uk)
23. United Nations Environment Programme (http://www.unep.org)
24. US Environmental Protection Agency (http://www.epa.gov)
25. US Forest Service (https://www.fs.fed.us)

Other literature searches

We will search the bibliographies of any review articles retrieved that satisfy the inclusion criteria.

Estimating the comprehensiveness of the search

To test the search string, RS provided a list of potentially relevant studies that had not been considered during initial development and testing of search terms (Table 3). We assessed the relevance of each article using the inclusion criteria, but retained all articles for the search test in order to also provide an indication of search specificity. We then used the search string in Table 2 and the resulting hits from Scopus to check whether the studies identified were returned. As shown by Table 3, all of the relevant studies were found by the search, but the two studies suggested that were not regarded as relevant were not returned.

Table 3: Test of search terms. Potentially relevant studies suggested by RS to test the search terms. We first determined whether each study was relevant, using the inclusion criteria described below. The table shows whether each of these articles are returned by each component of the search string. All studies identified as relevant prior to the search were retrieved successfully, whilst studies that were not relevant (grey) omitted at least one part of the search string and so were not returned.

Reference	Title	Relevant to systematic map?	Population	Pest/ pathogen	Intervention	Outcome
Brown et al. 2018	Predisposition of forests to biotic disturbance: Predicting the distribution of Acute Oak Decline using environmental factors	Yes	Yes	Yes	Yes	Yes
Chakraborty et al. 2017	Influence of multiple biotic and abiotic factors on the crown die-back of European beech trees at their drought limit	No, study does not address impact of pests/pathogens on tree health	Yes	No	Yes	Yes
Cienciala et al. 2017	Recent spruce decline with biotic pathogen infestation as a result of interacting climate, deposition and soil variables	Yes	Yes	Yes	Yes	Yes
Jactel & Brockerhoff 2007	Tree diversity reduces herbivory by forest insects	Yes	Yes	Yes	Yes	Yes
Kabrick et al. 2008	The role of environmental factors in oak decline and mortality in the Ozark Highlands	No, study does not address impact of pests/pathogens on tree health	Yes	No	Yes	Yes
Moore et al. 1991	Herbivory by insects on oak trees in pure stands compared with paired mixtures.	Yes	Yes	Yes	Yes	Yes
Pasquier-Barre et al. 2001	Relationship of Scots pine clone characteristics and water stress to hatching and larval performance of the sawfly Diprion pini (Hymenoptera: Diprionidae).	No, study does not address outcome metrics specified in inclusion criteria	Yes	Yes	Yes	No

Article Screening and Study Eligibility Criteria

Screening Strategy and Consistency Checking

All articles returned by the search will be screened for relevance by one reviewer using the inclusion criteria described below. Article relevance will first be assessed based on the title, then based on the abstract. A random sample of studies will be independently screened for relevance by a second reviewer at the title (n=850), abstract (n=190) and full text stage (n=40). At each stage, the number of studies to be independently assessed by a second reviewer is the approximate number that can be processed within a day by experienced reviewers (Haddaway & Westgate, 2018; predictER, 2019). For each review stage, dual screening should therefore take approximately one day. Any disagreements during this process will be resolved by discussion and the eligibility criteria will be refined if necessary. The between-reviewer repeatability of decisions will be evaluated using a kappa test. If kappa scores are <0.6 (indicating below moderate repeatability), the inclusion criteria will be refined and the test will be repeated. This process is designed to give confidence that screening by a single reviewer is justifiable, to minimise subjectivity in decisions over article inclusion, and to ensure that such decisions are repeatable. All articles retained after abstract screening will then be assessed for relevance at the full-text stage by a single reviewer. If abstracts are not viewable within a publication database or if article relevance is unclear at the title or abstract screening stage, the article will be retained. If potentially relevant articles reach the full-text stage but cannot be obtained, we will contact the corresponding author to try to obtain a copy. A record will be kept of any articles that appeared to be relevant at title or abstract stage but for which a full-text could not be obtained. Reviewers will not assess article relevance for studies on which they are an author – any such cases will be handled by another member of the review team. To maintain transparency (and provide an additional resource), all articles read at full-text but subsequently excluded will be listed and the reason for exclusion will be documented

Inclusion Criteria

The proposed inclusion criteria were agreed through consultation within the project team and with the key funders and stakeholders for the work (Defra). Whilst we recognise that the restriction to studies published in English will omit some relevant papers, we lacked the resources to reliably search and translate studies and so elected to ensure that the area of greatest priority for the funding body was effectively captured. Note also that some studies not meeting other inclusion criteria may still provide valuable insights for forest managers and policymakers (e.g. studies examining pest/pathogen reproductive cycles and other biological characteristics).

LANGUAGE	Studies published in English.
DATE	No date restrictions will be applied.
POPULATION	Managed and unmanaged trees (including seedlings and urban trees) and wooded areas in temperate or boreal regions. In the case of managed trees and wooded areas (including tree plantations), studies will be included where the intended or potential resource extracted from the trees (if any) is not food – i.e., including biofuel, fibre, timber, amenity, conservation. Therefore, trees within agroforestry systems will be included whereas food-producing orchards will be excluded. The impact of pests/pathogens on wood post-harvest is outside the scope of this review. Studies can be carried out under laboratory, greenhouse, nursery or field conditions, and can focus on a single tree or on stands or forests.
INTERVENTION OR EXPOSURE	Study must consider at least one of the factors listed in Table 1, in relation to pests and pathogens. 'Pests' includes arthropods and nematodes, but does not include mammals (e.g. deer, squirrel, moose). 'Pathogens' includes fungi and bacteria. Studies considering impacts from individual pests/pathogens will be included, as will studies considering impacts from all pests/pathogens (e.g. insect herbivory damage not limited a named organism).
COMPARATORS	Trees or forests that differ in any of the factors in Table 1 spatially and/or before-after studies examining the effect of any factor in Table 1.

OUTCOMES	Metrics relating to the abundance or spread of a pest or pathogen or the damage or mortality caused by a pest or pathogen. Metrics can be at any scale (e.g. leaves, trees, stand, region). Studies that *only* consider factors affecting the impact of pests and pathogens on outcome metrics that have not been specified here will be excluded but noted for potential follow-up. Metrics must be directly determined (e.g. by field observation, remote sensing etc.) rather than predicted based on models of climate, host density etc.
STUDY TYPE	Primary research carried out under field, nursery, greenhouse, or laboratory conditions. Studies must examine how differences in the Outcome Metric for the Population relate to one or more of the Interventions/Exposures, and can involve temporal and/or spatial comparisons. Studies may be observational or experimentally manipulate the Intervention/Exposure or the pest/pathogen. Review articles in with our primary question as a prominent component will also be retained. Studies that model presence/absence/dispersal or that are primarily focused on the biology of the pest or pathogen will not be included (e.g. studies examining how temperature affects insect productivity or survival, or aiming to identify optimal growth conditions for particular organisms). Studies that only examine the abundance or impact of pests/pathogens without relating this to the Intervention will not be included. Qualitative studies will not be explicitly excluded, but we note that these are unlikely to be captured as reliably as quantitative studies given the search strategy and other inclusion criteria. We will reflect this when interpreting systematic map outputs.

Study Validity Assessment

We do not intend to critically appraise included studies

Data Extraction and Study Coding

Information will be extracted from all studies read at full-text that satisfy the inclusion criteria.

If information is unclear, we will contact the corresponding author for clarification. Table 4

provides an example of the type of information that we intend to extract from each study. Appendix 1 contains more detailed information on the proposed variables in the final database and provisional data extraction guidelines – the exact nature of the information to be extracted will also be informed and adapted as the map progresses. For example, because of the range of management practices and potential overlaps in terminology, we will extract descriptive information on the practice being considered (as stated by the study) and will subsequently code each study based on this information. Before data extraction proceeds on all retrieved articles, the repeatability of the data extraction process will be checked. Two reviewers will independently extract data from 10 articles, with clarification of the approach if needed.

Table 4: Example of the data extracted from a relevant study. See Appendix 1 for more detailed explanations of each coding variable. Y=YES, N=NO

Data Grouping	Coding variable	Extracted data
Article details	**Author_list**	B Castagneyrol; D Bonal; M Damien; H Jactel; C Meredieu; E Muiruri; L Barbaro
	Lead_author_institution	University of Bordeaux
	Funding_source	French Ministry of Ecology; French National Research Agency
	Article_title	Bottom-up and top-down effects of tree species diversity on insect herbivory
	Pub_year	2017
	Source	Ecology and Evolution
	Publication type	Journal
Study details	**Study question(s)**	Is herbivore damage greater in monocultures than in mixed species stands? Does water stress influence insect herbivory? Does predation pressure affect the leaf area removed by herbivores?
	Start_year	2015
	End_year	2015
	Study_duration	<1 year
	Intervention_start_year	2008 (species mixture); 2015 (irrigation)
	Intervention_end_year	2008 (species mixture); 2015 (irrigation)
	Study_type	Experimental (field)
	Scale_sampling	Leaf samples from 32 plots within 8 blocks; total area 12ha; SW France
	Scale_intervention	Stand
	Resilience_component	Resistance/Unclear

Data Grouping	Coding variable	Extracted data
Population	**Population_description**	**Stand age**: 7 years. **Tree species**: *Betula pendula, Quercus robur, Q. pyrenaica, Q. ilex, Pinus pinaster*. **Scale of outcome metric**: Individual trees **Forest type:** Broadleaved, Conifer, and Mixed all considered **Forest diversity:** Monoculture and mixed stand both considered **Type of system:** Experimental forest plot
	Geographic_information	**Country:** SW France
	Site co-ordinates	(44°440 N, 00°460 W)
Pest/pathogen	**Taxon**	ALL
	Pest/pathogen name	N/A
	Native_to_study_region	Both
Environmental factors	**Temperature (Y/N)**	N
	Precipitation (Y/N)	Y
	CC_measures	N
	Nat_disturb	N
	Soil_char	N
	Pollution	N
Forestry factors	**Tree_gen_var (Y/N)**	N
	Tree_sp_div (Y/N)	Y
	Tree_age_div (Y/N)	N
	Host_density_(Y/N)	N
	Tree_density_(Y/N)	N
	Nat_enemies_(Y/N)	Y
	Nat_enemy_name	Birds; Small mammals; Arthropods
	Management practice	N/A
	Biocontrol (Y/N)	N
	Describe_biocontrol	N/A
	Pesticide (Y/N)	N
	Describe_pesticide	N/A
	Recreation (Y/N)	N
	Recreation_measure	N/A
Geographic factors	**Forest_cover_(Y/N)**	N
	Forest_cover_measure	N/A
	Prox_to_source_(Y/N)	N
	Prox_to_source_measure	N/A
Other interventions or exposures	**Other_Int_Exp**	N
Outcome metrics	**Spread_(Y/N)**	N
	Spread_measure	N/A
	Abundance_(Y/N)	N
	Abundance_measure	N/A
	Damage_(Y/N)	Y
	Damage_measure	Leaf damage
	Mortality_(Y/N)	N
	Mortality_measure	N/A
	Other_outcome_metrics	Insectivory
Additional notes	**Comments**	N

Study Mapping and Presentation

The map will generate a searchable database of all relevant articles, categorised according to the data extracted. The final report will describe the review process and will identify topics where there is a dearth of research and topics where there is substantial existing research. A range of descriptive figures, such as co-occurrence matrices and maps, will accompany the report. Literature gaps will also be discussed in relation to policy priorities, and stakeholders will be consulted in order to identify potentially important novel research topics. Similarly, topics where there is a large volume of evidence will be considered as prospective subjects for more targeted systematic reviews.

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Declarations

The authors declare no competing interests

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Appendix 1: Provisional guidelines on extracting information from each study. The exact nature of the information to be extracted will also be informed and adapted as the map progresses

Data Grouping and Description	Coding Variable	Variable Description	Data Type
ARTICLE DETAILS (bibliographic information for study)	**Author_list**	List of authors, surnames only and in order reported in publication.	Descriptive
	Lead_author_institution	First author institution(s)	Descriptive
	Funding_source	The funding bodies as listed in the study acknowledgements	Descriptive
	Article_title	The title of the article in full	Descriptive
	Pub_year	The year of publication, if not published = NA	Categorical
	Source	Full name of publisher of article (e.g. name of academic journal, name of government department, website etc.)	Descriptive
	Publication type	E.g. academic journal or book; government report; other report	Categorical
STUDY DETAILS (spatial and temporal scale, study question etc.)	**Study question(s)**	List key questions or objectives to be addressed by study as reported by authors	Descriptive
	Start_year	First year in which data on the outcome metric(s) were collected. For reviews that contain primary research with multiple start years = N/A.	Categorical
	End_year	Final year in which data on the outcome metric(s) were collected. For reviews that contain primary research with multiple end years = N/A.	Categorical
	Study_duration	Number of years between the start and end year of data collection	Categorical
	Intervention_start_year	The year in which an intervention (or exposure) commenced (e.g. thinning, pollution event, change in forest cover). Where no start date is reported = NR. For reviews = N/A	Categorical
	Intervention_end_year	The year in which an intervention (or exposure) ended. Where no end date is reported = NR. For reviews = N/A	Categorical
	Study_type	**Experimental (field)**: e.g. field plots comparing different levels of a factor that has been manipulated (e.g. tree diversity) **Experimental (lab/nursery)**: e.g. material planted in laboratory or greenhouse/nursery to examine the effect of a factor **Observational**: collects data from field sites that have not been experimentally manipulated for the purposes of the study **Review:** synthesis of primary research articles that examine one or more factors that may affect the resilience of outcome metric(s)	Categorical

Data Grouping and Description	Coding Variable	Variable Description	Data Type
STUDY DETAILS (contd.)	**Scale_sampling**	The spatial extent over which data on the outcome metric were collected (field studies only). Where reported, record information on the sampled area (e.g. $1m^2$, individual trees or stands), the woodland areas within which multiple samples were collected (e.g. four woodlands ranging in size from $2\text{-}5km^2$) and the regional level that encompasses all sampled sites (e.g. county or state, and the country or countries). Categorical coding will be applied after complete data extraction.	Descriptive
	Scale_intervention	The spatial extent over which an intervention (or exposure) occurs. Categorical coding will be applied after complete data extraction.	Descriptive
	Resilience_component	**Resistance**: if the study examines resistance to impacts, e.g. the outcome metric during/immediately after pest or pathogen exposure, or time-series data examining whether outcome metrics decline. **Recovery**: if the study examines recovery from impacts, e.g. the return to the pre-disturbance state following a known outbreak (calculated either by time-series data or by a snapshot after the event) **Adaptation**: if the study examines changes to the system in response to disturbances that preserve the system and enables it to maintain similar functions. **Transformation**: if the study examines radical changes (either intentional or unintentional) so that the system is fundamentally different. **Unclear**: if none of the resilience components above can be assigned to the study	Categorical
POPULATION (The focal tree species, forest, region etc. – effectively)	**Population_description** (the resilience 'of what')	A description of the population, including: - Approximate tree/stand age (e.g. seedling, mature, mixed-age) - Tree species considered (species names if stated) - Whether the study is assesses the resilience at the level of individual trees or at the level of forests (e.g. forest mortality, crown damage) - Broadleaved, coniferous or mixed - Monoculture or mixed-species - Type of system (e.g. agroforestry, urban, timber plantation, conservation) This variable may be converted into several categorical variables following extraction and depending on the information reported.	Descriptive

Data Grouping and Description	Coding Variable	Variable Description	Data Type
POPULATION (contd.)	**Geographic_information**	**Country**: name of country if study carried out within a single country. **Region**: if study carried out in multiple countries (e.g. 'North America', 'Scandinavia'). **Global**: study not geographically restricted	Categorical
	Site co-ordinates	List the geographical coordinates of study sites as reported (e.g. longitude and latitude, degrees and minutes).	Categorical
PEST/PATHOGEN CHARACTERISTICS (the resilience 'to what'?)	**Taxon**	**Arthropod:** if the study focuses on the spread/abundance of arthropod pests or the damage caused (either by a single species or in general) **Nematode:** if the study focuses on the spread/abundance of nematode pests or damage caused (either by a single species or in general) **Fungus**: if the study focuses on the spread/abundance of pathogens or the damage caused (either from a single species or in general) **Bacteria:** if the study focuses on the spread/abundance of bacteria or the damage caused (either from a single species or in general) **All**: if the study considers all of the above taxonomic groups, or does not indicate a taxonomic focus.	Categorical
	Pest/pathogen name	Species name, if stated	Descriptive
	Native_to_study_region	**Native**: if the study examines resilience against pests and/or pathogens that are native to the region in which the study is carried out. **Non-native**: if the study examines resilience against pests and/or pathogens that are non-native to the region in which the study is carried out. **Both**: if the study examines resilience against native and non-native pests/pathogens, or does not specify which pests/pathogens are being considered	Categorical
ENVIRONMENTAL FACTORS EXAMINED. Yes/No indication of the environmental factors potentially affecting resilience that the study considers and descriptive information on certain factors.	**Temperature (Y/N)**	**Yes**: if the effect of temperature is assessed	Categorical
	Precipitation (Y/N)	**Yes**: if the effect of precipitation (including drought or water stress) is assessed	Categorical
	CC_measures	If the study is expressly conducted to understand climate change impacts, specify the type of climate change under consideration (e.g. extreme or unseasonal weather	Descriptive
	Nat_disturb	Specify the type of disturbance under consideration (e.g. flood, drought, fire etc.)	Descriptive

Data Grouping and Description	Coding Variable	Variable Description	Data Type
ENVIRONMENTAL FACTORS (contd.)	**Soil_char**	Specify the soil characteristics investigated e.g. soil type (clay, sandy, silt, peat, chalky, loam), pH, moisture, nutrients levels. This variable may be converted into categorical variables following extraction and depending on the information reported.	Descriptive
	Pollution	Nitrogen; Sulphur; Nitrogen & Sulphur; N/A	Categorical
FORESTRY FACTORS EXAMINED. Yes/No indication of the forestry factors potentially affecting resilience that the study considers and descriptive information on certain factors.	**Tree_gen_var (Y/N)**	**Yes**: if the effect of tree genetic variation is assessed	Categorical
	Tree_sp_div (Y/N)	**Yes**: if the effect of tree diversity or species richness is assessed, including studies comparing monocultures with plantations.	Categorical
	Tree_age_div (Y/N)	**Yes**: if the effect of tree or stand age (e.g. young vs. mature) or in age class diversity (e.g. even vs. uneven-aged) is assessed	Categorical
	Host_density_(Y/N)	**Yes**: if the effect of the density of tree species that are hosts to the pest/pathogen is assessed, including where both hosts and non-host species are examined.	Categorical
	Tree_density_(Y/N)	**Yes**: if the effect of tree density is assessed but where the species examined are not known hosts or it is unspecified.	Categorical
	Nat_enemies_(Y/N)	**Yes**: if the effect of predators or parasitoids on pests and pathogens is assessed (excluding release of these organisms as biocontrol agents)	Categorical
	Nat_enemy_name	Specify the natural enemy being considered	Descriptive
	Management practice	**The management practice specified by the review.** This variable will be converted into several categorical variables following extraction depending on the information reported.	Descriptive
	Biocontrol (Y/N)	**Yes**: if the effect of predators or parasitoids intentionally released to control pests and pathogens is assessed.	Categorical
	Describe_biocontrol	Specify the organisms involved	Descriptive
	Pesticide (Y/N)	**Yes**: if the effect of pesticide is assessed	Categorical
	Describe_pesticide	Specify the pesticide used	Descriptive
	Recreation (Y/N)	**Yes**: if the impact of recreational uses of woodlands are assessed e.g. visitor numbers or the impact of different activities such as dog-walking, cycling, horse riding.	Categorical
	Recreation_measure	Specify the type of recreational activity investigated	Descriptive

Data Grouping and Description	Coding Variable	Variable Description	Data Type
GEOGRAPHIC FACTORS EXAMINED. Yes/No indication of the geographic factors potentially affecting resilience that the study considers and descriptive information on certain factors.	**Forest_cover_(Y/N)**	**Yes**: if the effect of forest cover is assessed (including connectivity and landscape heterogeneity)	Categorical
	Forest_cover_measure	Specify which measures related to cover, fragmentation or connectivity are assessed e.g. forest area, patch size, patch number, distance to nearest patch, matrix dissimilarity.	Descriptive
	Prox_to_source_(Y/N)	**Yes**: if the effect of proximity to known or suspected sources of infection is assessed e.g. other woodlands, roads and urban or agricultural areas.	Categorical
	Prox_to_source_measure	Specify the potential source of infection assessed e.g. roads, urban areas.	Descriptive
OTHER INTERVENTIONS OR EXPOSURES	**Other_Int_Exp**	Any additional interventions or exposures examined. Note that these have not been intentionally searched for, and so are provided for information only	Descriptive
OUTCOME METRICS: The outcome metrics used by the study	**Spread_(Y/N)**	**Yes**: where the aim is to assess factors affecting the movement of the pest/pathogen through a landscape	Categorical
	Spread_measure	Specify measure of spread e.g. presence/absence in the context of spatial changes including range changes, rate of spread.	Descriptive
	Abundance_(Y/N)	**Yes:** where the aim is to assess factors affecting the pest/pathogen abundance	Categorical
	Abundance_measure	Specify abundance measure(s), e.g. presence/absence, change over time, biomass, area affected.	Descriptive
	Damage_(Y/N)	**Yes:** where the aim is to study damage caused by pests/pathogens to any part of a tree, or to a stand or woodland.	Categorical
	Damage_measure	Specify the type of damage, e.g. 'Leaf damage', 'Bark damage', 'Crown loss', 'Disease lesions', 'Disease symptoms".	Descriptive
	Mortality_(Y/N)	**Yes:** where tree mortality has been measured.	Categorical
	Mortality_measure	Specify the measures of mortality reported, e.g. 'Mortality', 'Annual mortality', 'Area of mortality', 'Time to mortality'.	Descriptive
	Other_outcome_metrics	Any additional outcome metrics examined. Note that these have not been intentionally searched for, and so are provided for information only	Descriptive
Additional notes	**Comments**	Additional comments on study	Descriptive