

Systematic review of modelling approaches assessing eradication and containment measures for the pinewood nematode (PWN) *Bursaphelenchus xylophilus*

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The declarations of interest of all scientific experts active in EFSA's work are available at <https://open.efsa.europa.eu/experts>.

Abstract

This Scientific Opinion reviews existing models that assess eradication and containment strategies of the pinewood nematode (PWN) *Bursaphelenchus xylophilus*. The objective was to characterise modelling approaches, validation data and methods used to investigate possible interventions. A literature search was conducted in Web of Science and Scopus in October 2025 with no restriction on publication date. After removal of deduplication, 1560 references were recorded. The systematic literature review was conducted in three stages: Phase 1 identified studies reporting spread models; Phase 2 pre-selected models able to represent host-vector systems and intervention measures; and Phase 3 consisted of a structured technical appraisal informed by a set of 85 items covering biological realism, spatial and temporal structure, parameterisation, validation, management scenarios and operational applicability. These items supported qualitative appraisal and were not used for formal scoring. The review retained 125 studies after Phase 1 and 28 after Phase 2. In Phase 3, six modelling studies were identified that investigate the efficiency of actionable intervention protocols for PWN outbreaks. Ordinary differential equation models and several partial differential equation models were not considered sufficient for spatially defined measures, such as clear-cutting and buffer zones, because they lacked the required spatial resolution or biological and operational detail. The most suitable approaches were spatially explicit grid-based, network-based or individual-based models able to represent local spread, landscape heterogeneity and vector-mediated transmission. In these modelling studies, validation efforts addressed space–time patterns of observed outbreak data from different regions. Although none of the six identified modelling studies were suitable for a comprehensive investigation of sets of intervention measures, all were considered potentially adaptable through targeted refinement and improved parameterisation. Required improvements include explicit representation of surveillance and detection, sequential application of measures in response to outbreak development, implementation delays in control measures, incomplete host removal, host dynamics, climate or landscape variability and, where relevant, human-mediated pest dispersal. The review identifies existing models and

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additional capabilities required for quantitative assessment of PWN control and containment strategies.

KEYWORDS

buffer zones, *Bursaphelenchus xylophilus*, clear-cutting, containment, eradication, pest risk management, pine wilt disease, pinewood nematode, spatially explicit models, spread modelling

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1 | BACKGROUND AND TERMS OF REFERENCE

1.1 | Background

European and Mediterranean Plant Protection Organization (EPPO) published a pest risk analysis for *Bursaphelenchus xylophilus* (pinewood nematode (PWN)) in 2009, an EU measure was adopted in 2012 and subsequently updated in 2018. Since then, PWN has been contained in Portugal and detected in several locations in Spain where an eradication approach has been applied. The pest has been recently found in new locations, or in some cases, the trend of new findings is increasing. Thus, experience has been gained for both containment and eradication approaches in the EU. In view of these recent developments, Member States have requested scientific assistance for the revision of the eradication/containment measures, in particular as regards the size of the clear-cut preventive felling and the buffer zones.

1.2 | Terms of Reference as provided by the requestor

EFSA is requested, pursuant to Article 29(1) and Article 31(1) of Regulation (EC) No 178/2002, to provide scientific assistance for the assessment of the effectiveness of the EU measures on PWN.

Task A

Under task A, EFSA is requested to provide a literature review of control measures and a review of existing models which could be used to assess the effectiveness of different clear-cut widths and size of the buffer zone as set out in Decision EU 2012/535 for both containment and eradication strategies. In particular, the review would include models that were published within the last decade and/or after the publication of the EPPO PRA on PWN.

Task B

Under Task B, EFSA is requested to perform modelling to evaluate the effectiveness of clear-cut preventive felling under an eradication strategy, to prevent the spread of *Bursaphelenchus xylophilus* (PWN) in areas of the EU where the pest could establish. The evaluation should incorporate recent scientific findings and available data from outbreaks within the EU territory.

The modelling should consider scenarios reflecting different clear-cutting strategies, including a range of clear-cut widths and, when possible, different geographical contexts, with the aim of supporting the assessment and potential adjustment of current measures. EFSA is also requested to model different scenarios for buffer zone widths under both eradication and containment strategies. These scenarios may include variations in buffer size and the integration of complementary measures, such as enhanced surveillance, to determine combinations that ensure effective pest control.

1.3 | Interpretation of the Terms of Reference

The PWN is a quarantine pathogen and subject to regular legislation and phytosanitary measures aimed at restricting movement and preventing introduction to new areas (Back et al., 2024). PWN was first detected in Europe in 1999 in Portugal, then Spain (2008) and France (2025) where EU eradication measures were implemented. The objective of the current Opinion was the review of existing models which assess the effectiveness of different clear-cut widths and buffer zone sizes, as set out in Decision EU 2012/535, under both eradication and containment strategies for *B. xylophilus*. Thus, the modelling component of Task A of the mandate is addressed. The review of control measures requested under Task A is addressed separately and is not part of the present opinion.

The modelling literature on pine wilt disease includes a broad range of approaches, from non-spatial compartmental transmission models to spatially explicit spread models. For the purposes of the present mandate, and in preparation for the modelling work foreseen under Task B, the objective was not only to identify models addressing pinewood nematode and insect vector populations, but to determine whether they had the structural capacity needed to support the EFSA PLH Panel in the evaluation of the dimensions of intervention measures such as spatial extent, coverage of treatment and temporal horizons.

This report is based on a structured review of scientific literature and a structured technical appraisal of the reviewed models to determine which include a comprehensive evaluation of management strategies of PWN outbreaks or would technically be amendable to do so. Although the terms of reference (ToR) refer to models published within the last decade and/or after the EPPO PRA on PWN, no publication date restriction was applied in order to avoid excluding older studies that might still be methodologically informative. The review was therefore intentionally broad at the identification stage, with model relevance and suitability subsequently considered through staged screening and technical appraisal.

While the present opinion does not provide the modelling assessment requested under Task B, it does structure the landscape of available PWN modelling efforts and appraise them with a view to facilitating a comparative, quantitative evaluation of explicit intervention protocols. It also supports the definition of the practical requirements for subsequent modelling work.

2 | DATA AND METHODOLOGIES

This section describes the approach used to identify, screen and validate studies relevant to the modelling component of Task A of the mandate. The work was based on a structured review of the scientific literature, designed to identify existing models with potential relevance for assessing the effectiveness of different clear-cut widths and buffer zone sizes under eradication and containment strategies for *B. xylophilus* (PWN).

2.1 | Literature search

A structured literature search was conducted to identify published studies describing models relevant to the spread of PWN and to the assessment of spatial management measures under eradication and containment strategies. The search was designed to support a staged review process, beginning with a broad identification of potentially relevant studies and followed by a progressively more detailed screening and appraisal. The overall process is summarised in the following PRISMA flow diagram (Figure 1).

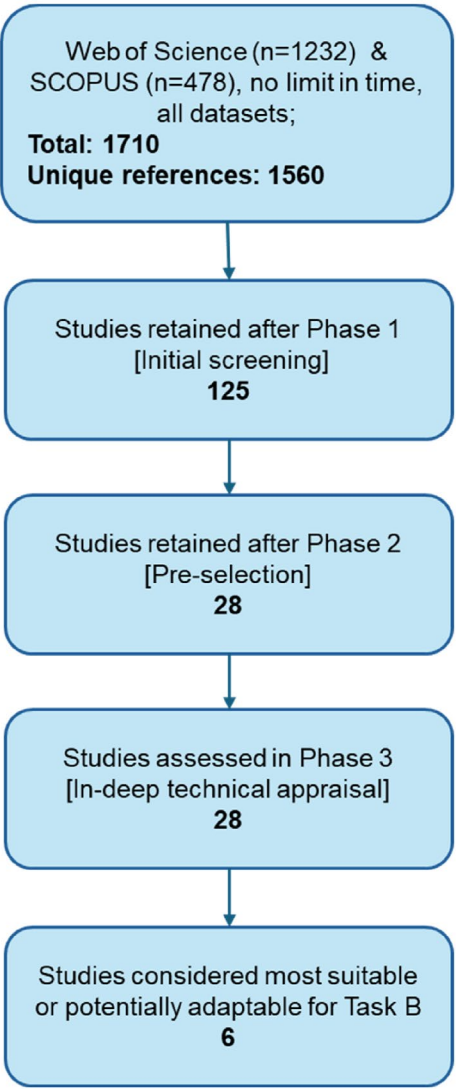


FIGURE 1 Systematic literature review workflow (PRISMA).

2.1.1 | Scope

The scope of the literature search was to identify published studies describing models relevant to the spread of PWN and its insect vector and the assessment of eradication and containment strategies. In line with the ToR, particular attention was given to models that could potentially support the evaluation of spatial management measures, including different clear-cut widths and buffer zone sizes.

The search string was intentionally broad to identify all studies reporting a spread model of PWN or its insect vector. No temporal restrictions were applied to the search, to avoid excluding older studies that might still be methodologically

relevant to the appraisal. The broad scope adopted at the search stage was subsequently complemented by more specific eligibility and screening criteria applied during the different phases of the review (see Section 2.1.2).

2.1.2 | Search strategy and search string

The search string (Figure 2) was implemented in Web of Science (WOS) and Scopus and run on 10 October 2025 and was designed to favour sensitivity and minimise the risk of excluding studies of possible relevance to the objectives.

(("Bursaphelenchus xylophilus" OR "Aphelenchoides xylophilus" OR "Bursaphelenchus lignicolus" OR "dennenhoutaaltje" OR "pine wilt disease" OR "pine wood nematode" OR "pinewood nematode" OR "déperissement des pins" OR "nématode du bois de pin" OR "nématode du pin" OR "Kiefernholz-nematode" OR "nematode del pino" OR "węgorek Sosnowiec" OR "nemátode da madeira do Pinheiro" OR "nematodo de la madera del pino" OR "tallvedsnematod" OR "monochamus" OR "sawyer") AND ("pine wilt disease model*" OR "individual-based" OR "agent-based" OR "grid-based model*" OR "lattice model" OR "network-based model*" OR "mechanistic model*" OR "process model*" OR "spread model*" OR "mathematical model*" OR "disease model*" OR "transmission model*" OR "transmission coefficient" OR "expansion rate" OR "transmission dynamic*" OR "disease dynamic*" OR "spread dynamic*" OR "natural spread" OR "deterministic model*" OR "stochastic model*" OR "dispers* model*" OR "spatially explicit model*" OR "theoretical model*" OR "simulation model*" OR "epidemiological model*" OR "epidemic model*" OR "compartmental model*" OR "SIR model*" OR "spread rate" OR "simulat*" OR "ODE" OR "reaction-diffusion model*" OR "predator-prey model*" OR "differential equation*" OR "PDE" OR "diffusion model*" OR "network model*" OR "cellular automat*" OR "integro-difference equation*" OR "ecological model*" OR "model* for pine wilt disease" OR "population dynamic model*" OR "mathematical system of equations" OR "population dynamic*" OR "individual-based" OR "agent-based" OR "mechanistic model*" OR "kernel"))

FIGURE 2 Systematic literature review: Search string (Web of Science and Scopus) October 2025.

2.1.3 | Eligibility and inclusion criteria

Eligibility and inclusion criteria were applied through a three-phase review process to progressively identify studies relevant to address the mandate. The phased approach was designed to combine sensitivity at the identification stage with progressively targeted assessment of model relevance and potential applicability to Task B.

2.1.3.1 | Phase 1: Initial screening

The objective of phase 1 was to identify all studies reporting a spread model of PWN or its insect vector, including those in which the model was described only in broad terms. At this stage, each reference was screened based on its title and abstract and the criteria were inclusive. References were retained when they met at least one of the following criteria: (i) they described a mathematical model of PWN spread or its insect vector or (ii) they referred to spatial and/or temporal analyses potentially relevant to the assessment of vector-mediated PWN spread. Studies characterising vector flight capacity, movement behaviour, environmental suitability, host distribution or associations between infestation and explanatory variables were not retained unless they included a spread-modelling component.

2.1.3.2 | Phase 2: Preselection

The studies retained from the first screening step were assessed to identify models with sufficient biological and operational relevance to warrant in-depth technical appraisal.

To progress to the next phase, a model had to meet the following criteria: (i) be capable of representing current detection and control measures; (ii) represent vector-mediated spread of PWN and the infection status of host trees; and (iii) not be redundant or superseded by a more recent or more complete implementation of the same modelling framework.

An inventory of the studies assessed during Phase 2 was compiled to support systematic screening and more detailed examination (see Annex A in the supplementary material). As part of this pre-selection, the model type (e.g. ordinary differential equation, partial differential equation, grid-based or individual-based models) was recorded to support interpretation of the model structure and its potential applicability but was not used as a stand-alone selection criterion.

2.1.3.3 | Phase 3: In-depth technical appraisal

Objective of phase 3 was to identify which of the studies selected in phase 2 could potentially be used or adapted to address Task B of the mandate.

The three inclusion criteria for phase 3 were:

- I. the modelling approach should describe the spatial and temporal spread of PWN accounting for the mediating role of the insect vector and provide measurable outputs, such as spread rate, infestation burden or vector density.
- II. the approach demonstrates biological realism using observational data of the dynamics of recorded pest outbreaks.
- III. the model presents an accessible implementation of detailed control measures and management elements such as clear-cutting, buffer zones and effects of alternative surveillance efforts therein.

These criteria favour those models which technically separate parameterisation and validation of the pest-vector-host system dynamics from the experimental manipulation of strategy implementations.

To ensure consistent and transparent comparisons between models in phase 3, each study was evaluated against a structured set of 85 appraisal items. The appraisal implements existing protocols and frameworks of good modelling practice e.g. Overview, Design concepts, and Details (ODD) (Grimm et al., 2006), Purpose, Organisation, Evidence (POE) (Grimm et al., 2020), Transparent and Comprehensive Evaluation (TRACE) (Grimm et al., 2014; Schmolke et al., 2010). This covered bibliographic information, the purpose and intended use case, biological realism, technical characterisation, parameterisation and validation, model parsimony and trustworthiness, treatment of management scenarios, inclusion of human-assisted dispersal processes and notes on strengths, limitations. The assessment template used for the phase 3 appraisal is provided in the supplementary material of the Opinion (see Annex B in the supplementary material).

The comprehensive set of appraisal items enabled models to be systematically prioritised by their suitability to assess the effectiveness of different management strategies for both containment and eradication, while also highlighting their specific strengths and limitations and remaining gaps. The resulting inventory (see Annex C in the supplementary material) was used to support prioritisation of candidate models and specify needs in relation to the modelling requested under Task B.

2.1.4 | Validation

Validation procedures were incorporated into the screening process to support consistency and transparency in study selection.

In phase 1, papers excluded during screening were independently reassessed by a second reviewer and with support from the Artificial Intelligence Distiller tool (DistillerSR, 2026). This step was introduced to reduce the risk of erroneous exclusion at the broad identification stage. The tool was used to support the re-evaluation process, but final inclusion and exclusion decisions were made by the reviewers. In cases of disagreement, the reference was re-evaluated and the final decision was reached by discussion between reviewers.

In subsequent phases, the papers were assessed by two reviewers. Disagreements, where present, were resolved through discussion and consensus. This multi-step validation approach was intended to ensure that potentially relevant studies were not excluded prematurely and that progression through the review stages was based on consistent application of the screening criteria.

3 | ASSESSMENT

3.1 | Literature overview

The systematic literature search retrieved 1710 records in total, comprising 1232 records from Web of Science and 478 from Scopus. After removal of duplicates, 1560 unique references were screened in Phase 1 based on title and abstract, of which 125 were retained for further assessment. Following Phase 2 preselection, 28 studies were taken forward to Phase 3 for in-depth technical appraisal. The references retained after Phase 2 preselection and those selected for Phase 3 appraisal are listed in Table 1.

TABLE 1 References retained after Phase 2 preselection and selected for Phase 3 in-depth technical appraisal. The Phase 2 set included 125 records, of which three were duplicate records not identified during automatic deduplication and are marked with an asterisk (*); therefore, the table lists 122 unique references, including the 28 selected for Phase 3.

References – Phase 2			
Agarwal et al. (2019)	Ahmad et al. (2024)	Ahmad et al. (2023)	Aldwoah et al. (2025)
Ali & Ameen (2020)	Ameen et al. (2024)	Aslam et al. (2021)	Awan et al. (2018)
Awan et al. (2016)	Chawla et al. (2022)	Chen et al. (2021)	Chon et al. (2009)
de la Fuente et al. (2018)	de la Fuente & Beck (2019)	de la Fuente & Saura (2021)	Dimitrijevic & Bacic (2013)
Ding & Yu (2025)	Dong, Hou, & Ding (2023)	Dong, Sui, & Ding (2023)	Dwinell (1994)
El-Mesady et al. (2023)	El-Sayed et al. (2020)	Gordillo & Kim (2012)	Gruffudd et al. (2019)
Halik & Bergdahl (1986)	Hao, Huang, Zhang, Chen, Fang, Guo, Huang, et al. (2025)	Hao, Huang, Zhang, Chen, Fang, Guo, & Zhang (2025)	Hou & Ding (2024a)

(Continues)

TABLE 1 (Continued)

Hou & Ding (2024b)	Hou & Ding (2024c)*	Hou et al. (2025)*	Huang et al. (2008)
Huang et al. (2024)	Huang et al. (2012)	Hussain, Aslam, et al. (2021)	Hussain, Awan, et al. (2025)
Hussain, Ozair, et al. (2025)*	Hussain, Ozair, et al. (2021)	Isaev et al. (1996)	Jung et al. (2024)
Khan et al. (2017)	Khan, Khan, et al. (2018)	Khan, Shah, et al. (2018)	Khan, Ullah, et al. (2018)
Khan et al. (2020)	Khan et al. (2021)	Kim & Park (2024)	Kiselev & Ovchinnikova (1991)
Kumar et al. (2025)	Kumbinarasaiah & Manohara (2025)	Lai & Lai (2000)	Lashari & Lee (2017)
Lee et al. (2007)	Lee & Kim (2013)	Lee (2014)	Lee & Lashari (2014a)
Lee & Lashari (2014b)	Li et al. (2017)	Li, Ding, & Song (2025)	Li, Ding, & Jiang (2025)
Li & Ding (2025)	Liu & Zhang (2022)	Magal & Zhang (2018)	Mao et al. (2012)
Massoun (2022)	Mimura et al. (2004)	Nguyen et al. (2017)	Osada et al. (2018)
Ozair (2014)	Ozair et al. (2016)	Ozair, Hussain, Awan, et al. (2020)	Ozair, Hussain, Shi, et al. (2020)
Ozair et al. (2021)	Ozair et al. (2022)	Padmavathi, Alagesan, et al. (2022)	Padmavathi, Magesh, et al. (2022)
Pang et al. (2018)	Peng et al. (1997)	Preethi et al. (2023)	Pukkala et al. (2014)
Rahman et al. (2018)	Raza et al. (2019)	Raza et al. (2022)	Robinet et al. (2009)
Robinet et al. (2011)	Robinet et al. (2012)	Robinet et al. (2013)	Robinet et al. (2015)
Robinet et al. (2020)	Leiton et al. (2020)	Schafstall et al. (2024)	Shah et al. (2020)
Shah et al. (2024)	Shi & Song (2013)	Shi et al. (2023)	Shigesada et al. (1996)
Shigesada et al. (1998)	Shigesada et al. (2001)	Shigesada et al. (2002)	Shoaib et al. (2023)
Stare et al. (2013)	Tabassum et al. (2022)	Takasu et al. (2000)	Takasu (2009)
Takasu (2009)	Togashi (1980)	Togashi & Shigesada (2006)	Togashi (2025)
Wang & Li (2008)	Wang & Dong (2009)	Wang et al. (2010)	Wang et al. (2024)
Weiss et al. (2019)	Wu et al. (2025)	Xia et al. (2022)	Xu & Yuan (2023)
Yamamoto et al. (2000)	Yoshimura et al. (1999)	Yusuf et al. (2021)	Zhang et al. (2017)
Zhou (2020)	Zhou et al. (2024)		
References – Phase 3			
Agarwal et al. (2019)	Ahmad et al. (2024)	Aldwoah et al. (2025)	Ameen et al. (2024)
Awan et al. (2016)	de la Fuente & Saura (2021)	Dimitrijevic & Bacic (2013)	Ding & Yu (2025)
Dong, Sui, & Ding (2023)	El-Mesady et al. (2023)	Gordillo & Kim (2012)	Hao, Huang, Zhang, Chen, Fang, Guo, Huang, et al. (2025)
Huang et al. (2012)	Hussain, Ozair, et al. (2025)	Khan et al. (2020)	Lee & Lashari (2014b)
Li & Ding (2025)	Li, Ding, & Song (2025)	Mao et al. (2012)	Ozair et al. (2022)
Ozair, Hussain, Shi, et al. (2020)	Pukkala et al. (2014)	Robinet et al. (2020)	Schafstall et al. (2024)
Weiss et al. (2019)	Xia et al. (2022)	Xu & Yuan (2023)	Zhou et al. (2024)

3.2 | Review outcome

The systematic literature review (Phase 1) identified a total of 125 studies, all of which were screened in phase 2. During phase 2, 24 studies were excluded because (i) they were duplicate records not identified during automatic deduplication ($N=3$), (ii) no full text was available ($N=5$); (iii) the publication was a review rather than original research ($N=2$); (iv) no quantitative model was presented ($N=7$); or (v) the study was not available in, or readily translatable to, English ($N=7$). A further 48 studies were excluded because they did not represent any control measures. In addition, 25 studies were classified as redundant and excluded because a more recent publication covered the same model framework or provided a more comprehensive or up-to-date implementation.

Overall, a total of 28 studies were retained, as they presented applicable modelling frameworks incorporating control measures, making them suitable for in-depth evaluation during phase 3.

Of the 28 studies assessed, the majority (16) were based on ordinary differential equation models describing population and infection dynamics via infested and non-infested compartments representing the vector or host population. While valuable for theoretical analyses, these models reflect the effect of control measures by proportional reductions applied to a single targeted system component, e.g. insecticide reduces the vector reproduction parameter, whereas clear cutting reduces the size of the infested host compartment. Such formulations provide only an indirect and aggregated representation of control, with limited correspondence to the underlying biological processes through which interventions exert an effect. Weak linkages between management actions and systems dynamics, with mixed formulation of pest-vector-host dynamics and intervention efforts, hinder consideration of dedicated management plans, which ideally must be formulated in a spatially and temporally explicit manner to inform actionable decisions. Consequently, these models were evaluated as demanding very substantial adaptation to become sufficiently targeted and useful in addressing Task B of the mandate.

A further four studies based on partial differential equation models were also considered as not oriented to the purpose here, despite in principle being capable of representing spatial spread and spatially differentiated intervention efficiency. The models were overly simplified or insufficiently validated or lacked representation of essential components – such as host and nematode infection dynamics, landscape heterogeneity or relevant operational constraints – thereby limiting the extent to which their outputs could be used to address the ToR requirements i.e. the quantitative assessment of the effectiveness of different intervention plans in the spatial and temporal context of a pest outbreak.

The remaining eight studies, four grid-based models and four individual-based models, were considered suited to satisfy the ToR within the bounds of requiring a reasonable amount of adaptation. The underlying modelling approaches are inherently characterised by sufficient flexibility in representing local spread processes within heterogeneous landscapes in combination with spatio-temporally discrete formulations of intervention plans. Therefore, in the following, these eight models are subjected to detailed reporting of the outcome of Phase 3.

However, two of the grid-based models were judged to require enormous adaptation of model logic to satisfy the intended purpose. The main reason was the age of the studies, which were developed when computational standards were limiting for the complexity of ecological models. Although both models were spatially explicit and incorporated representations of host removal, they used substantial simplifying assumptions to implement system details. Key components were missing, notably explicit vector and/or nematode infection dynamics and explicit representation of operational interventions such as clear-cutting or buffer zones. In addition, both had very limited validation against empirical data.

The remaining six models span a range of approaches, including cellular automaton (Pukkala et al., 2014), network-based (de la Fuente & Saura, 2021) and individual-based models (Robinet et al., 2020; Schafstall et al., 2024; Weiss et al., 2019; Xia et al., 2022). All six models explicitly represent spatial spread processes and incorporate biologically informed representations of vector-mediated transmission, with several also including climate suitability and host susceptibility (de la Fuente & Saura, 2021; Pukkala et al., 2014; Schafstall et al., 2024), and in some cases very detailed validation against empirical data (de la Fuente & Saura, 2021; Xia et al., 2022). The key characteristics of the six models identified as the most promising candidates for further consideration under Task B are summarised in Table 2.

TABLE 2 Summary of the six models identified as most promising for further consideration under Task B.

Reference	Model type	Key characteristics relevant to task B
Long-term projections of the natural expansion of the pinewood nematode in the Iberian Peninsula (de la Fuente & Saura, 2021).	Process-based network model	Spatially explicit network model for long-term geographical spread of PWN. Represents infection probabilities across connected landscape nodes and includes host susceptibility and climate scenarios. Applies pattern-oriented output validation against data from Portugal and Spain
Comparison of the potential spread of pinewood nematode (<i>Bursaphelenchus xylophilus</i>) in Finland and Iberia simulated with a cellular automaton model (Pukkala et al., 2014).	Cellular automaton/grid-based model	Spatially explicit cellular automaton model simulating PWN spread across Europe, illustrated for Iberia and Finland. Includes climate constraints, vector-mediated local dispersal, human-mediated long-distance spread, land cover, pine fraction, elevation and population-density-based transport proxies. Validation is based on reported presence of pest in local region of Setúbal, in Portugal.
Effectiveness of clear-cutting in non-fragmented pine forests in relation to EU regulations for the eradication of the pinewood nematode (Robinet et al., 2020).	Individual-based model	Individual-based model representing local movements of adult beetles, maturation and starvation-related mortality. Directly evaluates the effectiveness of an individual clear-cut zone as function of radius and the effect on simulated pest burden. Validation is approached by narrative comparison with De la Fuente et al. (de la Fuente et al., 2018).
Assessing the effect of invasive organisms on forests under information uncertainty: The case of pinewood nematode in continental Europe (Schafstall et al., 2024).	Combination of an individual-based forest model and a grid-based disturbance model	Combines the spatially explicit iLand individual-based forest landscape model with the BITE disturbance model. Represents forest dynamics, host susceptibility, climatic suitability, vector dispersal through a distance-based kernel and host mortality driven by vector pressure. Validation is approached by qualitative comparison with Portugal spread rates (de la Fuente et al., 2018)
Modelling the incursion and spread of a forestry pest: Case study of <i>Monochamus alternatus</i> Hope (Weiss et al., 2019)	Individual-based model	Landscape-based model with spatially explicit host layers and detailed individual-based representation of vector development, maturation, mating, oviposition and dispersal. Includes local and wind-driven dispersal and host-density-dependent spread. Validation is based on comparison with reported nematode-positive tree locations from the 1999/2000 Melbourne incursion.
Simulating Pine Wilt Disease Dispersal with an Individual-Based Model Incorporating Individual Movement Patterns of Vector Beetles (Xia et al., 2022).	Individual-based model	Spatially explicit individual-based model representing vector beetles as agents moving across a regular grid of trees. Validation is based on comparison with individually mapped infested trees in Gijang-gun, Busan.

3.3 | Implications of the review for the modelling work under Task B

The mandate defines the core problem of the modelling performed under Task B. i.e. the quantitative assessment of control and containment strategies of PWN outbreaks. The present review was necessary to determine to what extent the problem can be addressed by reusing existing models. The review outcome described in Section 3.2 underpins that model suitability for Task B depends on both the quality of the modelling of the pest-vector-host system, and on the model's adequacy for the purpose of the modelling under Task B i.e. representing specific biological, spatial and operational processes expected to be systematically investigated in response to the mandate. Starting from the lessons learned concerning what existing models of the pest-vector-host system may contribute to an evaluation of intervention strategies, the operational expectations for the (re)-used model were expanded into a task book of required quality demonstrations and output data from the model analysis. The following seven tasks go beyond the capacity of any of the reviewed models in some respects, but reflect a synthesis of the available models when the purpose of modelling is to compare alternative intervention strategies, as is foreseeable under Task B.

First, the modelling is expected to be able to reproduce, at least in broad terms, the observed spatial and temporal spread of pinewood nematode by its insect vector under EU outbreak conditions. Simulated spread dynamics of the pest or its vector and the infestation patterns in pine trees should be compatible with the empirical information available from affected regions, including rates of spread, geographical extent and temporal development of infestation and disease.

Second, the modelling is expected to be able to represent the current EU reference framework for eradication and containment in an operationally meaningful way. This includes, as appropriate, the representation of defined surveillance and detection protocols, confirmation of infestation, clear-cut felling around detected trees, buffer zone implementation and the time interval over which measures are maintained after the last detection.

Third, the model is expected to be suitable to assess the effectiveness of different clear-cut widths including zero and buffer zone sizes under eradication and containment strategies. This includes the capacity to compare the current regulatory approach with alternative spatial configurations and to determine whether alternative measures would maintain, improve or compromise pest control.

Fourth, it would be purposeful if the modelling facilitates the examination of factors likely to affect the performance of management measures. These include the time between pest introduction and first detection, the time between detection and implementation of removal measures and the quality of implementation of sanitary felling and wood removal. Where relevant, the modelling may be used to assess the consequences of imperfect implementation, including delayed removal, incomplete removal of infested material and residual opportunities for vector emergence or continued spread.

Fifth, the modelling should target the exploration of variation across ecological and geographical settings relevant to the EU. This includes, where possible, differences in host composition, forest structure, landscape composition and fragmentation, climatic conditions and other factors likely to affect vector ecology, pest development and spread, detectability and the effectiveness of control measures.

Sixth, purposeful modelling must support the systematic comparison of different management scenarios beyond a single idealised implementation of clear-cutting. Where relevant, this may include intensified surveillance, selective tree removal strategies, alternative inspection protocols, complementary measures and different assumptions regarding re-introduction or continued spread.

Finally, the most purposeful modelling would generate outputs directly relevant to decision-making under the mandate. These include, as appropriate, the extent of disease remaining in the landscape, the realised rate of spread, the number or proportion of infested trees removed, the number or proportion of healthy trees removed, the time to eradication or clearance and the occurrence of detections within or beyond the buffer zone.

The seven expectations define the practical requirements for the modelling in response to Task B. They therefore form an integral part of the conclusions of the systematic review on the landscape for PWN system-dynamic models and clarify how the outcome of the review will be translated into the subsequent modelling work.

4 | CONCLUSIONS AND RECOMMENDATION

The modelling approaches addressing the efficiency of practical intervention protocols were spatially explicit grid-, network- or individual-based models. The models represented local spread, landscape heterogeneity and vector-mediated transmission as well as explicit intervention protocols. The six models were in alphabetical order (de la Fuente & Saura, 2021), (Pukkala et al., 2014), (Robinet et al., 2020), (Schafstall et al., 2024), (Weiss et al., 2019) and (Xia et al., 2022).

These modelling studies provided different validation efforts, addressing the space-time patterns of observed outbreak data from different locations in the world.

Although none of the six identified modelling studies demonstrated its suitability for a systematic investigation of sets of intervention measures, all are considered potentially adaptable through targeted refinement and improved parameterisation.

The required improvements concern the integration of the operational expectations identified in Section 3.3, including explicit protocols for surveillance and detection, the sequential application of measures in response to outbreak development, the comparison of alternative clear-cut widths and buffer zone sizes, implementation delays in control measures, incomplete host removal, host dynamics, climate or landscape variability and, if relevant, human-mediated pest dispersal.

ABBREVIATIONS

EPPO European and Mediterranean Plant Protection Organization
 PLH Plant Health
 PWN Pinewood Nematode
 ToR Terms of Reference
 WoS Web of Science

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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ANNEXES

The following annexes are available under the Supporting Information section in the online version of this scientific output:

Annex A, containing the Phase 2 screening inventory.

Annex B, containing the review protocol and screening criteria used for the staged assessment of modelling studies.

Annex C, containing the final model inventory from the Phase 3 in-depth technical appraisal.