

Supplementary Materials

From Cryptic Infection to Forest-Scale Risk Mapping: A Critical Review of Remote Sensing Technologies, Indicators, and Research Priorities for Heterobasidion and Armillaria Root Rot

This document contains Section S1 (complete search questions and eligibility criteria) and Section S2 (duplicate and related publication families). Supplementary Tables S1–S6 are provided in the accompanying Excel file.

Section S1. Complete Search Questions and Eligibility Criteria

The review used three complementary semantic evidence streams. Searches, screening and structured extraction were completed and exported on 1 July 2026. Records were obtained from academic publications indexed in Semantic Scholar and OpenAlex through a relevance-ranked semantic discovery workflow. The 500 records ranked as most relevant to each question were exported, giving 1,500 workflow records.

Evidence stream	Complete semantic search question	Retrieved	Retained	Screening criteria
RQ1 — Indicators and biological interpretation	What spectral, structural, thermal, textural, phenological and terrain-related indicators had been used to detect or infer the presence, severity or spatial distribution of root rot caused by <i>Heterobasidion</i> spp. and <i>Armillaria</i> spp. in boreal, hemiboreal and temperate moist forests, and how consistently had these indicators been associated with pathogen infection rather than with non-specific tree stress, drought, nutrient limitation, bark beetle damage, stand age or site conditions?	500	80	Climate zone; detection objectives; field validation; geographical scope; indicator types; methodology; pathogen scope; publication quality; publication type; inclusion of the target pathogens.
RQ2 — Technologies and comparative performance	How have satellite-based, UAV-based, airborne and ground-based imaging approaches compared in detecting <i>Heterobasidion</i> and <i>Armillaria</i> root rot with respect to sensor type, spatial and temporal resolution, spectral domain, use of LiDAR or terrain-derived predictors, statistical or machine-learning methods, ground-truthing strategy, classification performance, transferability and practical applicability to forest management?	500	16	Field application; forest ecosystem type; ground-truthing or validation; pathogen specificity; publication type; relevant outcome measures; remote-sensing technology; inclusion of the target pathogens.
RQ3 — Scientific, methodological and operational gaps	What scientific, methodological and operational limitations had constrained reliable mapping of <i>Heterobasidion</i> and <i>Armillaria</i> infection, and what research had been identified as necessary for improving early detection, pathogen-specific discrimination, multi-sensor data fusion, repeated time-series monitoring, field validation, uncertainty reporting and integration with forest inventory, harvester, soil, hydrological and climate data?	500	10	Ecosystem scope; forest ecosystem type; pathogen scope; publication type; remote-sensing application; remote-sensing component; remote-sensing technology; inclusion of the target pathogens.

Eligibility Criteria

Eligibility domain	Included evidence	Excluded or restricted evidence
Ecological and geographical scope	Boreal, hemiboreal or temperate moist forests. Location, forest type and dominant host could establish eligibility when climate-zone terminology was absent.	Studies exclusively in tropical, subtropical dry, Mediterranean, arid, agricultural, orchard or controlled-environment systems, unless retained as a directly relevant methodological analogue.
Pathogen and disease scope	<i>Heterobasidion</i> spp., <i>Armillaria</i> spp., annosum root rot, <i>Armillaria</i> root disease, root and butt rot, heartwood rot and related stem-decay conditions. Rot without species-level confirmation was retained as decay evidence.	Unrelated pathogens or stressors, except selected analogues used to evaluate confounding, pre-visual stress detection or transferable methods.
Remote-sensing and imaging scope	Satellite, crewed airborne, aerial photography, UAV/UAS, hyperspectral, multispectral, RGB, thermal, LiDAR, TLS, photogrammetry and spatially explicit proximal imaging.	Conventional field or laboratory methods as stand-alone detection technologies. These methods were retained when used as reference evidence or mechanistic support.
Outcome scope	Indicators, spatial patterns, accuracy or class-specific metrics, regression estimates, probability maps, sensor characteristics, transferability, reference standards, uncertainty and management applicability.	Publications without an outcome relevant to detection, mapping, validation, biological interpretation or operational implementation.
Publication scope	Peer-reviewed articles, conference papers, theses, technical reports and selected repository records containing relevant empirical or methodological evidence.	Clearly non-scholarly or duplicative records without additional evidence; duplicate versions were linked rather than counted as independent studies.
Language and date	No formal publication-year restriction; retained evidence spanned 1970–2025. Records were screened from the information available in the exported English-language metadata.	No formal date exclusion. Publications could be excluded where available metadata was insufficient to establish relevance.

Screening, Deduplication and Evidence Tiers

Titles and abstracts were screened separately within the three evidence streams. Individual criteria were classified as yes, maybe or no and combined into a holistic screening judgement. A fixed numerical score was not used as the sole inclusion threshold.

The indicator stream retained 80 of 500 records, the technology-comparison stream retained 16 of 500, and the research-gap stream retained 10 of 500. After cross-stream deduplication using normalised titles and DOI identifiers, followed by manual examination of near-identical titles and repository or publication versions, the 106 retained workflow entries yielded 84 unique publications.

All 1,394 excluded workflow entries were assigned the broad exported reason ‘Other/below screening threshold’; reason-specific exclusion counts could therefore not be reconstructed.

Tier 1 comprised direct diagnostic or remote-mapping evidence (16 publications). Tier 2 comprised supporting biological, epidemiological, structural or operational evidence (61 publications). Tier 3 comprised methodological analogues or broader forest-health evidence (7 publications).

Section S2. Duplicate and Related Publication Families

The 84 publication records did not represent 84 fully independent experiments. Publications were grouped where titles, sites, imagery, trees, harvest-reference observations or study descriptions indicated reuse of the same or closely related evidence. Family membership was used to avoid treating related outputs as independent geographic replication.

The table is conservative. A publication family does not imply inappropriate duplicate publication: several papers addressed distinct questions using shared experimental material. Exact overlap should be verified from full texts where the available abstracts did not report site names, dates or sample identifiers.

Family	Study family	Record IDs	Member publications	Probable overlap	Treatment in synthesis	Confidence
F1	New Zealand Armillaria root disease in Pinus radiata series	R025; R026; R027	Armillaria root disease of Pinus radiata in New Zealand. 3: Influence of thinning and pruning; 4: Assessment of stand infection; 5: Stand assessment using aerial photography.	Multi-part research series addressing related plantations, disease assessments and management questions.	Linked as one study family; individual papers retained for distinct outcomes but not interpreted as independent geographic replication.	High
F2	Norwegian Norway spruce imaging and harvest-reference studies	R066; R067; R070; R072	Satellite/LiDAR heartwood-rot detection; airborne hyperspectral detection; UAV hyperspectral detection; airborne hyperspectral and ALS wood-decay detection.	Related Norwegian sites, airborne laser scanning, hyperspectral observations and harvest-derived rot labels; exact sharing of sites and trees varies among publications.	Considered a related programme of studies. Sensor comparisons were retained, but the publications were not treated as four independent demonstrations of transferability.	Moderate; exact site and tree overlap could not be fully established from the available information.
F3	Southern Swedish Scots pine survey outputs	R074; R075	Doctoral thesis on Heterobasidion root rot infections in Scots pine; journal survey reporting high prevalence on apparently low-risk sites.	The journal article was derived from, or formed part of, the same southern Swedish survey programme described in the thesis.	Linked during interpretation; thesis and article retained for complementary methodological and epidemiological information.	High
F4	Swiss National Park mountain-pine disease-centre studies	R029; R035; R037; R038	Tree-life history prior to death; incidence and distribution of Heterobasidion and Armillaria; spread of root-rot fungi; signs and symptoms in dead and dying mountain pine.	Related mountain-pine stands and disease centres in the Swiss National Park, with overlapping ecological context and potentially shared trees or sites.	Used for complementary evidence on growth, distribution, spread and symptoms, but not regarded as independent geographic validations.	Moderate; the exact degree of overlap could not be fully established.