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Swedish University of Agricultural Sciences

SLU Risk Assessment of Plant Pests

SLU.ua.2026.2.6-1020

March 27, 2026

Questions related to the risk of *Fusarium circinatum* to Sweden

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Recommended citation:

Boberg, J. & Björklund, N. (2026) Questions related to the risk of *Fusarium circinatum* to Sweden. Technical report SLU.ua.2026.2.6-1020. SLU Risk Assessment of Plant Pests, Swedish University of Agricultural Sciences.

Acknowledgement

We gratefully acknowledge the valuable comments on an earlier draft of this report provided by Juha Tuomola and Mariela Marinova-Todorova (Finnish Food Authority) and by Audrius Menkis and Michelle Cleary (Swedish University of Agricultural Sciences). We would also like to thank Lena Slånberg (Föreningen Sveriges skogsplantproducenter) for providing information about fungicides that are approved for use in Swedish forest nurseries.

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1. Background

Fusarium circinatum (EPPO code: GIBBCI) was previously regulated in the European Union (EU) following provisional emergency measures (Commission Decision 2007/433/EC), which were repealed in 2019. Since 2019, the pathogen is regulated as a quarantine pest through Regulation (EU) 2019/2072. While surveys for *F. circinatum* were mandatory for all EU Member States following 2007/433/EC, currently the pathogen can be excluded from regular surveys following (EU) 2016/2031 in case it can be 'unequivocally concluded' that ecoclimatic conditions or the absence of hosts prevent the establishment or spread of *F. circinatum* in the Member State.

Previously, it was assessed that the conditions, especially the climatic conditions, were not suitable for establishment of *F. circinatum* in Sweden based on information included in the EFSA pest survey card (EFSA et al. 2020). However, new information included in a quick risk assessment for Sweden conducted for the pathogen using the FinnPRIO risk ranking model suggests that the earlier conclusion may need to be revised (Boberg & Björklund 2024, unpublished FinnPRIO assessment sheet).

SLU Risk Assessment of Plant Pests was requested by the Swedish Board of Agriculture to provide a more detailed analysis to support their decision on whether *F. circinatum* should be part of regular surveys in Sweden. Furthermore, the FinnPRIO assessment also raised questions related to the level of susceptibility of *Pinus sylvestris* and *Picea abies* to infection by *F. circinatum* and the associated potential impacts.

The following specific questions were investigated and assessed in this report:

(i) How suitable is the current and future climate in Sweden for the establishment of *F. circinatum* considering conditions both in the field and in forest nurseries?

(ii) How susceptible is *Pinus sylvestris* to infection by *F. circinatum*?

(iii) How susceptible is *Picea abies* to infection by *F. circinatum*?

Furthermore, based on the results and conclusions of the questions above, we assessed the potential for establishment of *F. circinatum* in Sweden within the coming 20 years and identified the potential area of establishment. In a subsequent step, not included in this report, the FinnPRIO assessment will be updated, as appropriate, based on the information presented here.

2. How suitable is the climate in Sweden for establishment of *Fusarium circinatum*?

Fusarium circinatum is commonly known as the causal agent of the disease pine pitch canker. Pine pitch canker was first recognized in 1945 in North Carolina, US (Hepting and Roth, 1946; Gordon et al. 2015). It is suggested that *F. circinatum* is probably native in Mexico from where it has spread to other parts of the world (Drenkhan et al. 2020; EPPO 2025b). *Fusarium circinatum* is currently reported to occur in the southern and western USA (Alabama, Arkansas, California, Florida, Georgia, Indiana, Louisiana, Mississippi, North Carolina, South Carolina, Tennessee, Texas, Virginia), Mexico, Guatemala, Haiti, Chile (only in nurseries), Colombia, South Africa, Japan (Kyushu, Ryukyu Archipelago), South Korea, Pakistan, and under eradication in Portugal and Spain (mainland) (EPPO 2026). In France and Italy, the pathogen has been successfully eradicated: in France following observations in both nurseries and the field, and in Italy following observations in the field (EPPO 2025a,b).

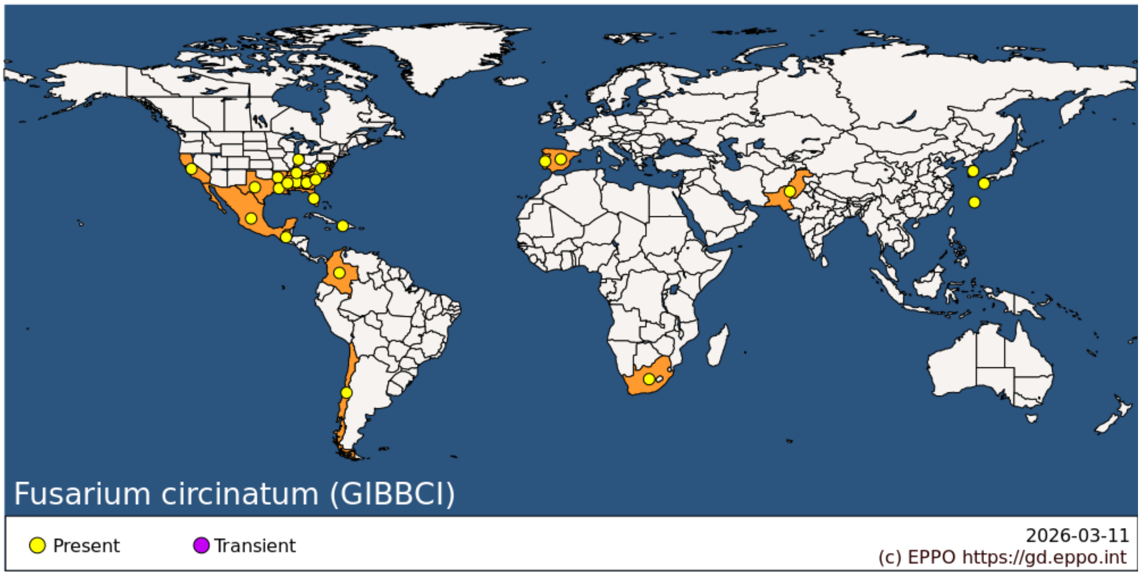

Figure 1. Distribution map of *Fusarium circinatum* from EPPO Global database (EPPO 2026).

2.1 Suitability of climatic conditions in the field

Pine pitch canker is generally known to occur with high incidence in Mediterranean and sub-tropical climates but also occurs in regions with temperate climates (e.g. in northern Spain) (Drenkhan et al. 2020; Beck et al. 2023; EPPO 2025b). Temperature and moisture are two of the most important climatic factors affecting distribution, spread and symptom development (Drenkhan et al. 2020). It has been suggested that cooler temperatures restrict the disease (Gordon et al. 2001; EPPO 2025b). Studies by Inman et al. (2008) indicate that the lower germination and growth rates of the fungus observed at lower temperatures (10°C) coupled with a decrease in susceptibility of host wounds as they age (from day 2) would lead to a reduced infection frequency. Wounds are reported to be important for infection (Gordon et al. 2001; EPPO 2025b). Higher disease severity has also been linked to coastal areas presumably due to higher moisture levels (Gordon et al. 2001; Zamora-Ballesteros et al. 2019). Zamora-Ballesteros et al. (2019) considered it unlikely that *F. circinatum* would become established in natural forests of northern latitudes. Note that this refers to conditions in the field and that the situation may be different in forest nurseries which may offer more protected conditions (see Section 2.2).

Phenological studies indicate that optimal temperatures for spore germination and mycelial growth would be around 20–30°C, with some variability observed for different strains and studies (Inman 2008; Mullet et al. 2017; Elvira-Recuenco et al. 2021). Spore germination and mycelial growth dropped at 10°C (Inman 2008; Elvira-Recuenco et al. 2021). Minimal mycelial growth and spore germination was observed at 5°C (Mullet et al. 2017; Elvira-Recuenco et al. 2021). Temperature effects on disease severity (measured as lesion length and standardized area under disease progress curve (sAUDPC)) depended on the isolate used for inoculating the seedlings (Elvira-Recuenco et al. 2021). Incubation in higher moisture conditions for 7h increased lesion length while longer moisture periods had no additional effect (Elvira-Recuenco et al. 2021).

The potential distribution of pine pitch canker has been analysed using the Compare Locations model of the CLIMEX software on numerous occasions based on climate data representing different time-periods including the potential future climate (Ganley et al. 2009; EFSA et al. 2010; Watt et al. 2011; Möykkynen et al. 2014; Tuomola and Hannunen 2023).[1] This CLIMEX model predicts a species potential distribution based on a number of climatic variables selected in order to reflect both the growth and reduction of the species population over the seasons (Kriticos et al. 2015). A model for a particular species is developed using data on the known distribution together with observed physiological responses of the species (e.g. growth in different temperature and moisture). A measure of the climatic suitability of a specific location for a species is provided by the model as an Ecoclimatic Index (EI) ranging from 0 to 100. An EI of 0 indicates unsuitable climate for the species while EI > 0 indicates some potential for establishment, with higher values reflecting greater climatic suitability (Kriticos et al. 2015).

A CLIMEX model for pine pitch canker was first developed by Ganley et al. (2009) that ran the model using climate data for the time-period 1961–1990. Parameter values were fitted based on the known occurrences of pine pitch canker and informed by laboratory temperature-response data cited in Ganley et al. (2009); for example, the lower temperature threshold was set to 10 °C. The same model parameters were used in a PRA for the EU (EFSA et al. 2010), which also ran the model using climate data for the time-period 1999–2007, as well as in studies by Watt et al. (2011) and Möykkynen et al. (2015). All these simulations predicted that the climate in Sweden would be unsuitable for pine pitch canker (Ganley et al. 2009; EFSA et al. 2010; Watt et al. 2011; Möykkynen et al. 2015). The potential distribution of pine pitch canker under future climate was analysed by Watt et al. (2011) using data centred on 2080 from three Global

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[1] Note that a MaxEnt model for *F. circinatum* was published recently (Zhang et al. 2025). However, since the occurrence data used contains records that were not verified to represent established population of the species the model output was considered unreliable.

Climate Models (GCM) under scenario A1B, and by Möykkynen et al. (2015) using data for 2071–2100 under scenario A1B (included using the built-in climate change parameter in CLIMEX). Watt et al. (2011) found no suitable conditions in Sweden in any of their simulations, whereas Möykkynen et al. (2015) indicated that parts of Skåne might become marginally suitable by the end of the century.

Tuomola and Hannunen (2023) further updated the CLIMEX model. The update was done to take into account the range expansion of pine pitch canker into areas in South Korea, Mexico and Spain, which had been predicted as unsuitable by the previous model, as well as considering the results of recent phenological studies. The update involved increasing the upper threshold and optimal temperatures, decreasing the number of degree days required for minimum amount of development, decreasing the rate of cold stress accumulation and increasing the threshold temperature for hot-wet and hot-dry stress (Tuomola and Hannunen 2023). They subsequently analysed the potential range of pine pitch canker using climate data for the time-period 1981–2010. The results of this updated model predict that the area suitable for pine pitch canker in Europe would be larger than estimated by the previous models and for example stretches slightly further north. However, their results indicate that the conditions were not suitable in Sweden (results here reproduced for convenience; Figure 1A).

An uncertainty analysis of the CLIMEX model was also performed by Tuomola and Hannunen (2023) in which the model was run 200 times with parameter values sampled around the fitted values. The results from the uncertainty analysis were presented as a map showing the proportion of model runs generating an EI value >0 (i.e., indicating some potential for establishment). For some parts of southern Sweden, the proportion of iterations with EI > 0 falls in the 1–20 % class (i.e., between 1 and 40 model runs generated EI values higher than 0). In fact, the proportion was 1–5% in a major part of this area and only very small areas in the southernmost coast near Denmark fell within the 5–20% class (Pers. comm. J. Tuomola, 30 Sept. 2025).

Assessing climate suitability in Sweden

The aim of this analysis was to assess the suitability of the Swedish climate for the establishment of *F. circinatum* within the next 20 years. We used the CLIMEX model developed for pine pitch canker acknowledging that the model was developed for the disease rather than the pathogen (see information on uncertainties below). We applied the updated parameters developed by Tuomola and Hannunen (2023) using CLIMEX version 4.1.1.0 (Kriticos et al. 2015; a prerelease version not publicly available online). Because climate data suitable for running the CLIMEX model for the target time-period were not readily available, we based the assessment on climate data for the periods 1981–2010 (which has already been performed by Tuomola and Hannunen (2023) and described above) and 2040–2059 available at CliMond (Kriticos et al. 2012). The future climate datasets were based on Representative Concentration Pathways (RCP) emission scenario 8.5, which is a high emission scenario (IPCC 2024). Data were available from four GCMs developed by different institutions, i.e., ACCESS 1.0 (Commonwealth scientific and Industrial research organisation (CSIRO)/Bureau of Meteorology (BoM), Australia), CNRM-CM5 (Centre National de Recherches Météorologiques, France), GFDL-ESM-2M (Geophysical Fluid Dynamics Laboratory, US) and NorESM1-M (Bjerknes Center for Climate Research, Norwegian Meteorological Institute). It should be noted that all these models are fully coupled atmosphere–ocean GCMs, so changes in Atlantic Ocean circulation are embedded in the climate fields used by CLIMEX (ACCESS1-0: Bi et al., 2013; CNRM-CM5.1: Voldoire et al., 2013; GFDL-ESM2M: Dunne et al., 2012; NorESM1-M: Bentsen et al., 2013).

The results of the CLIMEX modelling indicate that, under the RCP8.5 scenario assumptions, areas with suitable conditions for the pine pitch canker will expand further north in Europe in a future climate (Figure 1). Under the future climate scenarios, the area with suitable conditions is projected to cover parts of Skåne county in all four GCMs but also to reach slightly further north along the coastal regions in the model results for some of the GCMs (Figure 1, B–E). The large majority of Sweden is still projected to be unsuitable under these future climate scenarios.

An analysis of individual CLIMEX model indices, which together forms the EI, show that the modelled potential distribution in Sweden is limited by low temperatures, e.g., by the number of degree days (Appendix 1). In the CLIMEX model for pine pitch canker developed by Tuomola and Hannunen (2023), the parameter for positive degree days (PDD) was set to 1000 degree days above 10 °C. Mapping the PDD shows that this threshold is not reached anywhere in Sweden under the recent climate (1981–2010). In the future climate projections, the GCM projecting the largest suitable area in Sweden (ACCESS) showed that conditions would still be unsuitable in northern Sweden, for example due to cold stress (Appendix 1). However, the requirement for PDD is the main factor limiting the projected suitable area, i.e., regions where this threshold is met matches those with EI > 0 (Appendix 1).

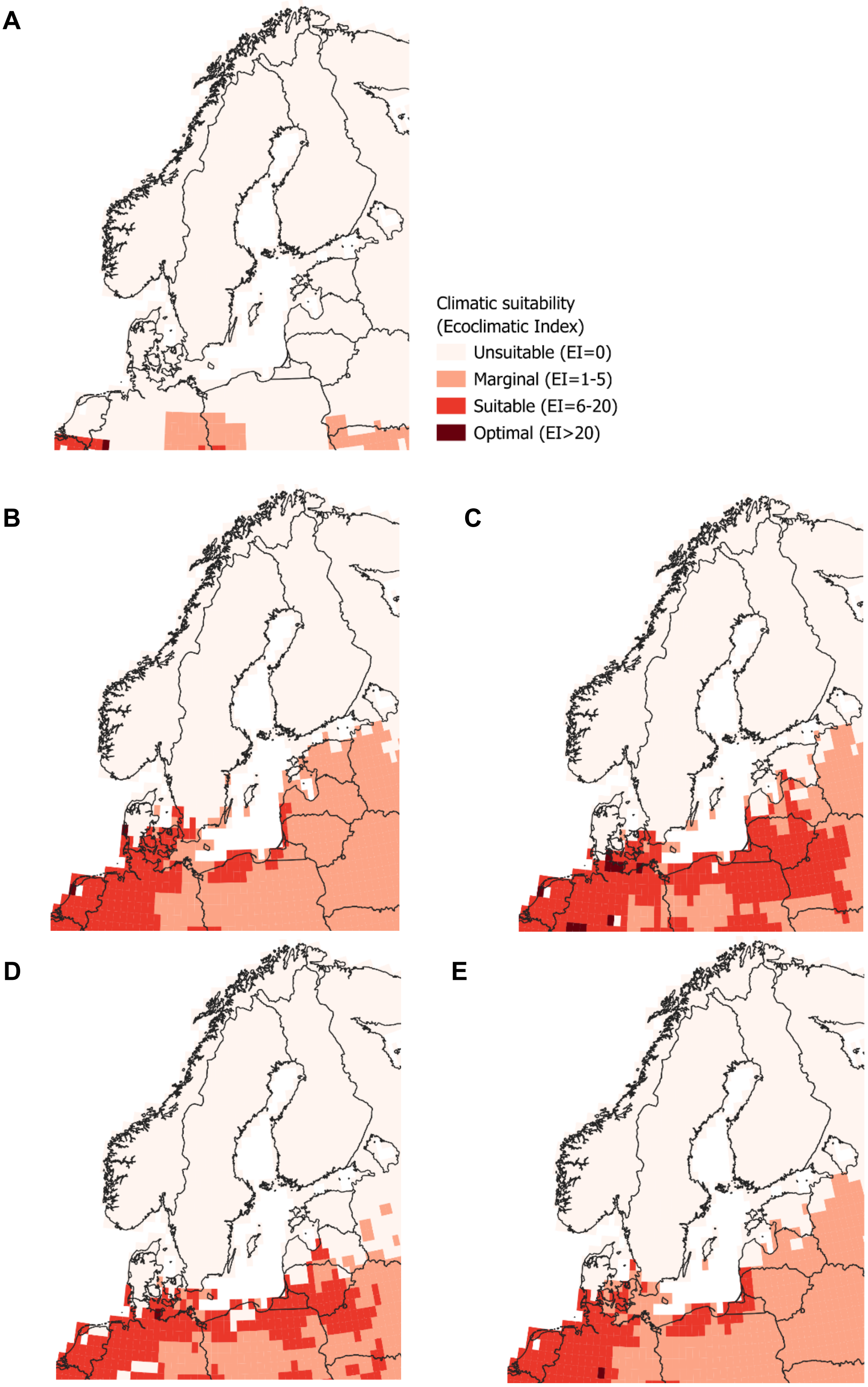

Figure 1. Climate suitability for pine pitch canker based on a CLIMEX model developed by Tuomola and Hannunen (2023) run using climate data from Climond (Kriticos et al. 2012) representing recent climate 1981–2010 (A) and future climate for 2040–2059 based on RCP8.5 generated using different global climate models, i.e., ACCESS 1.0 (B), CNRM-CM5 (C), GFDL-ESM-2M (D) and NorESM1-M (E).

The modelling outputs should be interpreted with caution as there are several uncertainties associated with the results. The CLIMEX model may underestimate the potential distribution of the pathogen since its development relied primarily on the currently known distribution range of the pine pitch canker disease. The true current range of the pathogen may be larger since *F. circinatum* is known to be able to cause asymptomatic infections and thus there may be a difference between the true occurrence range of the pathogen and the reported range, which is mainly based on observations of disease. On the other hand, the prediction made using future climate scenario data may overestimate the potential distribution since the climate data used was generated using RCP8.5. This is a high emission scenario, which has been proposed to be a scenario with a low probability to be realized by 2100 (Sarofim et al. 2024). However, the projections used here represent a mid-century period (2040–2059), and differences in projected temperature change between emission scenarios are smaller at this time horizon than they are by 2100 (Rosace et al. 2024). Nonetheless, the use of RCP8.5 represents a precautionary approach and is likely to show a larger suitable area than would be expected under more moderate emission scenarios.

Furthermore, it should also be considered that the modelling is based on climate, which is averaged over 20–30 years, and with rather low spatial resolution, i.e., it is based on average climate in rather large grid cells. The spatial resolution of the climate data used is 30′, which corresponds to a grid cell size of approximately 56 x 20–32 km in Sweden. Thus, neither local climate (including coastal versus inland contrasts at smaller scales), microclimate, nor fluctuations in weather between years are captured in the model outputs. As a result, conditions may for example be suitable in some specific location but not be captured by the model. From a surveillance and early detection perspective, urban and peri-urban environments may be particularly relevant in this regard. Urban areas are generally observed to be warmer than rural areas due to the urban heat island phenomenon (Lauwaet et al. 2024) and are also potential entry points as end consumers of ornamental plants for planting and other commodities identified as potential pathways of entry (EPPO 2025b). See Appendix 2 for a map of the degree days calculated using temperature data with a higher spatial resolution.

Alternative modelling approaches could test the robustness of the presented findings and incorporate additional predictors but were not implemented here due to time constraints.

In conclusion, based on the information and analysis provided above, the recent climate was not suitable for establishment of *F. circinatum* in the field. The CLIMEX modelling based on climate projected for the time-period 2040–2059 and scenario RCP8.5 predict that climate would become suitable in Skåne and the coastal areas of southern Sweden.

2.2 Suitability of temperature and moisture in forest nurseries

Pine pitch canker is an important disease in forest nurseries in areas where it occurs (EPPO 2025b). In some countries it is only known to occur in forest nurseries, e.g. in Chile and Brazil (EPPO 2025a; Drenkhan et al. 2020). Since forest nurseries may provide higher and more stable temperature and moisture regimes, it is suggested that the pathogen may be able to thrive in nurseries located in areas with otherwise unsuitable climate (Drenkhan et al. 2020). For example, Gordon et al. (2015) suggest that weather conditions will have less or no effect on *F. circinatum* as a soilborne pathogen and thus that areas with predicted unsuitable climate may still sustain damage in the form of seedling mortality in nurseries and transplant failure due to latent infections. However, *Fusarium circinatum* has so far only been reported from forest nurseries in regions in which the climate is suitable for pine pitch canker in the field (Ganley et al. 2009; Drenkhan et al. 2020; EPPO 2025a). Specifically, no report was found of established populations of the pathogen in greenhouses in regions where climate in the field is predicted to be unsuitable, e.g., in northern North America.

Tuomola and Hannunen (2023) recently assessed the suitability of temperature and moisture conditions for *F. circinatum* in forest nurseries in Finland. They rated the likelihood of temperature and moisture conditions being suitable for establishment in forest nurseries as high, with a high level of uncertainty.

In Sweden, forestry seedlings of pine and spruce are generally produced in greenhouses for around 5–10 weeks and are then moved outdoors (Larsson 2024; Svenska skogsplantor 2025; see Appendix 3 for information about the origin of the seedlings). Winter storage of the seedlings is generally done in freezers at -3 to -5°C or outdoors in Swedish forest nurseries (Larsson 2024; Skogskunskap, 2024). The warmer and more humid conditions created in greenhouses are likely to be suitable for *F. circinatum* growth, reproduction and dispersal. The nursery environment outdoors and during winter storage is also expected to offer more stable and thus more suitable conditions than in the field. In particular, areas where the conditions in the field are expected to become suitable in the future may offer such conditions (see Section 2.1). However, no information was found on the low temperature thresholds for the pathogen and no evidence of persistent survival in forest nurseries in areas with otherwise unsuitable climate was found.

3. Host susceptibility

Following the request from the Swedish Board of Agriculture the level of susceptibility of the plant hosts were investigated with a focus on the assessment of the potential direct impact *F. circinatum* would have in Sweden, should it establish in the country (c.f. question IMP1 in FinnPRIO risk ranking model). In particular, we examine whether infection of the plants is likely to cause losses for the relevant plant production sector in Sweden. The plant susceptibility is also relevant for other parts of a risk assessment, i.e., entry, spread, establishment and impact. The influence of host susceptibility for potential establishment is included in section 4. The likelihood of entry and spread is not assessed in this report but some important notes in relation to host susceptibility are provided in section 3.3.

3.1 Susceptibility of *Pinus sylvestris* to *Fusarium circinatum*

The potential threat of *F. circinatum* to *Pinus sylvestris* in Europe has been the focus of numerous studies. We here present a review of the data found in a literature search to gather evidence on the ability of the fungus to infect *Pinus sylvestris* and induce symptoms of disease.

Evidence of natural infections

Natural infection of *P. sylvestris* by *F. circinatum* has been reported. The pathogen has, for example, been isolated from *P. sylvestris* in a nursery in Spain (Pérez-Sierra et al. 2007). Infected *P. sylvestris* in nurseries was also reported by the NPPO of Spain (no details provided; EPPO 2006) and in reports from official surveys in Castilla y León where infected plants of *P. sylvestris* were detected in both nurseries and in reforestations (2005–2008; Junta de Castilla y León 2008).

The literature search did not identify any additional documentation of natural infections of *P. sylvestris* by *F. circinatum*, nor any information about damage levels due to natural infections (although the infected seedlings had symptoms in Pérez-Sierra et al. 2007). In California*, P. sylvestris* was not included in the list of pine species found to be naturally infected (Storer et al. 1995). Similarly, no observation of infected trees of *P. sylvestris* was reported by Aegerter et al. (2003), but the authors also point out that this is not necessarily indicative of resistance since the occurrence of this tree species close to natural inoculum is infrequent in California.

In Spain, studies of the occurrence of *F. circinatum* have been conducted across different plant material and locations as follows. Investigations of seeds of different *Pinus* species did not detect the pathogen in seeds of *P. sylvestris* although it was present, i.e., it was found in seeds of *P. radiata* and *P. pinaster* (overall the detection level was 40%; González Penalta et al. 2008). The authors do point out that this result should be interpreted with caution since the number of batches from *P. sylvestris* was much lower than for the other pine species. Landeras et al. (2005) did not observe any symptoms of disease in *P. sylvestris* seedlings in a nursery with diseased *P. radiata* and *P. pinaster*. In the study by Pérez-Sierra et al. (2007), the pathogen was obtained from *P. sylvestris* only in nurseries (5 isolates). In contrast, for other *Pinus* species, 21–68 isolates per species were recovered across several environments and materials (e.g., seeds, nurseries, reforestation sites, forests). No isolates were obtained from *P. sylvestris* in pine plantations during the survey, which was conducted 2004–2006 (Pérez-Sierra et al. 2007).

Iturritxa et al. (2013) surveyed 29 field plots in Basque Country, a region in northern Spain, that included *P. sylvestris* trees without finding visible symptoms of infection (disease incidence was 1.5 and 16.8% for *P. pinaster* and *P. radiata*, respectively). Furthermore, Martínez-Álvarez et al. (2014) report that no symptoms in *P. sylvestris* have been observed in nature in Spain, despite the fact that stands are grown beside severely affected *P. radiata* stands in for example Cantabria.

Evidence from artificial inoculation studies

Numerous studies have been made with artificial inoculations of seedlings of different ages with information about disease symptoms and mortality rates (Table 1). The observed level of susceptibility ranged from no display of disease to high levels of mortality. The susceptibility of *P. sylvestris* to disease by *F. circinatum* appears to vary with growing conditions, plant age, inoculum size, provenance and genotype. This has also been pointed out by others (e.g. Drenkhan et al. 2020; Woodward et al. 2025). It has, for example, been suggested that *P. sylvestris* acquires age-related resistance against *F. circinatum* (Gordon et al. 2001; Martín-García et al. 2017; 2018). Few studies appear to have investigated the effect of the different factors in a systematic way, but some examples are available. Woodward et al. (2022) inoculated emerging seedlings of 19 populations of *P. sylvestris* and showed that the susceptibility to disease varied between populations of *P. sylvestris* and with the spore dose used as inoculum. Furthermore, Davydenko et al. (2018) inoculated 12 Polish provenances of *P. sylvestris* and reported differences in mortality between them.

In a review, Woodward et al. (2025) estimated the susceptibility to *F. circinatum* across the phylogeny of *Pinus* based on experiments of both artificial and natural infection. The susceptibility of *P. sylvestris* was estimated as intermediate (slightly closer to the resistance side than susceptible on a continuous scale).

Interpreting the evidence found in the reviewed literature

A large majority of the reviewed studies of the susceptibility of *P. sylvestris* to *F. circinatum* were based on artificial inoculations of small plants (≤ 3 years old) (Figure 2; Table 1). The question is how these results should be interpreted in a risk assessment context. Artificial infection can be achieved using different methods. Generally, the studies reviewed here involved inoculation of the pathogen either by creating a wound in the stem in which inoculum was placed or by growing seeds and seedlings in growing media inoculated with spores. It is expected that the latter approach would more closely resemble natural infection than the former. It is, however, uncertain whether the spore concentrations in natural conditions are likely to be similar to the tested concentrations and how conditions in natural settings in a forest nursery (incl. both abiotic and biotic factors) would affect the pathogen-host interaction. In the reviewed studies where inoculum was applied via growth substrate, most studies used sterilised seed and/or sterilised substrate, which may affect comparability with operational nursery substrates, although this comparability issue may be less pronounced because nursery substrates are often peat-based (commonly described as having a relatively low initial pathogen load compared with many alternative media). Sterilisation may reduce microbial competition and antagonism (potentially increasing infection success), whereas it may also alter plant-associated microbiota and plant defence, potentially affecting disease expression in the opposite direction. Overall, as pointed out by Davydenko et al. (2024) results from experiments based on greenhouse inoculations require further validation.

Whether artificial inoculations of seedlings can reliably indicate genetic resistance has been examined in various pine species. Gordon et al. (1998) report a good correspondence between the extent of lesion development in 3–4 years old inoculated seedlings in greenhouse experiments and infection in the field of different pine species in California. However, in further work it is also observed that current year succulent growth tends to be more susceptible compared to woody tissue of the same tree (Gordon et al. 2001 citing unpublished material) and the extent of genetic resistance expressed in young seedlings is unknown (Gordon et al. 2001; Aegerter et al. 2003). Studies by Aegerter and Gordon (2006) found no significant correlation between mortality observed in emerging seedlings artificially inoculated as seeds and lesion length in inoculated 1.5 years old saplings among different *P. radiata* families. Furthermore, assessments of host susceptibility should not only be based on results from artificial inoculation but also on observations made under natural conditions. Observations of disease under natural conditions and subsequent symptom development demonstrate that infection and symptom development are possible. Lack of observed disease however must be interpreted in relation to exposure to the pathogen and does not provide any evidence of resistance if no exposure was expected.

Susceptibility can also be influenced by environmental and management factors. For some pine species, fresh or larger wounds with sufficient surface moisture increase infection success, although wounding can, in some controlled contexts, induce defensive responses and enhance resistance; elevated nitrogen availability has been associated with higher incidence and severity (Sakamoto and Gordon 2006; Amaral et al. 2022).

In conclusion, natural infection of *P. sylvestris* seedlings is known to occur. However, there is no evidence of significant damage under natural conditions. Results from studies conducted using artificial inoculation of seedlings show varying levels of susceptibility ranging from not susceptible (no display of disease), to highly susceptible (100% mortality). The reasons for this observed variability are not clear. Studies have shown differences for example between provenances and between populations of *P. sylvestris*, but no study included Swedish or Scandinavian provenances. Controlled inoculation experiments on these provenances could provide valuable information on local susceptibility.

Assessment of susceptibility and associated potential impact

We assess that it is very likely that *P. sylvestris* in Swedish nurseries could become infected under conducive conditions should inoculum be present. Whether such infections would result in significant losses in nurseries is highly uncertain, as this has never been recorded for *P. sylvestris*. As a precautionary assessment, given the limited information available specifically for *P. sylvestris* and drawing on reports of losses in other *Pinus* species, such losses are considered likely. The magnitude of potential impact is highly uncertain, partly because nursery management practices in Sweden may limit losses (see Section 4.2).

We were not able to find any evidence of natural infection of *P. sylvestris* that have passed the seedling stage, nor any studies reporting artificial inoculation of such trees. It should be noted that in most regions where *F. circinatum* is present, caution is needed when interpreting the absence of reports of infection in *P. sylvestris*, since the pathogen's distribution is often very limited (e.g. in Portugal) or *P. sylvestris* is uncommon. In the US, *P. sylvestris* has been widely planted, especially for Christmas tree production, but it is unclear to what extent the distribution range of the fungus overlaps with that of the tree species (Skilling 1990; EPPO 2025a). An important exception is northern Spain, where *F. circinatum* is present in some parts and the primary cause of damage to *P. radiata* in nurseries and plantations (EPPO 2025a). Here *P. sylvestris* also forms natural forests and is widely planted both within and beyond its native range (Houston Durrant et al. 2016; Martínez García & Montero 2000). A systematic survey in Spain including mature *P. sylvestris* trees did not find any symptoms of disease (Iturritxa et al. 2013). Potential damage would not only depend on the susceptibility of the tree but also on the environmental conditions (Aegerter et al. 2003; Drenkhan et al. 2020) and the climate suitability analysis (see Section 2.1) suggest that the climate is unsuitable for the disease in a major part of Sweden. Thus, natural infection of trees in the field cannot be totally ruled out but based on the evidence available we assess that it is unlikely to lead to losses in Sweden. The uncertainty of this assessment is high.

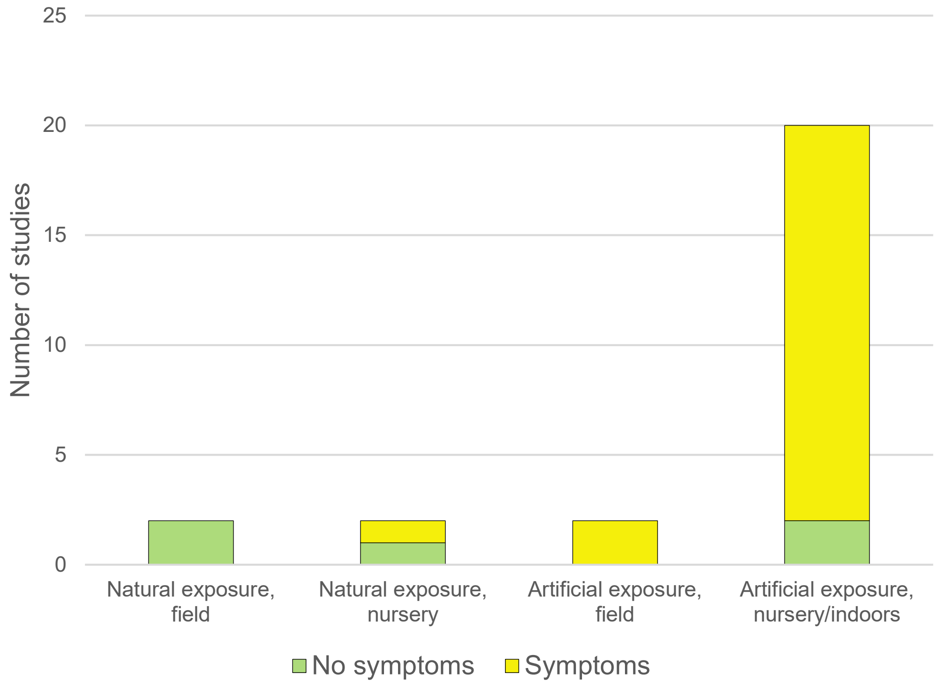

Figure 2. Studies reporting information regarding symptom development in *P. sylvestris* seedlings following exposure to *F. circinatum* were broadly categorized according to type of exposure and whether symptoms occurred (See Table 1 for detailed information). The figure shows that the number of studies from natural settings are very limited in number and that no symptoms of disease have been observed following natural exposure in the field.

Table 1. *Pinus sylvestris*: Summary of information regarding the ability of *F. circinatum* to induce symptoms of disease in *P. sylvestris* from the literature. In order to provide an overview of the results from all studies, we classified the susceptibility as 'not susceptible' if no symptoms of disease were reported, 'susceptible' if symptoms were reported but did not meet the threshold for 'Highly susceptible', or 'Highly susceptible' if near complete mortality was reported. Note that in some studies the information provided was very limited for determining the level of susceptibility.

Type of exposure	**Conditions**	**Susceptibility**	**Symptoms/impact**	**Plant age**	**Origin of provenance (No.)**	**Reference**
Natural	Field plots	Not susceptible	No disease was observed in any *P. sylvestris* trees within the 29 plots surveyed	Trees, i.e., not seedlings	Spain?*	Iturritxa et al. 2013
Natural, field plots adjacent to infected *P. radiata* stands	Field plots	Not susceptible	No symptoms of disease observed within 17 months (although none were observed on seedlings of *P. radiata* either)	Seedlings	Spain (1)	Martínez-Álvarez et al. 2014
Natural, growing in nurseries with infected seedlings of *P. radiata* and *P. pinaster*	Nursery	Not susceptible	No symptoms	Seedlings	Spain?*	Landeras et al. 2005
Natural, nursery grown seedlings	Nursery	Susceptible	*F. circinatum* was isolated from symptomatic seedlings	Seedlings	Spain?*	Pérez-Sierra et al. 2007
Artificial, stem wound inoculation with spore suspension	Field plots	Not susceptible - susceptible	AUDPC (Area under the disease progress curve) values not different from control plots, but some symptoms of disease observed at some point	Seedlings (same as above, >17 months)	Spain (1)	Martínez-Álvarez et al. 2014
Artificial, stem wound inoculated with spore suspension	Field plot	Susceptible	Significantly higher AUDPC for inoculated seedlings, no significant effect on collar or height growth and live crown length	3 years	Spain?*	Martínez-Álvarez et al. 2016

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Artificial, stem wound inoculation with mycelia	Nursery	Not susceptible	No symptoms	2 years	Italy?*	Carlucci et al. 2007
Artificial, spore suspension at different concentration added to growth medium	Growth chamber	Not susceptible	No pre-emergence mortality. Survival probability not significantly affected	15 days	Romania (1)	Martín-García et al. 2017
Artificial, seeds grown in spore-inoculated media at 3 different concentrations	Growth chamber?	Not susceptible - Highly susceptible Depending on spore dose and population	**Low spore conc.** resulted in 25% mortality overall at termination (~80 days post-emergence) but 10 populations (out of 19) showed no mortality while 3 populations sustained 100% mortality **Medium and high spore conc.** resulted in 100% mortality 12-16 days post-emergence in all provenances	Emerging seedlings	In total 19 populations: Austria (4), UK (7), Greece (1), Poland (3), Serbia (1), Turkey (2), Spain (1)	Woodward et al. 2022
Artificial, stem wound inoculated with spore suspension	Greenhouse	Susceptible	Shoots were girdled in 13-21 days	Seedlings	?	McCain et al. 1987
Artificial, stem wound inoculated with spore suspension	Greenhouse	Susceptible	Symptoms observed and mortality 0 or 8 % 12 weeks post-inoculation depending on the trial	3 years	?	Enebak & Stanosz 2003
Artificial, grown in infected soil	?	Susceptible	Growth significantly lower and mortality significantly higher (no details provided). 3% of surviving seedlings were infected	6 months	German?*	Schröder 2006 (conference abstract)

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Artificial, stem wound (trial 1) or cut tip (trial 2) inoculation with spore suspension	Greenhouse	Susceptible	After four weeks 34 % (trial 1) or 77% (trial 2) of the seedlings developed lesions in the lowest category (0-6 mm) while 4 % (trial 2) or 37% (trial 1) developed lesions in the highest category (>15 mm)	2 years	Spain (2)	Iturritxa et al. 2012
Artificial, stem wound inoculation with spore suspension	Greenhouse	Susceptible	Lesions developed	2 years	Spain (1)	Iturritxa et al. 2013
Artificial, seeds grown in spore-inoculated Petri dishes	Growth chamber	Susceptible	No significant pre-emerging mortality. Post-emergence mortality reached 39-52% (after 30 days) depending on the provenance	Emerging seedlings	Poland (6), Lithuania (2), Ukraine (2)	Davydenko et al. 2024
Artificial, grown in spore-inoculated growth media	Greenhouse	Susceptible	Mortality ranged 60–70% after 6 months depending on the provenance, except for one provenance which had 48% mortality. Across provenances 5-14 % of seedlings displayed no symptoms	4 months	Poland (6), Lithuania (2), Ukraine (2)	Davydenko et al. 2024
Artificial, grown in spore-inoculated growth media or stem wound inoculation with spore suspension	?	Susceptible	55 seedlings died out of the initial 77 seedlings compared to 4 dead seedlings of control plants.	Emerging seedlings or 4 months	German	Douanla-Meli et al. 2021 (conference abstract)

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Artificial, grown in spore-inoculated media	Greenhouse	Susceptible – Highly susceptible	After 4 months: high mortality (up to 100%) observed in 10 provenances while high survival 82-86% was observed in 2 provenances	2 months	Poland (12)	Davydenko et al. 2018
Artificial, grown on mycelia	Growth chamber	Highly susceptible	97-100% mortality after 21 days	15 days	Poland (3)	Davydenko et al. 2018
Artificial, stem wound inoculated with spore suspension	Greenhouse	Highly susceptible	90% mortality after 4 months	1 year	Poland (1)	Davydenko et al. 2018
Artificial, stem wound inoculation with mycelium	?	Highly susceptible	100% mortality 56d post-inoculation	7-8 months	Spain?*	Pérez-Sierra et al. 2007
Artificial, seeds grown in medium inoculated with spore suspension	Laboratory	Highly susceptible	Significantly lower emergence. >90% mortality after 90 days	Emerging seedlings	Spain (1)	Martínez-Álvarez et al. 2014
Artificial, stem wound inoculated with mycelia	Growth chamber?	Highly susceptible	Mean number of days until death post-inoculation was approx. 26 days (98% mortality after 40 days)	1 year	Spain?*	Mullett et al. (2017)
Artificial, stem wound inoculation with spore suspension	Growth chamber	Highly susceptible	About 50% mortality within 3 months (100% mortality after 8.5 months)	1.5 years	Czech Republic (1)	Martín-García et al. 2018
Artificial, seeds grown in spore-inoculated growth media	Growth chamber	Highly susceptible	No significant pre-emergence mortality. Mortality reached 100% after 40 days	Emerging seedlings	Spain (1)	Silva-Castro et al. 2018

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Artificial, stem wound inoculation with spore suspension	Growth chamber	Highly susceptible	Severe wilting observed in all seedlings 28 days post-inoculation. Complete mortality was observed after 6 weeks.	1 year	Spain (1)	Nordström et al. 2022; I. Nordström, pers. comm.

*Origin of provenance not provided but assumed from the context.

3.2 Susceptibility of *Picea abies* to *Fusarium circinatum*

No reports of naturally infected *Picea* species were found in the literature search. In fact, apart from *Pinus* the only other conifer genus known to be naturally infected by *F. circinatum* is *Pseudotsuga menziesii* (Boa 2024; EPPO 2025b).

Some studies have been made with artificial inoculations of *Picea abies* seedlings of different ages (Table 2). The studies confirm the potential of seedlings of *P. abies* to become infected but their susceptibility to disease varied between trials. Seedling emergence was not affected by the presence of the pathogen (Martínez-Álvarez et al. 2014), but germinating seedlings grown in inoculated media showed high levels of post-emergence mortality (Martínez-Álvarez et al. 2014; Martín-García et al. 2017), indicating that the pathogen mainly affects seedlings after their germination. By contrast, seedlings that were inoculated after they had already developed for some time appeared to be more tolerant to infection (Martínez-Álvarez et al. 2014; Martín-García et al. 2018). It has been suggested that *P. abies* seedlings may acquire age-related resistance to disease as they grow older, similar to what has been suggested for *P. sylvestris* (Martínez-Álvarez et al. 2014; Martín-García et al. 2018).

The symptoms and mortality observed following artificial inoculation of *P. abies* seedlings must be interpreted carefully as described earlier in Section 3.1. It is unknown to what extent *P. abies* has been naturally exposed to *F. circinatum*. Nevertheless, the tree species is categorized as introduced in Spain by POWO (2025) and low occurrence is reported in the northern parts of Spain where *F. circinatum* has been reported (Caudullo et al. 2016; Drenkhan et al. 2020). It could also be noted that *F. circinatum* is able to induce symptoms of disease in several other tree species than *Pinus* spp. and *Pseudotsuga menziesii* following artificial inoculation of seedlings (see Section 3.3) but natural infections have not been reported for any of them (EPPO 2025a).

In conclusion, we assess that it is likely that *P. abies* in Swedish nurseries could become infected under conducive conditions. Infection could also lead to some level of disease and subsequent losses. Similarly, as for seedlings of *P. sylvestris* the magnitude of potential impact in Swedish nurseries is highly uncertain considering the general management practices. We assess that it is very unlikely that *P. abies* would become infected in the field. These assessments have a high uncertainty due to the limited information available from both artificial inoculation trials and natural exposure, i.e., the limited occurrence of this tree species in areas where the pathogen is present.

Table 2. ***Picea abies***: Summary of information regarding the ability of *F. circinatum* to induce symptoms of disease in *P. abies* from the literature. In order to provide an overview of the results from all studies, we classified the susceptibility as 'not susceptible' if no symptoms of disease were reported, 'susceptible' if symptoms were reported but did not meet the threshold for 'Highly susceptible', or 'Highly susceptible' if near complete mortality was reported. Note that in some studies the information provided was very limited for determining the level of susceptibility.

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Natural, Field plots adjacent to infected *P. radiata* stands	Field plots	Not susceptible	No symptoms of disease observed within 17 months (although none were observed on seedlings of *P. radiata* either)	Seedlings	Eastern Europe (1)	Martínez-Álvarez et al. 2014
Artificial, stem wound inoculation with spore suspension	Field plots	Not susceptible - susceptible	AUDPC (Area under the disease progress curve) values not different from control plots, but some symptoms of disease observed at some point	Seedlings (same as above, >17 months)	Eastern Europe (1)	Martínez-Álvarez et al. 2014
Artificial, no details	?	Not susceptible	No details but stated that "appeared not to be susceptible to the disease"	?	?	Berry and Hepting 1959
Artificial, stem wound inoculation with spore suspension	Growth chamber	Not susceptible - Susceptible	Some symptoms in 25% of plants (resinosis beyond the point of inoculation) – no mortality (no significant effect on AUDPC)	3.5 years	Czech Republic (1)	Martín-García et al. 2018
Artificial, seeds grown in medium inoculated with spore suspension	Laboratory	Susceptible	No significant effect on emergence. ~60% mortality after 90 days	Emerging seedlings	Eastern Europe (1)	Martínez-Álvarez et al. 2014

Type of exposure	Conditions	Susceptibility	Symptoms/impact	Plant age	Origin of provenance (No.)	Reference
Artificial, grown in spore-inoculated growth media or stem wound inoculation with spore suspension	?	Susceptible	47 seedlings died out of the initial 77 seedlings compared to 0 dead seedlings of control plants.	Emerging seedlings or 4 months	German	Douanla-Meli et al. 2021 (conference abstract)
Artificial, spore suspension at different concentration added to growth medium	Growth chamber	Susceptible – Highly susceptible	No pre-emergence mortality. About 40–90% mortality depending on spore concentration	15 days	Romania (1)	Martín-García et al. 2017

3.3 Additional information relevant for a risk assessment

Other host species

Additional conifer plant species reported to be naturally infected and which may be relevant in a Swedish context are *Pseudotsuga menziesii* and *Pinus contorta* var. *contorta* (sometimes treated as *Pinus contorta* subsp. *contorta* in the literature) (Storer et al. 1995; Gordon et al. 2001). Note that the variant of *P. contorta* planted in Sweden is *P. contorta* var. *latifolia* (Jacobson and Hannerz 2020). Artificial inoculation studies have also shown the potential of seedlings of other conifer genera to become infected, e.g. *Abies alba*, *Larix decidua* and *Picea sitchensis* (Martínez-Álvarez et al. 2014; Martín-García et al. 2018; Garcia-Serna 2011).

Several non-conifer plant species have also been found to become naturally infected (without any symptoms being observed). Plant species in this category, which are also listed as established in Sweden (cf. SLU Artdatabanken 2025) are: *Agrostis capillaris* (sv. rödven), *Holcus lanatus* (sv. luddtåtel), *Hypochaeris radicata* (sv. rotfibbla), *Sonchus oleraceus* (sv. kålmolke) (Swett and Gordon 2012; Hernandez-Escribano et al. 2018; Drenkhan et al. 2020; EPPO 2025a). *Zea mays* (sv. majs) has been shown to become infected in inoculation studies (Swett and Gordon 2009; 2015).

Relevance of host susceptibility for entry and spread

Movement of infected seed is the main pathway of introduction into new regions (Zamora-Ballesteros et al. 2019). But infected seedlings may also provide means of entry and especially spread from nurseries into forests (Zamora-Ballesteros et al. 2019). Infections may also be asymptomatic, which have been reported both for naturally infected hosts as well as for inoculated seedlings. For example, *F. circinatum* was re-isolated from inoculated seedlings of *P. sylvestris* without symptoms in experiments running for 180 days (Davydenko et al. 2024) and asymptomatic infections were recorded in seedlings of *Picea abies* and *Larix decidua* up to 8.5 months after artificial inoculation (Martín-García et al. 2018). Such asymptomatic infections decrease the likelihood of detection and may serve as a source of inoculum for further spread. Asymptomatic infection of e.g. herbaceous plant species may also act as an inoculum reservoir but their role in the epidemiology is not clear (Gordon et al. 2015; Hernandez-Escribano et al. 2018; Herron et al. 2020).

4. Assessing the potential for establishment in Sweden

4.1 Method and definition

The assessments were done as requested to support management decisions related to survey of *F. circinatum*, and in particular in relation to the requirements of surveys of union quarantine pests (see Section 1.1). The potential for establishment was assessed using the method and definitions described in a previous report (Björklund and Boberg 2021). Establishment is defined according to FAO (IPPC Secretariat 2024) as the “Perpetuation, for the foreseeable future, of a pest within an area after entry”.

The potential for establishment was assessed based on the likelihood of the pest to survive and reproduce taking into account the availability of suitable hosts, the presence or potential establishment of vectors (if necessary for the transmission of the pathogen) and climate/abiotic conditions.

The degree to which conditions are suitable for establishment in Sweden was assessed both in the field and in forest nurseries. The following scale and definitions were used:

- “Not suitable”, i.e., the conditions do not support establishment.
- “Unlikely to be suitable”, i.e., the conditions are unlikely to support establishment.
- “Likely to be suitable”, i.e., the conditions are likely to support establishment.
- ”Very likely to be suitable”, i.e., the conditions are very likely to support establishment.

The most likely option was selected and the uncertainty was also assessed and presented as the plausible minimum and maximum options.

Following (EU) 2019/2072 a pest may also be excluded from regular surveys if ecoclimatic conditions or the absence of hosts prevents spread. In Sweden, conditions are not expected to prevent the spread and transmission of *F. circinatum* once introduced, since the pathogen can spread by spores that can be disseminated by wind, rain and insect vectors (Zamora-Ballesteros et al. 2019). Many of the insect species associated with *F. circinatum* in Spain also occur in Sweden, e.g., *Pityophthorus pubescens*, *Hylurgops palliatus*, *Ips sexdentatus*, *Hylastes attenuates* and *Tomicus piniperda* (Romón et al. 2007; Bezos et al. 2015; SLU Artdatabanken 2025). The pathogen may also be disseminated by movement of contaminated seed, growing substrate and containers as well as with infected asymptomatic seedlings (Zamora-Ballesteros et al. 2019). Thus, the potential for spread and transmission does not exclude establishment.

4.2 Assessment and justification

The specific task was to assess the likelihood of establishment of *F. circinatum* within the coming 20 years and, if establishment in Sweden is assessed as possible, the area suitable for establishment should be identified. The assessment was mainly based on the literature review and analysis presented in Sections 2–3, but some additional information was also taken into account as described below.

Under field conditions, the climate suitability analysis indicates that the climatic conditions in Sweden were unsuitable for establishment in recent climate (1981–2010) but are predicted to be marginal or suitable in some areas in southern Sweden under a future climate (2040–2059, RCP8.5) (Section 2.1). Note that the future climate projections extend slightly beyond the coming 20-year period specified for this assessment. Considering the relatively high uncertainties associated with the modelling of climate suitability (Section 2.1), the range of possible outcomes includes both that no suitable conditions will exist anywhere in Sweden and that areas could become suitable. We assess that it is possible, though not likely, that the climate will become suitable within the next 20 years in some regions of southern Sweden, based on a comparison of Fig. 1A and 1B–E. This assessment is associated with a high uncertainty. We were unable to find any evidence that *P. sylvestris* would become infected if exposed to the pathogen in the field. This does not mean that this could not occur but the lack of reports of infected trees of *P. sylvestris* from Spain, where these occur adjacent to infected stands of *P. radiata*, indicate that trees of *P. sylvestris* are less susceptible to disease. Seedlings of *P. sylvestris* may become infected in nurseries, however, we were not able to find any reports of natural infection of seedlings in the field. Although *P. sylvestris* has been demonstrated to be susceptible to infection other factors also affect the pathogen-host interaction as mentioned earlier and evidence also suggests that disease development and persistence would depend on relatively high and sustained inoculum levels. We assessed that the conditions are unlikely to be suitable for establishment in Sweden in the field (Table 3). The uncertainty is high and plausible minimum and maximum assessments range from not suitable to likely to be suitable.

Under forest nursery conditions, the abiotic conditions are expected to be more suitable than under field conditions since both the temperature and humidity are expected to be higher and more stable than in the field, especially in greenhouses. There is evidence showing that in nurseries in northern Spain, *F. circinatum* is the primary cause of damage to another species of *Pinus*, i.e., *P. radiata*, and that seedlings of *P. sylvestris* can become infected in forest nurseries (Section 3.1). Inoculation studies also indicate that other tree species commonly produced in Swedish forest nurseries can potentially become infected, e.g. *P. abies*. While spread among seedlings in protected forest nursery conditions would likely occur to some extent if the pathogen was introduced, it is much less certain whether such an introduction would result in establishment of the pest.

Common management practices may also affect the interaction between the pathogen and the host and the environment. In Sweden, most tree seedlings are produced as containerised seedlings in cultivation trays placed in a system elevated from the ground (Larsson 2024). In 2024, 100% of pine seedlings and 89% of spruce seedlings were produced as containerized seedlings (Skogsstyrelsen 2026). The seedlings are generally kept for 5–10 weeks in greenhouses and thereafter moved outdoors (Larsson 2024). In the autumn the seedlings are either sold for outplanting or stored at the nursery during winter, generally at -3 to -5°C in freezers or outdoors (Larsson 2024; Skogskunskap 2024). The fungus is not known to produce any survival structures such as chlamydospores, which is observed in e.g. *F. oxysporum*, a common pathogen of forest nurseries (Gordon et al. 2015). Nevertheless, *F. circinatum* has been observed to survive in soil for 6–12 months and in host tissue for 1–3 years depending on the conditions (McNee et al. 2002; Wingfield et al. 2008; Serrano et al. 2017). Whether similar survival would occur also in conditions prevailing in Swedish nurseries during winter when temperatures reach below zero at least for some time is not known. The pathogen has been present in North America since at least the 1940s and so far, the disease has not been reported to occur in northern states, including in protected conditions, which could indicate that conditions similar to those in Sweden have prevented establishment (unsuitable climate and/or unsusceptible hosts). However, the expected increase in temperatures in a future climate are likely to also improve conditions for survival in forest nurseries (cf. Section 2).

In nurseries, the cause of outbreaks is thought to mainly be due to contaminated soil or seed (Ganley et al. 2009; Gordon et al. 2015). General sanitary management such as washing containers between usage and using clean growing substrate would thus further decrease the likelihood of persistence of the pathogen (Skogsstyrelsen et al. 2016; Skogskunskap 2024). Furthermore, the likelihood is also influenced by monitoring, sanitation, and the substrate (growing-medium) microbiota and biological control practices (Martín-García et al. 2019; Iturritxa et al. 2017). Chemical treatments are also used in the nurseries against fungal diseases (Larsson 2024), however, we were not able to find any data on the amounts of fungicides used in Swedish forest nurseries. A literature search on the active compounds found in fungicides approved for application in Swedish forest nurseries (Jordbruksverket 2026; KEMI 2026), provided the following information about efficacy against *F. circinatum* (Appendix 4). One of the active compounds, i.e., prothioconazole, appear to be efficient but is mainly used against birch rust (*Melampsoridium betulinum*) in Swedish forest nurseries (L. Slånberg, pers. comm.). The other active compounds showed low or inconsistent efficacy or no information on efficacy was found (Starkey and Enebak 2011; Berbegal et al. 2015; Mullet et al. 2017; Appendix 4). Interactions with other microorganisms, including the growing-medium microbiota and applied biocontrols, may predispose seedlings to or protect them from *F. circinatum*. Co-infections with for example *Pythium* or *Phytophthora* have been deemed likely to exacerbate losses, whereas for example *Trichoderma* spp. have reduced infection in some trials (Elvira-Recuenco et al. 2020; Morales-Rodríguez et al. 2018). See Appendix 4 for biocontrol agents approved in Sweden and information about their efficacy against *F. circinatum*. However, because Regulation (EU) 2016/2031 allows exclusion from regular surveys only on the basis of ecoclimatic conditions or host absence, we did not include these other factors in our assessments.

We assessed that the conditions are likely to be suitable for establishment in Sweden in forest nurseries (Table 3). The uncertainty ranges from unlikely to likely to be suitable.

Table 3. Assessment of the degree to which conditions are suitable for establishment in Sweden within the coming 20 years.

	Not suitable	Unlikely to be suitable	Likely to be suitable	Very likely to be suitable
In the field				
Most likely	☐	☒	☐	☐
Uncertainty range	☒	☒	☒	☐
In forest nurseries				
Most likely	☐	☐	☒	☐
Uncertainty range	☐	☒	☒	☐

Semiquantitative estimates of entry and establishment probabilities and likely impacts in Sweden will be provided in a forthcoming FinnPRIO assessment.

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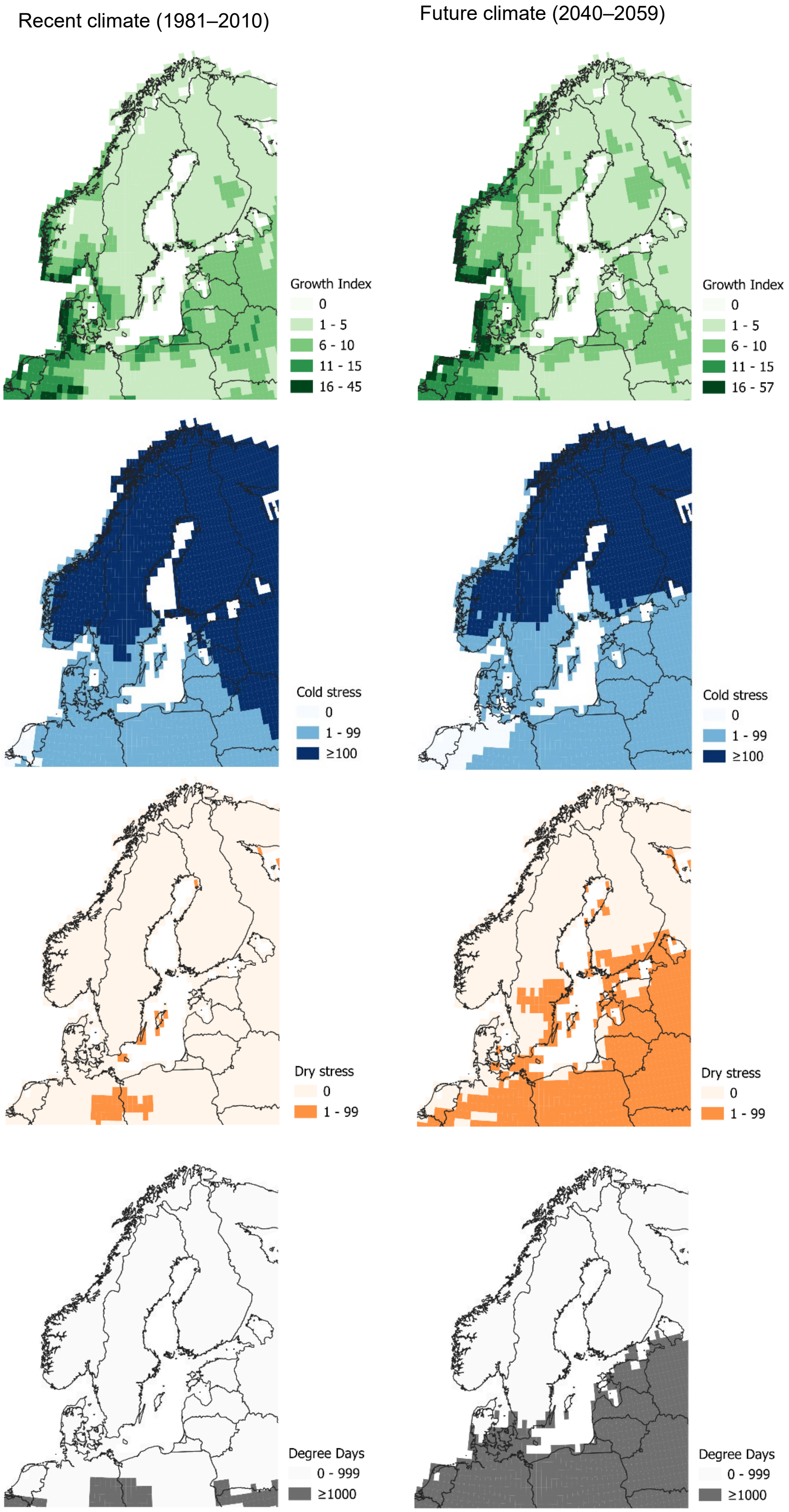
Appendix 1. Analysis of CLIMEX model variables and indices

The output of individual indices from the CLIMEX model for *Fusarium circinatum*, which are combined to generate the EI, were mapped separately to visualize how they vary across Sweden. Here we show the annual growth index, cold stress index, dry stress index and degree-days obtained from the CLIMEX model for *F. circinatum* based on parameter values defined by Tuomola and Hannunen (2023) and using CLIMEX version 4.1.1.0 (Kriticos et al. 2015; a prerelease version not publicly available online).

The annual growth index describes the potential growth of a population during the favourable season while different stress indices, which relate to conditions during the unfavourable season, limit the population persistence (Kriticos et al. 2015). The annual growth index ranges from 0 (no growth) to 100 (optimal for growth year-around) (Ganley et al. 2009). For the stress indices, a value of 0 corresponds to no stress while values greater than 100 correspond to lethal conditions (Ganley et al. 2009). The parameter positive degree days (PDD) is the thermal accumulation required to complete a minimum amount of development (Kriticos et al. 2015). If the threshold is not reached the species cannot persist and the EI is set to 0. The PDD was set to 1000 degree days above 10 °C (Tuomola and Hannunen 2023).

In Sweden, the growth index was >0 in almost the whole country with the highest indices projected for the west coast area in both recent climate and future climate (Figure A1). Mainly cold stress and to a limited extent dry stress affect the population, while no hot nor wet stress or any of the stress interactions (i.e., hot-wet and hot-dry stress) was projected. Some degree of cold stress was projected for the whole country and lethal cold stress was projected in the northern parts of Sweden in both recent and future climate. Dry stress was projected for a few areas in recent climate while a larger area was projected in a future climate. No lethal dry stress was projected. The PDD threshold was not met anywhere in Sweden in recent climate while some areas were projected to reach or exceed the threshold in a future climate.

Figure A1 (below). The annual growth index, cold stress index, dry stress index and degree days obtained from the CLIMEX model for *Fusarium circinatum* run with climate data from CliMond (Kriticos et al. 2012) representing recent climate 1981–2010 or future climate for 2040–2059, here based on RCP8.5 generated using the global climate model ACCESS 1.0.


Recent climate (1981–2010)
Future climate (2040–2059)
Growth Index
0
1 - 5
6 - 10
11 - 15
16 - 45
Growth Index
0
1 - 5
6 - 10
11 - 15
16 - 57
Cold stress
0
1 - 99
≥100
Cold stress
0
1 - 99
≥100
Dry stress
0
1 - 99
Dry stress
0
1 - 99
Degree Days
0 - 999
≥1000
Degree Days
0 - 999
≥1000

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Appendix 2. Degree day mapping using high spatial resolution data

The CLIMEX analysis was based on climate data with a spatial resolution of 30′ (i.e., grid cell size of approximately 56 x 20–32 km). Sub-grid heterogeneity with regard to temperature could be explored using higher-resolution Swedish gridded temperature datasets for the recent-climate period. Here we used SMHI 4×4 km daily gridded temperature data for the time period 2003–2022 (SMHI, 2023) to calculate the number of degree days to illustrate the warmer urban/peri-urban and coastal settings at a finer (though not microclimatic) spatial scale. The calculation was done using Method 1 by McMaster and Wilhelm (1997) in R and maps were created with qGIS (R Core Team 2024; QGIS Development Team 2025).

The temperature data used here is for the time period 2003–2022, however, under the working assumption that the spatial pattern of relative warm hotspots remains broadly similar over the near-term horizon, this can serve as indication of areas most likely to approach suitable conditions in the next 20 years. Note that this screening considers temperature only, whereas the CLIMEX analysis also includes other factors affecting the climate suitability (e.g. dry stress). Furthermore, since the threshold of 1000 degree days was defined based on the low resolution climate data, the threshold can not be directly applied to this dataset.

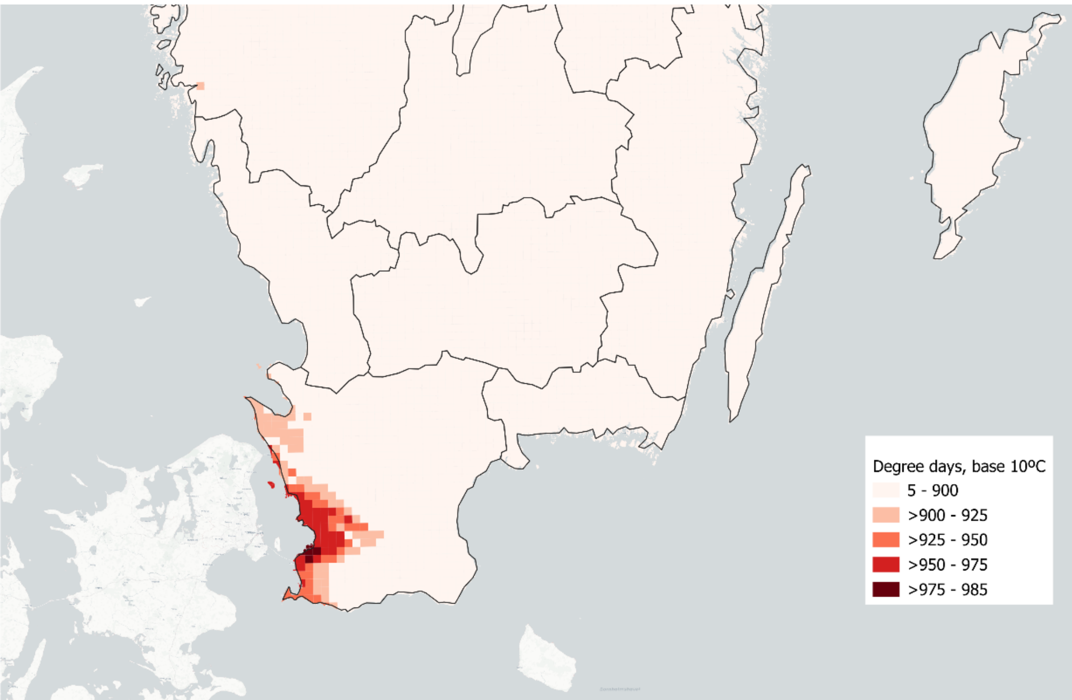

Figure A2. The map shows accumulated degree days above 10°C in the upper range. The degree days were calculated from SMHI 4×4 km daily gridded temperature data for the time period 2003–2022 (SMHI, 2023). The map of county borders was sources from SCB (2020) and the background map is by CartoDB, under CC BY 3.0.

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Appendix 3. Origin of forest reproductive material in Swedish forest nurseries

According to the Swedish Forest Agency (Skogsstyrelsen) official statistics on delivered forest seedlings for use in Sweden in 2024, the majority of planting stock is derived from Swedish seed sources; however, a non-negligible fraction is produced from foreign seed lots and/or delivered as plants from abroad (Swedish Forest Agency 2025a).

Propagation method (seed vs. vegetative propagation)

- *Pinus sylvestris*: 100% seed-propagated in 2024 (Swedish Forest Agency 2025b).
- *Picea abies*: 99.9% seed-propagated and 0.1% vegetative propagation in 2024 (Swedish Forest Agency 2025b).

Seed origin (pine and spruce)

- *Pinus sylvestris*: 96% Swedish seed-orchard seed; 2% foreign seed-orchard seed (remainder no information available) (Swedish Forest Agency 2025c). Total delivered: 219 million (Swedish Forest Agency 2025b); therefore, the minimum number of plants derived from foreign seed-orchard seed is ≥4.38 million.
  For context, mean annual seed traded into Sweden during 2017–2020 was 96 kg pine seed per year (Widenfalk et al. 2022).
- *Picea abies*: 83% Swedish seed; 17% foreign seed (Swedish Forest Agency 2025c). Total delivered: 166 million (Swedish Forest Agency 2025b); therefore, the approximate number of plants associated with foreign seed origin is 28 million.
  For context, mean annual seed traded into Sweden during 2017–2020 was 844 kg spruce seed per year (Widenfalk et al. 2022).

Plants traded into Sweden

- In 2023, 50.5 million forest plants were traded into Sweden from other countries. This corresponds to 12% of all delivered plants in 2023 (431 million in total) (it is however unclear whether the plants were delivered in the same year they were brought into Sweden) (Swedish Forest Agency 2025a). Of the plants traded into Sweden in 2023, 63% originated from the Nordic and Baltic region, and 37% from other European countries (Swedish Forest Agency 2025a). Note that although the plants were traded from other countries the origin of the seed could still be from Sweden (Swedish Forest Agency 2025a).
- Widenfalk et al. (2022) report mean annual forest seedlings traded into Sweden of 4 million pine seedlings and 41 million spruce seedlings per year during 2017–2020.

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Appendix 4. Efficacy of fungicides and biocontrol agents

Table A4. Active substances and biocontrol agents approved against fungal pathogens in forest nurseries in Sweden (Jordbruksverket 2026; KEMI 2026) and documented efficacy against *F. circinatum* found in the literature search.

Active substance	**Documented efficacy against *F. circinatum***
Chemical substances	
Azoxistrobin	-
Bensovindiflupyr	-
Boscalid	Boscalid and pyraclostrobin applied together in laboratory trials decreased mycelial growth but growth was not eliminated (Starkey and Enebak 2011).
Cyprodinil	Cyprodinil applied in laboratory trials had no effect on mycelial growth and inconsistent activity on germination (Berbegal et al. 2015).
Fenhexamid	-
Fludioxonil	• Fludioxonil applied in laboratory trials had no effect on mycelial growth and inconsistent activity on germination (Berbegal et al. 2015). • Fludioxonil applied in laboratory trials on 42 isolates of *F. circinatum* had varying efficacy on mycelial growth rates among the isolates (Mullet et al 2017).
Fosetyl	-
Kresoximmetyl	-
Potassium bicarbonate	-
Propomokarb	-
Protiokonazol	100% reduction of mycelial growth observed in laboratory trials and biweekly application in greenhouse trials controlled *F. circinatum* on seedlings of three different pine species and seedings production increased (Starkey and Enebok 2011).
Pyraclostrobin	• Boscalid and pyraclostrobin applied together in laboratory trials decreased mycelial growth but growth was not eliminated (Starkey and Enebak 2011). • Pyraclostrobin applied in laboratory trials decreased mycelial growth and conidial germination (Berbegal et al. 2015). • Pyraclostrobin applied in laboratory trials on 42 isolates of *F. circinatum* had varying efficacy on mycelial growth rates among the isolates ranging from highly effective to ineffective (Mullet et al 2017).
Pyrimetanil	-
Sulphur	-
Biocontrol agents	
Bacillus amyloliquefaciens, strain QST 713	-
Clonostachys rosea, strain J1446	No information found for strain J1446, but: Pre-treatment of *P. radiata* seedlings with *C. rosea* strain Cr7, reduced the length of lesions caused by the inoculation of *F. circinatum* (Moraga et al. 2024). However, the effect appears to be found only in resistant genotypes of the host and only for some strains of *C. rosea* (Moraga-Suazo et al. 2016).
Trichoderma asperellum, strain T34	Application of *T. asperellum* strain T34 together with *F. circinatum* to different types of compost reduced disease incidence pre- and post-emergence of germinating seedlings of *P. radiata* in the composts that were moderately suppressive (López-López et al. 2016).

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