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The role of stump treatment as a preventive control method against Heterobasidion root rot in forestry

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ABSTRACT

Heterobasidion root rot is the primary pathogen threatening forest health and causing significant economic losses in temperate and boreal coniferous forests. Once established, there is no fully effective method to eradicate the infection. However, applying stump treatment during harvesting can prevent new spore infections in healthy stands, as newly created stumps serve as ideal entry points for primary infections. Additionally, climate change is altering the period during which spores are produced, thereby affecting the timing and necessity of stump treatment. Three main substances currently available for stump treatments are urea, borates, and living saprophytic fungi *Phlebiopsis gigantea* (Fr.) Jülich. Although the use of urea and borates is restricted in many countries, we argue they remain essential piece in the toolkit for enhanced forest health, especially as rising temperatures associated with climate change may reduce the efficacy of living organisms like *P. gigantea*. This mini-review summarizes and critically evaluates the different stump treatment methods used against *Heterobasidion* species, with a particular focus on their application in the boreal region.

1. Introduction

Heterobasidion species are regarded as the most economically significant root rot pathogens affecting coniferous forests in the Northern Hemisphere (Garbelotto and Gonthier, 2013). The *Heterobasidion annosum* sensu lato species complex includes three species that are native to Europe: *H. abietinum* (Niemelä and Korhonen), *H. annosum* s.s. (Fr.) Bref., and *H. parviporum* (Niemelä and Korhonen) (Korhonen, 1978). These species have distinct but partially overlapping host preferences, with the primary hosts being *Abies* spp. for *H. abietinum*, *Pinus* spp. for *H. annosum* s.s., and *Picea* spp. for *H. parviporum* (Korhonen, 1978; Capretti et al., 1990; Garbelotto and Gonthier, 2013). In North America, two species have been described: *H. irregulare* Garbel. and Otrosina and *H. occidentale* Otrosina and Garbel, which primarily attack *Pinus* and *Abies* species, respectively (Otrosina and Garbelotto, 2010). *Heterobasidion irregulare* was introduced to Italy during World War II and is now considered an invasive species, causing damage to Italian stone pine (*Pinus pinea* L.) and Aleppo pine (*Pinus halepensis* Mill.) along the western coastline of central Italy (Gonthier et al., 2014; Pellicciaro et al., 2021). There is a high possibility that invasive *H. irregulare* will extend its distribution, threatening European conifers. Thus, preventing new infections and further dispersal is crucial.

Primary infection by *Heterobasidion* spp. occurs, when basidiospores spread through the air and land on freshly exposed wood, such as newly cut stumps or wounds (e.g. damages from thinning operations) on stems (Redfern and Stenlid, 1998). After primary infection, fungus spreads to the neighboring uninjured trees through vegetative growth of the mycelium and root contacts (Garbelotto and Gonthier, 2013). Once the infection is established, there is no reliable method to completely eradicate the pathogen. For this reason, preventing new infections is both economically and environmentally beneficial for maintaining tree health. Stump protection against aerial spore infection is one of the main control strategies to prevent new infections. Another effective method to prevent spore infections is to schedule logging activities during the cold seasons when sporulation is inactive (Gonthier et al., 2005; Piri et al., 2023). However, as the climate warms, an increasing proportion of logging will occur during the growing season with higher risk for new spore infections (Kärhä et al., 2018). Furthermore, rising average temperatures may lead to higher infection rates and increased spread and decomposition activity of *Heterobasidion* spp. in forests (Müller et al., 2014). Therefore, controlling the dispersal of *Heterobasidion* spp. and preventing root rot infections through stump treatment will become increasingly important in the future. More importantly, due to the pathogen's etiology (infections through aerial spores, root rot, and

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basidiocarps in roots beneath forest litter), it can suddenly appear in unexpected areas of new distribution (Kaitera et al., 2023).

Fresh stumps can be protected with either biological or chemical control agents. The biological control fungus *Phlebiopsis gigantea* (Rotstop ®, PG Suspension®, PG IBL®), borates (e.g. $Na_2B_8O_{13}\bullet 4H_2O$, CELLU-TREAT®) and urea (CH_4N_2O) are the most commonly used control agents against *Heterobasidion* spp., and all of them are generally proven effective, although their effectiveness may vary under different circumstances (e.g. tree species, stump size, soil type) (Pratt, 2000; Pratt and Quill, 1996; Thor and Stenlid, 2005; Gunulf et al., 2012; Wang et al., 2012; Gonthier, 2019; Blomquist et al., 2020; Piri et al., 2023).

Scientific literature for this mini-review was identified through searches in Web of Science and Google Scholar covering the period from 1990 to 2025, using targeted keywords and their combinations, such as Heterobasidion root rot, stump treatment, borates, borax, urea, DOT and *Phlebiopsis gigantea*. Additionally, non-scientific sources—including government, EU, and agency websites, manufacturer pages, country reports, chemical databases, and legislation were reviewed via Google Scholar and general Google searches.

2. International usage of stump treatment

2.1. National regulations and guidelines

It is somewhat difficult to track the current use of stump treatments across different countries, as each country has its own legislation or recommendations. The authors are presenting Finland where new infections by *Heterobasidion* species must be controlled in risk areas during the thermal growing season. The obligation to control is written in law (Metsälaki [Forest Act] 1168/2021, 8 a §) and further specified in the Government Decree on the Control of Heterobasidion root rot (*Valtioneuvoston asetus juurikäävän torjunnasta*, 264/2016). Control is mandatory in southern and central Finland when Norway spruce or Scots pine make up more than 50 % of the stand volume. On mineral soils, this requirement applies in both regions if pine, spruce, or both combined exceed the 50 % threshold. On peat soils, treatment is required if Norway spruce exceeds 50 % of stand volume in either region, or if pine and/or spruce together exceed 50 % in southern Finland. All conifer stumps over 10 cm in diameter must be treated, and at least 85 % of each stump surface must be covered. Control is not required if the thermal growing season has not started, the minimum daily temperature during harvest is below 0 °C, there is continuous snow cover, or if the average minimum temperature has been below −10 °C for the past three weeks.

While many countries have guidelines and recommendations for preventing *Heterobasidion* spp. infections, they do not have strict legislation mandating stump treatment like in Finland. Instead, they rely on regional guidelines and best practices to manage the disease. Since legislation differs between countries, forest management practices also vary, which can impact research in this field.

2.2. Availability of treatment agents

As mentioned above, control is carried out by applying a solution of urea, borates or *P. gigantea* to stumps during logging. Three distinct biological control products based on *P. gigantea* have been developed: PG Suspension® in the UK, PG IBL® in Poland and Rotstop® in Finland (Pratt et al., 2000). Of these PG Suspension® and PG IBL® are applied to pine stumps, while Rotstop® is used both on pine and spruce stumps (Pratt et al., 2000). Rotstop® is the most commonly used biological control agent against *Heterobasidion* spp. and widely used in commercial forestry throughout Europe (Thor et al., 2006; Vasiliauskas et al., 2005). Rotstop-C® formulation used to be commercially available also in the North America, but the manufacturer, Lallemand Plant Care, decided to remove it from the North American market in May 2025 (Scanlon, 2025).

Main problem with stump treatment substances is that they are not available in every country. The case of urea in the European Union illustrates this regulatory complexity. Urea was reapproved in the European Union (EU, https://echa.europa.eu) as a low-risk active substance, with the decision taking effect on May 1, 2024, and valid until April 30, 2039. However, to our knowledge, Finland is the only country in the European Union using urea for stump treatment. This means Finland needs to obtain Northern zonal assessment to be approved in the EU to use urea as an active substance in plant protection products. To continue using urea as a plant protection substance in forestry, all holders of urea registrations in Finland must apply for authorization based on zonal assessment. In the EU, a zonal assessment of plant protection products—such as urea in this case—is a system in which one EU Member State, known as the zonal rapporteur Member State, evaluates the product's risks and prepares a comprehensive report for the entire zone, in this case the Northern Zone. Because stump treatment is obligatory in Finland, we believe it is critical to minimum preserve and ultimately expand the available options beyond the current two (Rotstop® and urea) available in Finland.

To the best of our knowledge, the United States is the only country currently using borates to control Heterobasidion root rot. Although borax (disodium tetraborate) was previously used in Canada, it is no longer registered there (Grondin and DesRochers, 2015). In the United States, the liquid borate formulation, Disodium Octaborate Tetrahydrate (DOT), marketed as CELLU-TREAT® by Nisus Corporation, is widely used (Dreaden et al., 2016). As Rotstop®C, formerly the only approved product for stump treatment in Canada (Canadian Forest Service, 2016), is no longer available, the selection of an alternative treatment remains uncertain, though borate-based options like Cellu-Treat® seem a likely alternative.

Both borax and DOT are frequently utilized in the production of compound or mixed fertilizers (Pratt, 1996). Similarly, urea is used as a fertilizer in agriculture, which complicates the search for relevant information on the official webpages of the European Chemicals Agency (ECHA), United States Environmental Protection Agency (EPA), Health Canada and similar agencies. It would be beneficial if this information could be provided separately for agriculture and forestry. The same applies to usage records for each country.

2.3. Influence of forest certification schemes

Forest certification schemes, such as the Forest Stewardship Council (FSC) and the Programme for the Endorsement of Forest Certification (PEFC), significantly influence the choice of stump treatment options by promoting the reduction or avoidance of chemical pesticide use in forestry. Thus, many European countries have opted for biological control agents over urea to minimize chemical use (Zaluma et al., 2021).

FSC, in particular, strongly discourages the use of chemical treatments and favors biological control methods (FSC International, 2023). PEFC also prioritizes biological and silvicultural alternatives but permits chemical stump treatments, provided that risks to human health and the environment are minimized and the use is economically justified (PEFC Council, 2024). In practice, these certification schemes may limit stump treatment options to biological methods in some countries, depending on how the international benchmark standards are interpreted and implemented at the national level.

3. Mode of action

The different stump treatment substances have different modes of action which affect their ease of use and efficacy in practical forestry. When urea (CH_4N_2O) is applied to stumps, it hydrolyzes into ammonia (NH_3) and carbon dioxide (CO_2). The formation of ammonia contributes to an increase in the pH value of the stump surface (Johansson et al., 2002). The protective effect of urea treatment is due to an increase in pH levels above 7, creating conditions in which *Heterobasidion* spp. basidiospores cannot germinate and the mycelium cannot survive (Johansson et al., 2002). A rapid increase in pH during the first few days after logging is crucial, as stumps are most vulnerable to primary infection during this time (Johansson et al., 2002).

Borax ($Na_2B_4O_7 \cdot 10\ H_2O$) and DOT ($Na_2B_8O_{13} \cdot 4\ H_2O$) are the two commonly used forms of borates for stump treatment against *Heterobasidion* spp. (Pratt, 1996). Borates penetrate rapidly into surface tissues of the stump and act as a chemical barrier that prevents infection and hinders the growth of *Heterobasidion* spp. in treated stumps (Pratt, 2000; Pratt and Quill, 1996). Lloyd (1997) concluded that primary mode of action of borates in stump treatment are their direct effects on fungal metabolism.

Phlebiopsis gigantea is naturally occurring saprotrophic fungus that effectively outcompetes *Heterobasidion* spp. for nutrients and space in woody stumps (Pratt et al., 2000; Zaluma et al., 2021). Therefore, the effectiveness of *P. gigantea* as a biocontrol agent against *Heterobasidion* spp. infection largely depends on how quickly and thoroughly *P. gigantea* can colonize the surface of a freshly cut stump (Sun et al., 2009).

Regardless of the substance used, stump treatment is most effective when applied immediately after the felling. However, conifer stumps may remain susceptible to infection for several weeks, with studies reporting a variable susceptibility period ranging from one to four weeks (Redfern and Stenlid, 1998). The exact duration of this susceptibility is not clearly determined, as it is likely influenced by factors such as the amount of airborne inoculum, tree species, and prevailing weather conditions at the time of infection (Gonthier, 2019).

3.1. Environmental effects

As urea treatment changes chemical properties of the stump surface, it has been shown to change fungal community structure of the stump (Vasiliauskas et al., 2004). However, a recent study showed no difference in fungal community composition or diversity in stumps after urea application (Drenkhan-Maaten et al., 2024).

In a Swedish study, both borate and urea solutions had strong negative effect to the majority of ground-vegetation species tested, with bryophytes being more affected than vascular plants, and urea being slightly more toxic than borate (Westlund and Nohrstedt, 2000). Urea also increased the soil pH by two units, but the pH returned to near-normal levels one year after treatment, while concentrations of boron in the soil remained slightly above the threshold for plant injury even after a year (Westlund and Nohrstedt, 2000). Several studies show that application of *P. gigantea* does not have significant or long-term effects on microbes, vegetation, or soil in the test areas (Westlund and Nohrstedt, 2000; Vasiliauskas et al., 2004; Terhonen et al., 2013; Sun et al., 2013; Drenkhan-Maaten et al., 2024). All in all, as the treatments are applied directly on the stump surface and not as blanket cover over large areas, risk of environmental pollution and negative effects on non-target species and areas can be considered rather small.

4. Efficiency trials

The control effectiveness of urea, borates and *P. gigantea* against *Heterobasidion* spp. has been studied extensively both in field trials and laboratory experiments. Appendix 1 presents a structured overview of numerous studies evaluating the performance of these agents across various tree species and geographic regions. While infection incidence is a commonly used metric, it is important to note that some studies emphasize the area colonized by the fungus as a more informative indicator. Studies have reported that even when infection rates remain high, some treatments reduce the colonized area, potentially limiting the pathogen's ability to spread via root contacts (Thor and Stenlid, 2005; Poloni et al., 2021). Therefore, results from the different studies are not necessarily directly comparable.

Although all three treatments have been proven effective, findings suggest that urea and borates tend to yield more consistent results, while the efficacy of *P. gigantea* appears more variable and potentially more susceptible to biotic and abiotic factors (see Appendix 1). Long-term studies by Oliva et al. (2008), (2010) demonstrated that both urea and *P. gigantea* can significantly reduce rot incidence over periods exceeding a decade. However, both treatments showed limited effectiveness in areas with a high level of pre-existing rot (Oliva et al., 2010).

Only a few studies have addressed the efficacy of stump treatment agents on peat soils (Pratt and Redfern, 2001; Piri et al., 2023). Research from the UK indicated that urea was unreliable on peat soils with high annual rainfall, likely due to poor hydrolysis in dead heartwood—the primary infection target in spruce stumps under such conditions (Pratt and Redfern, 2001). However, more recent research from drained peatlands in Finland demonstrated high and consistent efficacy of urea, both with Norway spruce and Scots pine (Piri et al., 2023). In contrast, *P. gigantea* showed variable performance, with effectiveness depending on site conditions and sometimes even increasing infection rates (Piri et al., 2023).

All the three treatments (urea, borates and *P. gigantea*) have had more uniform and better results when applied to Scots pine stumps compared to Norway spruce stumps (Lipponen, 1991; Pratt, 1996; Johansson et al., 2002; Kenigsvalde et al., 2016; Gonthier, 2019; Piri et al., 2023). This difference is especially true in the case of *P. gigantea*, which may be due to the greater natural susceptibility of pine stumps to *P. gigantea* infection compared to spruce stumps (Korhonen, 2003; Drenkhan et al., 2008; Sun et al., 2009; Kenigsvalde et al., 2016). However, Korhonen (2003) suggests that achieving good control efficiency in Norway spruce stumps is possible when the *P. gigantea* treatment suspension has spore concentration of 5 million spores per liter. Beyond pine and spruce, urea has also demonstrated promising results when tested on other conifer species, including European larch, silver fir (Gonthier, 2019), hybrid larch (Wang et al., 2012), and white fir (Poloni et al., 2021).

In general, manual application of the treatment tends to produce more effective results than mechanical application. Field trials have highlighted that achieving 85–100 % coverage of the stump surface is crucial for effective protection against infection (Berglund and Rönnberg, 2004; Kärhä et al., 2018). However, in a recent study Blomquist et al. (2023) found that nearly half of the stumps became infected with *Heterobasidion* spp. despite mechanical treatment with *P. gigantea* (Rotstop®). Even stumps that were assessed as having 100 % coverage showed a 45 % infection rate. Here, the researchers highlighted that forest operators are not achieving sufficient coverage on the stumps that leads to *Heterobasidion* spp. infections (Blomquist et al., 2023). However, it is good to consider that even full coverage does not guarantee complete protection against infection, as treatment efficiency is influenced by a complex interplay of factors, including the concentration and application of the treatment agent, environmental conditions, stump characteristics, and the handling and viability of biological control agents.

5. Factors affecting stump treatment efficiency

5.1. Treatment agent concentration and coverage

A critical factor for effective stump treatment is the initial concentration of the applied agent. In the case of urea, without continuous supply of ammonia by urease activity, initially toxic pH value may be lowered to the level that allows latent *Heterobasidion* spp. growth, as its conidiospores are capable of surviving at high pH values (Johansson et al., 2002). Therefore, high initial concentration of urea is needed to maintain high pH values on stumps for at least the length of time fresh stump surface remain susceptible to infection, which is approximately 2–4 weeks after felling (Johansson et al., 2002; Redfern and Stenlid, 1998). Good results have been obtained with 30 % and 35 % concentration (Brandtberg et al., 1996; Nicolotti and Gonthier, 2005; Thor and Stenlid, 2005; Oliva et al., 2010, 2008; Pellicciaro et al., 2021). Thus, high initial urea concentration (>30 %) is important for the success of stump treatment. Also, in the case of borates, concentration of the DOT solution should be at least 3 % to obtain sufficient control results (Lloyd and Pratt, 1997; Pratt, 2000).

Equally important is the thoroughness of stump surface coverage. A positive correlation exists between treatment effectiveness and the covered area, with 85 % or more coverage being a prerequisite for successful stump treatment (Kärhä et al., 2018). Incomplete coverage, leaves untreated areas vulnerable to colonization by *Heterobasidion* spp. (Blomquist et al., 2023). Moreover, Berglund and Rönnberg (2004) observed that over time *Heterobasidion* spp. spreads down the stump more rapidly than *P. gigantea*, highlighting the importance of treating the entire stump surface. Mechanized stump treatment often results in incomplete stump coverage, which in turn may negatively affect the performance of the treatment, especially in the case of *P. gigantea* (Berglund and Rönnberg, 2004; Oliva et al., 2010; Rönnberg et al., 2006; Blomquist et al., 2023). As Blomquist et al. (2023) demonstrated, there is discrepancy between the careful application by scientists in previous studies and the less controlled conditions in real-world use by harvesters.

5.2. Viability and handling of biological control agents

The efficacy of biological control agents like *P. gigantea* is highly dependent on spore viability, which can be compromised by inadequate storage and handling. *Phlebiopsis gigantea* products, such as Rotstop®, require cool storage conditions (<+5°C) before use, and any failures in the cold chain could compromise the viability of the spores, making the treatment ineffective regardless of coverage (Blomquist et al., 2023). Additionally, while diluted Rotstop® can be stored at room temperature for few days (48 h), the prepared mixture needs to be used within 36 h after preparation (https://rotstop.fi/en/product-info/). This creates some practical obstacles during logging as only the daily usage is recommended to be prepared. Furthermore, the product has a finite shelf life (6 months below +5°C or 12 months below −18°C), and refreezing is prohibited, with higher temperatures significantly reducing its longevity (https://rotstop.fi/en/product-info/).

5.3. Spore pressure and seasonality

If the stump treatment is done carefully and with adequate concentration, variations in the efficiency might be related to exceptionally high *Heterobasidion* spore pressure (Nicolotti and Gonthier, 2005). According to Gonthier (2019), frequency of stump infection by *Heterobasidion* spp. increases throughout the host growing season and most risky periods of primary stump infections are at the end of the growing season, possibly due to the higher availability of airborne inoculum. Even though the efficacy of treatments like urea may be slightly reduced during certain seasons or in the presence or high spore loads, their overall efficacy in preventing primary infections remains high (Gonthier, 2019). It is also good to remember that while stump treatment can prevent the establishment of new genets in already infected stands, it does not prevent the spread of already established *Heterobasidion* spp. colonies (Oliva et al., 2010). If forest has inoculum already from previous rotations, root rot incidence may increase despite the stump treatment.

5.4. Stump characteristics and tree species

Stump size, tree species and wood properties have also been shown to affect treatment efficiency (Johansson et al., 2002; Gonthier, 2019; Blomquist et al., 2020). Blomquist et al. (2020) studied efficacy of urea and *P. gigantea* in precommercial thinnings (stump diameter 2.0–15.9 cm) and final felling (stump diameter 11.25–58.0 cm). Urea performed better and had higher mean efficacy values (92–94 %) compared to *P. gigantea* (59 %-72 %) in precommercial thinnings, but there was not significant difference in the performance of two control agents in final fellings (Blomquist et al., 2020). Therefore, Blomquist et al. (2020) recommended using urea in precommercial thinnings if possible.

The distribution and activity of urease within the stump wood also influence urea treatment effectiveness. Johansson et al. (2002) observed that urea hydrolysis started briefly after treatment in whole sapwood of pine and in the outer sapwood of spruce, from where it slowly spread inwards. In spruce, urease activity decreased from outermost (youngest) annual rings towards inwards, with very low activity in the heartwood. The significantly higher urease activity in the whole pine sapwood might explain the stronger protective ability of urea on pine stumps compared to spruce (Johansson et al., 2002). Ultimately, the effectiveness of urea treatment depends on the availability of urease-rich sapwood, which is more abundant in young trees (Johansson et al., 2002).

In general, Gonthier (2019) suggested that tree species susceptibility to *Heterobasidion* spp. infections might be driven by wood characteristics such as presence and relative abundance of extractives.

5.5. Weather conditions

Weather conditions, particularly moisture and temperature, can significantly impact treatment efficiency. Drying out of the stump surface in combination with warm weather inhibits urea hydrolysis and reduces the effectiveness of urea treatment, and thus a dry period in summer may lead to reduced control efficacy (Johansson et al., 2002). However, Piri et al. (2023) did not find any effect of dry summer on stump moisture content, and efficacy of urea treatment was high regardless of dry and warm summer. In the case of *P. gigantea,* spores lose their viability at temperatures above 30 ° (Thor et al., 1997), and the manufacturer's page also states that Rotstop® should not be used at temperatures exceeding 40 °C, which can be easily reached in summertime final harvests at stump surfaces.

Conversely, Johansson et al. (2002) found that warm, rainy conditions can enhance urease activity in stumps, favor diffusion of urea and ammonia downwards into the stump wood as well as promote the establishment of urease-producing microorganisms. However, excessive moisture can also be detrimental. Pratt and Redfern (2001) observed that urea application on Sitka spruce stumps in areas with heavy rainfall did not protect against *Heterobasidion* spp. inoculation and even facilitated colonization on peat soils. This was hypothesized to be because *Heterobasidion* spp. benefits from additional nitrogen, especially in the drier heartwood, which becomes a preferred substrate in peatland environments with high annual rainfall (Pratt and Redfern, 2001). In contrast, Piri et al. (2023) found no evidence that urea treatment promotes *Heterobasidion* spp. infection on peatlands, with infections occurring mainly in the sapwood and at the sapwood-heartwood boundary. Although high wood moisture content does not prevent *Heterobasidion* spp. infection, it can hinder mycelial growth and colonization (Bendz-Hellgren & Stenlid, 1998). Additionally, heavy rainfall during or after felling can dilute any treatment agent on the stump surface, affecting inoculation success, as discussed by Blomquist et al. (2023).

6. Future directions and summary

Heterobasidion spp. are the primary fungal pathogens that reduces the value of conifer wood. Climate change is benefiting this pathogen by creating longer periods for spore production and reducing frost in forests in the Northern hemisphere, which leads to more inoculations due to thinning-related damages in trees. Currently, the most effective option to control its dispersal and distribution during growing season harvests is to treat stumps preventing new spore infections at healthy sites. Carrying out management operations during wintertime is effective yet not feasible especially in areas with intensive forest management. Other Heterobasidion control methods, such as tree breeding for resistance (Elfstrand et al., 2020), mycoviruses (Vainio et al., 2018), and change of

Table 1
Pros and cons of using urea, *Phlebiopsis gigantea* and borates in stump treatment.

Criteria	Urea	*Phlebiopsis gigantea*	Borates (DOT)
Temperature	Chemically stable across temperatures, but effectiveness depends on temperature and moisture; hydrolysis is inhibited in dry, warm conditions and enhanced in moist, warm conditions.	Loses viability at temperatures above 30°C, less effective in hot conditions.	Stable under various temperatures. DOT solubility is temperature-sensitive: maintaining higher concentrations (e.g., 10 %) becomes more difficult as temperatures drop below 10°C.
Host species	Tested to be effective on Scots pine, Norway spruce, Sitka spruce, white fir, European larch, and hybrid larch. More effective on Scots pine than on Norway spruce.	Tested to be effective on Scots pine, Norway spruce, white fir and hybrid larch. More effective on Scots pine than on Norway spruce.	Tested to be effective on Scots pine, Norway spruce and Sitka spruce. More effective on Scots pine than on Norway spruce.
Effects on soil and surrounding vegetation	May change fungal community structure, potential negative effects on surrounding vegetation (lichens, bryophytes), and a temporary increase in soil pH	Naturally occurring, minimal environmental impact, no significant effect on soil or vegetation. The commercialization is based on one strain.	Potential negative effects on surrounding vegetation, may increase concentrations of boron in the soil.
Application mechanically in the field (commercial thinnings and final harvests)	Reliable with proper concentration and coverage. Applicable in cold temperatures.	Practical difficulties: maintenance of cold chain, mixture must be used 36 h after preparation. Risk of freezing of the product in cold temperatures in harvester machine pipelines if the system lacks heating or thermal insulation.	Reliable with proper concentration and coverage. Risk of crystallization or freezing in the harvester machine's pipelines at temperatures below 10 °C if the system lacks heating or thermal insulation.
Precommercial thinnings	Good performance in smaller stumps (92–94 % efficacy in thinnings)	Less effective in smaller stumps (59 %–72 % efficacy in thinnings)	Not reported

managed species, target more on preventing secondary spread and their effects will be measured in longer time horizon compared to stump treatments. Similarly, the search for new biotic competitors that either affect the pathogen or improve tree health is time-consuming and requires long-term evaluation (Terhonen et al., 2019).

The stump treatment against *Heterobasidion* spp. has been intensively studied, but the results vary. To successfully prevent new infections in changing environmental conditions, both chemical and biological options for stump treatment are needed. The choice of method should be based on the site, tree species, practicality, and temperature (see Table 1). Since *P. gigantea* spores lose their viability at temperatures above 30 °C (Thor et al., 1997), urea or borates should be maintained as an option. Moreover, introducing a saprophyte to living tree cells (freshly cut stumps) raises questions about the evolution of *P. gigantea* and the potential to switch lifestyles. The increasing effects of climate change (more sunlight, higher temperatures) and the faster warming of the Nordics (Rantanen et al., 2022) create new challenges, and we need to have multiple options available.

Once root rot appears in a forest site, it cannot be reliably eradicated. We need to consider, in addition to stump treatment, strategies to increase the diversity of tree species in forests (not all suitable hosts are available, resulting in fewer root contacts) and to emphasize the importance of dead wood in maintaining biodiversity (which can support more competitors). We should also reflect on why *Heterobasidion* spp. are not a problem in natural forests.

Long-term research on eradicating/managing existing Heterobasidion infections is still ongoing, despite decades of study. A universally suitable management method that works across all countries and forest types has not yet been found. However, stump treatment has proven effective in preventing new infections. Effective forest management strategies should place strong emphasis on the prevention of new infections. In Finland, the use of urea and Rotstop® has shown good results. It is important that decision-makers, forest owners, and forestry professionals work together to ensure that at least these two options remain available for prevention of new infections. As climate change creates increasingly extreme conditions for trees, the environment, and pathogens, research should focus on testing the effectiveness of current control methods under such conditions. In parallel, new management options suitable for a changing climate should be developed.

Moreover, recommendations and obligations in each country should be communicated more openly and effectively. While writing this review, the authors noted that more work is needed on this topic, including the creation of a network involving researchers, stakeholders, and decision-makers not only national level rather international.

CRediT authorship contribution statement

Terhonen Eeva: Writing – review & editing, Conceptualization. **Wahlman Werna:** Writing – review & editing, Writing – original draft, Conceptualization. **Honkaniemi Juha:** Writing – review & editing, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1. Efficacy trials of urea, *P. gigantea* and borates

Reference	Country	Tree Species	Treatment	Application Method	Infection incidence / efficacy of treatment	Key findings
Brandtberg et al., (1996)	Sweden	Norway spruce	Urea (30 %)	Manual	85 % reduction in *Heterobasidion* spp. incidence compared to untreated stumps	Study was done in previously unthinned first-rotation stands on former arable land. Urea effectively reduced the *Heterobasidion* spp. incidence.
			Urea (20 %), transformed to a gel by adding 0.2 % carboxymethyl cellulose	Manual	62 % reduction in *Heterobasidion* spp. incidence compared to untreated stumps	
Nicolotti and Gonthier, (2005)	Italy	Norway spruce	Urea (10 %)	Manual	90 % infection incidence	Urea was less effective compared to Rotstop® and borax powder, although all treatments (except the 10 % urea solution) resulted in significantly lower colonization of stumps compared to controls. Study was done in heavily infested area, where at least 27 % of the trees were infected by *Heterobasidion* spp.
			Urea (20 %)	Manual	38 % infection incidence	
			Urea (30 %)	Manual	34 % infection incidence	
			Rotstop®	Manual	21 % infection incidence	
			Borax powder	Manual	28 % infection incidence	
			Control (untreated stumps)	-	100 % infection incidence	
Thor and Stenlid, (2005)	Sweden	Norway spruce	Urea (35 %)	Manual	3 % infection incidence	Urea was most effective and Rotstop® least effective treatment. When considering stump surface area colonized, all treatments significantly reduced colonized stump area by 88–99 % and effects of different treatments did not differ from each other, or from winter thinning.
			Urea (35 %)	Mechanical	19 % infection incidence	
			DOT (5 %)	Manual	18 % infection incidence	
			DOT (5 %)	Mechanical	34 % infection incidence	
			Rotstop®	Manual	12 % infection incidence	
			Rotstop®	Mechanical	42 % infection incidence	
			Control (untreated stumps)	-	90 % infection incidence	
Zaluma et al., (2021)	Latvia	Norway spruce	Rotstop® / covered with wooden discs	Manual	3 % infection incidence, 95.29 % control efficacy	Study evaluated the effectiveness of different substances against *Heterobasidion* spp., while also examining whether covering treated stumps with wooden discs would create a stable microclimate to enhance the efficacy of these substances. Urea was less effective compared to Rotstop® and *P. gigantea* strain 442. Control efficacy was calculated based on the proportion of infected stumps and area occupied by the pathogen.
			Rotstop® / uncovered	Manual	14 % infection incidence, 60.58 % control efficacy	
			P. gigantea strain 422 / covered	Manual	5 % infection incidence, 92.93 % control efficacy	
			P. gigantea strain 422 / uncovered	Manual	13 % infection incidence, 62.0 % control efficacy	
			Urea (35 %) / covered	Manual	38 % infection incidence, 47.71 % control efficacy	
			Urea (35 %) / uncovered	Manual	17 % infection incidence, 45. 78 % control efficacy	
			Control (distilled water) / covered	Manual	53 % infection incidence	
			Control (distilled water) / uncovered	Manual	35 % infection incidence	
Oliva et al., (2008)	Sweden	Norway spruce	Urea (35 %)	Manual	2.7 % rot incidence of which 0 % *H. annosum* s.l.	Long-term study conducted in first-rotation Norway spruce stands. After 15 years, the trees were sampled using an increment borer and observed for presence of rot and, following incubation, presence of *H. annosum* s.l. conidia. Urea effectively reduced Heterobasidion root rot even after long time period.
			H. annosum conidia suspension (artifical infection)	Manual	68.4 % rot incidence of which 23.4 % *H. annosum* s.l.	
			Urea treatment (35 %) of half of the stumps and artificial infection of the other half of the stumps	Manual	46.7 % rot incidence of which 10.7 % *H. annosum* s.l.	
			Control (no treatment)	-	43.2 % rot incidence of which 15.7 % *H. annosum* s.l.	
Oliva et al., (2010)	Sweden	Norway spruce	Urea (35 %), agricultural land	Mechanical	3.2 % infection incidence	Long-term study (13 years). Both urea and Rotstop® significantly reduced rot incidence in Norway spruce stands on former agricultural land, with urea showing slightly higher efficacy. In stands on former forest land, neither treatment showed a significant effect, likely due to the presence of preexisting Heterobasidion root rot infections. Effectiveness of Rotstop® was found to be more sensitive to incomplete stump coverage compared to urea.
			Urea (35 %), forest land	Mechanical	17.9 % infection incidence	
			Rotstop®, agricultural land	Mechanical	6.5 % infection incidence	
			Rotstop®, forest land	Mechanical	16.7 % infection incidence	
			Control (no treatment), agricultural land	-	20 % infection incidence	
			Control (no treatment), forest land	-	14.1 % infection incidence	
Pratt and Quill, (1996)	UK	Sitka spruce	DOT (4 %)	Manual	0 % sapwood and 0.5 % heartwood (surface area colonized by *H. annosum* s.l.)	After 10 months infection was more prevalent in heartwood than sapwood. Infection incidence remained high with both 2 % and 4 % DOT treatment, however, researchers suggest that the small area colonized by Heterobasidion spp. would likely be insufficient to produce viable inoculum for further root transmission.
			DOT (2 %)	Manual	0.1 % sapwood and 7.8 % heartwood	
			DOT (1 %)	Manual	3.1 % sapwood and 18.1 % heartwood	
			DOT (0.5 %)	Manual	8.4 % sapwood and 14.3 % heartwood	
			Control (no treatment)	-	3.7 % in sapwood and 22.1 % in heartwood	
Pratt, (2000)	UK	Sitka spruce	DOT (3 %)	Manual	0 % infection incidence at low inoculum density, 12 % at medium inoculum density	The effectiveness of DOT was tested in six trials using *H. annosum* spore inoculations at concentrations from 49 to 4.9 × 10^5 viable

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Reference	Country	Tree Species	Treatment	Application Method	Infection incidence / efficacy of treatment	Key findings
					and 52 % at high inoculum density	spores/ml. Here, 3 % DOT treatment was most effective, preventing infection at low spore densities and reducing infection at higher densities.
			DOT (1.5 %)	Manual	7 % (low inoculum density), 55 % (medium inoculum density) and 83 % (high inoculum density)	
				Control (no treatment)	-	
28 % (low inoculum density), 77 % (medium inoculum density) and 87 % (high inoculum density)						
Lloyd and Pratt, (1997)	UK	Sitka spruce	DOT (10 %)	Mechanical	0 % infection incidence	3 % DOT solution resulted in 24.5 % infection in Scots pine and Sitka spruce stumps, while higher concentrations (5 % and 10 %) led to 0 % infection.
		Sitka spruce	DOT (5 %)	Mechanical	0 % infection incidence	
		Sitka spruce, Scots pine	DOT (3 %)	Mechanical	24.5 % infection incidence	
		Sitka spruce, Scots pine	DOT (1.5 %)	Mechanical	74 % infection incidence	
		Sitka spruce, Scots pine	Control (no treatment)	-	84 % infection incidence	
Gonthier, (2019)	Italy	Norway spruce	Urea (30 %)	Manual	3.7 % infection incidence	Untreated Norway spruce had significantly higher infection rate than other tree species. Urea effectively reduced amount of infection in all tree species.
		Norway spruce	Control (no treatment)	-	29.4 % infection incidence	
		European larch	Urea (30 %)	Manual	2.9 % infection incidence	
		European larch	Control (no treatment)	-	12.3 % infection incidence	
		Scots pine	Urea (30 %)	Manual	0 % infection incidence	
		Scots pine	Control (no treatment)	-	5 % infection incidence	
		Silver fir	Urea (30 %)	Manual	0 % infection incidence	
		Silver fir	Control (no treatment)	-	10 % infection incidence	
Kenigsvalde et al., (2016)	Latvia	Norway spruce	Rotstop®	Manual	17 % infection incidence	Rotstop® reduced Heterobasidion spp. infection in Norway spruce stumps by an average of 64 % based on the number of infected stumps and by 89 % based on the infected wood area in sample discs. For Scots pine, the corresponding figures were 82 % and 95 %, respectively.
		Norway spruce	Control (no treatment)	Manual	52 % infection incidence	
		Scots pine	Rotstop®	Manual	3 % infection incidence	
		Scots pine	Control (no treatmnet)	Manual	28 % infection incidence	
Wang et al., (2012)	Sweden	Hybrid larch	Urea (40 %), (study I)	Manual	4.0 % infection incidence	Because of low levels of spore infection on the control stumps at some sites in study I, a follow-up study was done to further investigate the efficacy of *P. gigantea*. Both urea and *P. gigantea* effectively reduce infections on hybrid larch stumps, although urea tends to provide more consistent results.
			Rotstop® (study I)	Manual	18.2 % infection incidence	
			Control (study I)	Manual	24.6 % infection incidence	
			Rotstop® (study II)	Manual	10.1 % infection incidence	
			Control (study II)	Manual	32.2 % infection incidence	
Poloni et al., (2021)	USA (California)	White fir	Borate (12 %)	Manual	Reduced stump colonization by 91 %	Only borates significantly lowered the number of *H. occidentale* infected stumps. No statistically significant differences were found between treatments when considering colonized area.
			Urea (30 %)	Manual	Reduced stump colonization by 84 %	
			Californian isolates of *P. gigantea*	Manual	Reduced stump colonization by 68 %	
			Control (deionized water)	Manual	74 % of stumps infected	
Pratt and Redfern, (2001)	UK	Sitka spruce	Urea (17 %) (peat soil)	Manual	3.7 % infection incidence	Urea treatment of Sitka spruce stumps was found to fail in providing a consistent control on soils subjected to high annual rainfall. Although urea did not reduce the incidence of infection following artificial inoculation, it lowered the rate of natural infection. In inoculated stumps that became infected, urea significantly increased the extent of fungal colonization—especially on peat soils—whereas this effect was not observed in naturally infected stumps.
			Urea (17 %) + artificial inoculation (peat soil)	Manual	86.7 % infection incidence	
			Untreated (peat soil)	-	8.7 % infection incidence	
			Artificial inoculation (peat soil)	Manual	76.0 % infection incidence	
			Urea (17 %) (mineral soil)	Manual	3.3 % infection incidence	
			Urea (17 %) + artificial inoculation (mineral soil)	Manual	80.5 % infection incidence	
			Untreated (mineral soil)	-	9.0 % infection incidence	
			Artificial inoculation (mineral soil)	Manual	86.6 % infection incidence	

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Reference	Country	Tree Species	Treatment	Application Method	Infection incidence / efficacy of treatment	Key findings
Piri et al., (2023)	Finland	Scots pine	Urea (32.5 %) + artificial inoculation	Manual	1.4 % infection incidence, 99.5 % average control efficacy	Each stump was divided in half—one side was treated and the other left untreated as a control. Efficacy was calculated by comparing the area infected by Heterobasidion on the treated half versus the untreated half of the same stump. While urea provided consistent results across study sites and tree species, the effectiveness of *P. gigantea* varied widely, sometimes even increasing Heterobasidion infection rates in treated stumps.
		Scots pine	Rotstop® + artificial inoculation	Manual	47.5 % infection incidence, 54.3 % average control efficacy	
		Norway spruce	Urea (32.5 %) + artificial inoculation	Manual	59.5 % infection incidence, 85.3 % average control efficacy	
		Norway spruce	Rotstop® + artificial inoculation	Manual	71.2 % infection incidence, 37.3 % average control efficacy	
Berglund and Rönnberg, (2004)	Sweden	Norway spruce	Rotstop®, 100 % coverage	Manual	30 % infection incidence after 3 months and 26 % after 12 months	Stumps were treated with *P. gigantea* at varying coverage rates and sampled at 3 and 12 months. Untreated control stumps showed high infection rates, while 100 % coverage treatment had the lowest infection rates. Control efficacy, measured by infected stump area, ranged from 71 % to 78 % within 3–12 months after treatment.
			Rotstop®, 75 % coverage	Manual	51 % infection incidence after 3 months and 44 % after 12 months	
			Rotstop®, 50 % coverage (horizontal)	Manual	65 % after 3 months and 40 % after 12 months	
			Rotstop®, 50 % coverage (striped)	Manual	65 % infection incidence after 3 months and 54 % after 12 months	
			Untreated control	-	80 % infection incidence after 3 months and 69 % after 12 months	

Data availability

No data was used for the research described in the article.

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