

Review

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Review

Pruning Practices and Grapevine Trunk Diseases: A Critical Analysis of Infection Dynamics, Management Strategies and Research Gaps

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Abstract

Grapevine trunk diseases (GTDs), caused mainly by fungal ascomycetes and some basidiomycetes, threaten vineyard sustainability through yield losses, higher management costs and reduced vineyard lifespan. Because pruning wounds are the main infection courts, pruning decisions strongly shape GTD risk. This review critically analyses advances over the last decade, with a particular focus on studies published since 2018, on how pruning practices influence infection dynamics and management outcomes across GTD complexes. We synthesize evidence on spore dispersal and weather drivers, temporal patterns of wound susceptibility, and the performance of mitigation strategies, including pruning timing (early/late and double pruning), training systems and sap-flow-oriented pruning concepts, optimization of wound number and size, and inoculum reduction through sanitation and remedial surgery. We also review recent field evaluations of pruning-wound protectants under artificial inoculation and natural infection, covering fungicides, biological control agents and physical barriers. Reported outcomes are highly variable among regions, climates and pathogen groups, indicating that universal recommendations are unreliable without local epidemiological context. Priority research gaps include: (i) field validation of traditional pruning concepts (protective wood/desiccation cones and diaphragm preservation) under natural infection; (ii) the epidemiological contribution of growing-season wounds; (iii) mechanistic drivers of the wide range of reported wound-susceptibility duration; (iv) development of cold-tolerant biological control agents effective across pathogen-host combinations; and (v) validation and transferability of spore-dispersal and risk-forecast models across viticultural regions. Overall, GTD management is best approached as a region-adapted, integrated strategy combining pruning decisions, inoculum management and timely wound protection.

Keywords: fungal trunk pathogens; pruning wound protection; training systems; *Vitis vinifera*; wound susceptibility

1. Introduction

Grapevine (*Vitis vinifera* L.) is one of the world's most economically important fruit crops, with global production exceeding 77 million tonnes annually (FAOSTAT, 2023). Although grapevines are naturally vigorous lianas, training and pruning have been central viticultural practices for more than 2,000 years (Mullins et al., 1992). Pruning limits vegetative growth, adapts vines to specific training systems, and helps balance vegetative and reproductive development, ultimately supporting fruit quality and yield (Jackson, 2008). However, pruning inevitably creates wounds that act as primary infection courts for the fungal pathogens associated with grapevine trunk diseases (GTDs).

GTDs comprise several disease complexes, including *Botryosphaeria dieback*, the Esca complex, *Eutypa dieback*, *Phomopsis dieback* and other emerging wood diseases (Gramaje et al., 2018). Collectively, they reduce vineyard longevity, increase management and replanting costs, and can lead to substantial yield losses and vine death. In California alone, losses have been estimated at more than US\$1.5 billion annually (Kaplan et al., 2016). Although comparable annual economic estimates are not available for all grape-growing regions, the global distribution and chronic nature of GTDs make sustainable and region-adapted management strategies urgently needed.

Recent studies confirm that GTD impacts remain substantial but highly context-dependent. In Central Chile, *Botryosphaeria dieback* in 'Cabernet Sauvignon' vineyards was associated with estimated yield losses of 30.7-52.9% in 2010 and 42.0-52.3% in 2018, depending on region (Larach et al., 2020). In France, vineyard dieback has been estimated to reduce AOP yields by 4.6 hL ha⁻¹, corresponding to 3.4 million hL at the national scale, with projected economic losses reaching €2 billion in lost turnover if yield-loss trends continued (Mahé et al., 2019). However, long-term esca monitoring in Bordeaux also illustrates that economic impact can vary strongly with disease definition and scale: individual vines with a history of esca showed an average yield loss of approximately 41%, but parcel-scale yield losses were often limited because annual foliar symptom incidence was low and highly variable among years (Dewasme et al., 2022). These contrasting results highlight the need for management recommendations that are region-specific, disease-specific and based on realistic field impacts rather than generalized assumptions.

Since the comprehensive review by Gramaje et al. (2018) on the role of pruning wounds in GTD infection, significant advances have been made in understanding infection dynamics, evaluating protective treatments, and identifying critical research gaps. Recent studies have refined our understanding of airborne inoculum seasonality, rainfall- and humidity-driven spore release, pruning-wound susceptibility periods, biological control performance, chemical wound-protection strategies, remedial surgery, training system architecture, and the epidemiological relevance of spring/summer pruning wounds. These developments justify an updated synthesis focused specifically on pruning-related infection courts and management decisions.

The objectives of this review are to: (1) critically analyse research published since 2018 and available up to early 2026 on how pruning practices shape GTD infection dynamics, with emphasis on sources of variability among studies; (2) evaluate the performance and practical feasibility of key management strategies, including pruning timing, training systems, wound protection, and inoculum reduction, across regions and pathogen groups; and (3) identify major research gaps and priorities for future work. Rather than providing a purely descriptive compilation, we focus on contradictions among studies, methodological limitations, and an evidence-based framework for decision-making in GTD management through strategic pruning practices.

GTD development and symptom expression are also modulated by broader vineyard management and environmental factors, including water availability, nutrition, soil conditions, weed competition, cultivar/rootstock background and other biotic or abiotic stresses, as emphasized in systemic approaches to GTD complexity (Claverie et al., 2020). However, these factors are not reviewed comprehensively here. They are considered only where they directly interact with pruning-related processes, such as wound susceptibility and healing, vine vigour, sap-flow continuity, remedial surgery recovery, or the performance of pruning-wound protectants. This delimitation is necessary to maintain the focus of the review on pruning practices as infection courts and management levers for GTDs.

2. Fungal Biology and Epidemiology

2.1. GTD-Associated Pathogens and Their Infection Biology

GTDs are caused by a diverse assemblage of fungal pathogens, predominantly ascomycetes, with varying host specificity, virulence, and geographic distribution. The major GTD complexes include:

Botryosphaeria dieback, caused by species in the family *Botryosphaeriaceae*, particularly *Neofusicoccum parvum*, *Diplodia seriata*, *Botryosphaeria dothidea*, *Lasiodiplodia theobromae*, and several other species (Úrbez-Torres, 2011; Gramaje et al., 2018). These fungi are characterized by their ability to remain latent in asymptomatic wood and to cause disease under plant stress conditions (Slippers and Wingfield, 2007).

Eutypa dieback, primarily caused by *Eutypa lata* (family *Diatrypaceae*), though other diatrypaceous fungi such as *Cryptovalsa ampelina* and *Eutypella* spp. have also been implicated (Trouillas et al., 2010; Trouillas and Gubler, 2010). *Ea. lata* produces phytotoxic compounds that cause characteristic dieback symptoms in affected vines.

Esca complex, a multifaceted disease involving several fungi including *Phaeoconiella chlamydospora*, *Phaeoacremonium minimum*, and wood-degrading basidiomycetes such as *Fomitiporia mediterranea* (Gramaje and Eichmeier, 2026). The disease manifests in multiple forms, including young esca (Petri disease in nursery plants; Gramaje and Armengol, 2011) and esca proper in mature vineyards (Lecomte et al., 2012).

Other trunk diseases include Phomopsis dieback (caused by *Diaporthe ampelina*, formerly *Phomopsis viticola*) (Úrbez-Torres et al., 2013), and Cytospora canker, caused by species in the genus *Cytospora* (Lawrence et al., 2017).

All these pathogens share a common infection pathway as shown in Figure 1. While this figure specifically depicts *Botryosphaeria* dieback, similar cycles apply to other GTDs with variations in spore morphology, dispersal patterns, and environmental requirements. GTD pathogens colonize grapevine wood primarily through pruning wounds, though natural wounds (e.g., leaf scars, frost cracks, mechanical damage) can also serve as entry points. Following wound colonization, pathogens grow systemically through the vascular tissue, causing wood necrosis, vascular dysfunction, and ultimately the characteristic external symptoms of each disease complex. The latency period between initial infection and symptom expression can range from months to several years, complicating disease diagnosis and management (Gramaje et al., 2018).

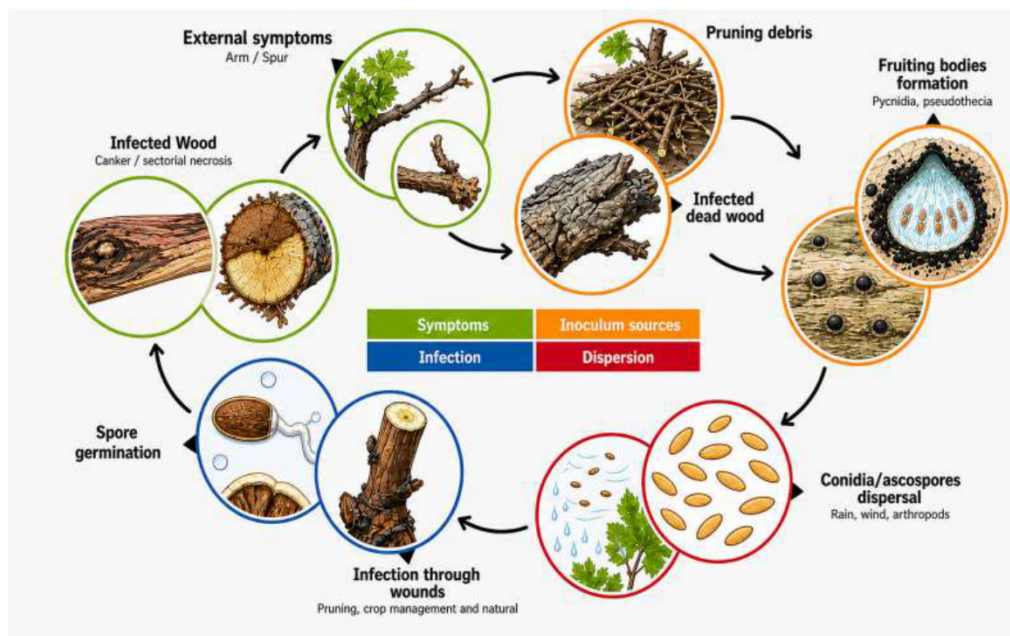


Figure 1. Schematic life cycle of *Botryosphaeria* dieback in grapevine. Infected wood and pruning debris act as inoculum sources, where fruiting bodies produce conidia that are dispersed mainly by rain splash and wind-driven rain. Spores infect susceptible pruning or natural wounds, germinate on exposed xylem, and colonize woody tissues, leading to internal necrosis, cankers, dead spurs or arms, and external dieback symptoms. Although illustrated for *Botryosphaeria* dieback, similar pruning-wound infection pathways apply to several

grapevine trunk disease pathogens, with differences in spore morphology, dispersal biology and environmental requirements.

2.2. Spore Dispersal Patterns and Environmental Drivers

Understanding spore release and dispersal dynamics is essential for optimising pruning timing and wound protection in GTD management. Across pathogen groups, rainfall is a major trigger of spore release, while temperature and humidity modulate seasonal availability; however, the relative importance of these drivers varies strongly among taxa and viticultural regions.

Spore-trapping studies across regions reveal marked climatic contrasts (Figure 2). **A recent quantitative synthesis of 247 spore-trapping studies confirmed that airborne inoculum of GTD fungi shows broad seasonal structure but also strong syndrome- and hemisphere-dependent variability: *Botryosphaeriaceae* inoculum was generally more frequent during autumn-winter periods, *Esca*-associated fungi showed less uniform patterns, and *Eutypa*-associated fungi displayed narrower regional peaks** (Ji et al., 2024). In Mediterranean climates, spore release is often concentrated in winter and overlaps with dormant pruning (Úrbez-Torres et al., 2010; van Niekerk et al., 2010; González-Domínguez et al., 2020; Fujiyoshi et al., 2021). In maritime or humid climates, such as New Zealand and some Australian regions, spore availability can extend for longer periods or occur year-round (Amponsah et al., 2009; Billones-Baaijens et al., 2023). Desert conditions represent an important exception: in Coachella Valley, California, *Diatrypaceae* (*Eutypella* spp.) spores were detected year-round, with autumn-winter peaks and weak rainfall dependence, suggesting that alternative inoculum reservoirs or dispersal mechanisms may operate under arid conditions (Úrbez-Torres et al., 2020).

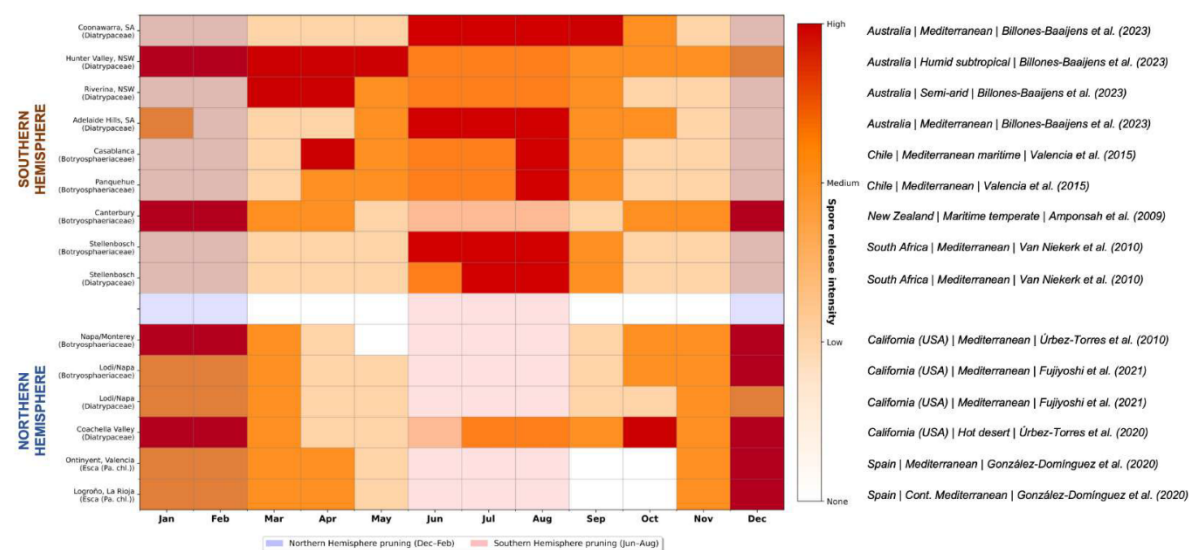


Figure 2. Regional variation in seasonal spore release patterns of grapevine trunk disease pathogens across six viticultural regions. Heat map showing monthly spore release intensity based on field spore-trapping studies conducted in Australia, Chile, New Zealand, South Africa, California (USA), and Spain. Colour intensity represents relative abundance of trapped spores: white (no spores detected), light orange (low), medium orange (medium), and dark orange-red (high). Shaded vertical bands indicate typical dormant pruning periods for Northern Hemisphere (blue, December-February) and Southern Hemisphere (red, June-August). Data are grouped by hemisphere and ordered by country. Pa. chl. = *Phaeomoniella chlamydospora*; Cont. = Continental.

For *Botryosphaeria dieback*, conidial release by *Botryosphaeriaceae* is typically rainfall-driven, but the duration and timing of risk differ among regions. Winter peaks have been reported in Mediterranean regions of California (Úrbez-Torres et al., 2010), year-round presence in New Zealand (Amponsah et al., 2009), and autumn-winter peaks in Mediterranean/ocean-influenced vineyards of Chile (Valencia et al., 2015). **Recent work in Oregon further confirms that *Botryosphaeriaceae* spore**

release can be seasonally restricted but regionally variable, with detections concentrated from late autumn to winter and associated more strongly with cumulative humidity, precipitation and temperature conditions than with single weather variables alone (Hernandez and Kc, 2024). For *Diatrypaceae*, ascospore detection also varies strongly among regions; rainfall is a main driver in many temperate and Mediterranean areas, and hydrated stromata can sustain release after rain, whereas high temperatures can suppress it (van Niekerk et al., 2010; Billones-Baaijens et al., 2023; Sosnowski et al., 2023). However, the desert pattern described above challenges the assumption of universal rainfall dependence (Úrbez-Torres et al., 2020).

Spore dispersal of esca-associated fungi remains less clear. Although *Pa. chlamydospora* DNA has been detected during dormancy using molecular approaches (González-Domínguez et al., 2020), several studies report limited or no capture with conventional trapping, suggesting a greater role for short-distance splash dispersal, vectors or infected propagation material (van Niekerk et al., 2010; Fujiyoshi et al., 2021; Sosnowski et al., 2024). Predictive modelling approaches have provided important progress. González-Domínguez et al. (2020) modelled *Pa. chlamydospora* spore detection in Spanish vineyards using hydrothermal time, showing that integrating rainfall and temperature improves prediction accuracy and may support decision tools, despite occasional detections under high humidity without recorded rainfall.

Overall, these findings demonstrate that universal pruning-timing recommendations are inappropriate. GTD management should instead be adapted to regional spore dispersal patterns, climatic conditions and dominant pathogen species. In regions with defined high-risk periods, delayed or double pruning may reduce infection risk, whereas in areas with continuous or poorly predictable spore availability, consistent wound protection is likely to be more effective than timing alone.

3. Influence of Spring and Summer Shoot Management

Compared with dormant pruning, the epidemiological role of spring/summer canopy operations (“green pruning”) as infection courts for GTD pathogens remains comparatively understudied. Shoot thinning, positioning, leaf removal and cluster thinning generate numerous fresh wounds during active vine growth, when spores of some GTD pathogens may also be present.

Experimental evidence confirms that growing-season wounds can be intrinsically susceptible. Under greenhouse conditions with artificial inoculation, Sosnowski and Ayres (2022) showed that shoot-removal wounds can be infected by *Da. seriata* and *Ea. lata*, indicating that green operations could contribute to GTD development. However, such assays mainly quantify susceptibility under high inoculum pressure and controlled exposure, and therefore do not necessarily translate into infection risk under commercial conditions.

Field evidence highlights the gap between wound susceptibility and real-world infection. In Australia, shoot-thinning wounds created by tearing (“socket” wounds) or secateurs showed substantial pathogen recovery under artificial inoculation, but negligible natural infection (0-11%), indicating that infection depends on the coincidence of susceptible wounds with inoculum and conducive weather, particularly rainfall that promotes dispersal and wound wetness (Sosnowski et al., 2025). In contrast, natural detections of GTD pathogens in green tissues in South Africa suggest that growing-season infections may occur under higher inoculum pressure and/or more frequent rainfall (Makatini et al., 2023).

Spore presence during the growing season supports a plausible infection window. *Botryosphaeriaceae* conidia can be detected year-round in maritime climates, with summer peaks reported in New Zealand (Amponsah et al., 2009), and diatrypaceous spores have been detected sporadically across the year in Australian surveys (Billones-Baaijens et al., 2023). Yet, the relative contribution of spring/summer infections versus dormant-season infections to long-term trunk disease development remains unresolved.

From a practical perspective, protecting the large number of green-operation wounds is challenging and is often not supported by registered products. **Biological protection of growing-**

season wounds has nevertheless been explored: in South Africa, application of *Trichoderma atroviride* Eco-77® to sucker wounds reduced recovery of *Pa. chlamydospora*, although protection against *De. ampelina* was not significant, suggesting that BCA performance on green-operation wounds may be pathogen-dependent (Makhathini Mkhwanazi et al., 2024). Until stronger field evidence is available, a feasible interim strategy may be to schedule canopy operations to avoid rainfall or imminent rain events, particularly in regions where natural infections are rain-associated. Priorities include quantifying the epidemiological contribution of green-wound infections across regions, defining risk windows, validating weather-based guidance, and determining whether infections progress into perennial wood or remain localized and are removed at dormant pruning.

4. Removal of Inoculum Sources

4.1. Sanitation of Pruning Debris

Removal or destruction of pruning debris represents a fundamental sanitation practice aimed at reducing inoculum availability in vineyards. Pruning wood harbours reproductive structures (pycnidia, perithecia, pseudothecia) of GTD pathogens and serves as a primary source of spores for wound infection (Elena and Luque, 2016a). Traditional practice in many regions involves removing pruning debris from the vineyard and burning them, though environmental regulations and labour costs increasingly limit this approach.

Alternative sanitation methods include shredding or mulching pruning debris and incorporating it into the soil. While this practice offers benefits for soil organic matter and reduces disposal costs, concerns exist about whether shredded wood continues to serve as an inoculum source. Limited research suggests that decomposition of woody debris can occur relatively rapidly under favourable conditions, potentially reducing viable inoculum within one growing season (Guerrero-Cabrera et al., 2025). However, the rate of decomposition and loss of pathogen viability likely varies with climate, wood size, and pathogen species, and this remains an area requiring further investigation.

The longevity of viable inoculum in pruning debris is a critical factor influencing the effectiveness of sanitation practices. Elena and Luque (2016a) showed that *Da. seriata* can remain viable in naturally infected pruning debris under vineyard conditions for at least 3.5 years. Although conidial production, abundance, and germination declined markedly over time, viable and infective conidia were still detected 42 months after pruning. These findings demonstrate that pruning debris constitutes a long-lasting inoculum source and that nearby disposal sites may contribute to disease pressure if located within spore dispersal range. The polyphagous nature of many *Botryosphaeriaceae* (Slippers and Wingfield, 2007; Úrbez-Torres, 2011) and *Diatrypaceae* (Moyo et al., 2019) species also means that inoculum can be produced on non-grapevine hosts surrounding vineyards, providing additional external inoculum sources.

Lecomte et al. (2006) evaluated composting as an alternative approach to managing pruning debris and found that this process could efficiently reduce the presence of *Da. seriata* and other GTD pathogens in pruned wood. However, the practical implementation of large-scale composting programs and the conditions required for effective pathogen elimination require further investigation.

The spatial scale of spore dispersal from inoculum sources, and the relative contribution of within-vineyard versus external inoculum sources, represent important but poorly understood aspects of GTD epidemiology. Given that *Botryosphaeriaceae* conidia are primarily splash-dispersed with relatively limited dispersal distances (Úrbez-Torres et al., 2010; van Niekerk et al., 2010), removal of pruning debris from the immediate vineyard vicinity is likely to reduce local inoculum pressure. However, the demonstration of viable inoculum persisting for multiple years emphasizes that sanitation must be a consistent, long-term practice rather than a single-season intervention.

4.2. Remedial Surgery and Trunk Renewal

Beyond preventive strategies focused on protecting healthy vines, remedial approaches aimed at managing existing infections have received increasing attention. Remedial surgery involves the physical removal of diseased wood from infected vines, with the goal of eliminating or reducing pathogen populations and extending vine productive life.

Sosnowski et al. (2011) conducted a long-term field trial evaluating remedial surgery for *Eutypa dieback* management in South Australia. The study involved removing symptomatic cordons and retraining vines from healthy wood. Results showed that remedial surgery could successfully restore vine productivity in many cases, though success rates varied depending on the extent of existing infection and the timing of intervention. Vines subjected to remedial surgery early in disease development (when symptoms were limited to one cordon) had higher success rates than vines with more advanced infections. However, the study also noted that remedial surgery is labour-intensive and requires skilled workers capable of identifying diseased tissue and making appropriate cuts to healthy wood. Sosnowski et al. (2021) subsequently compared remedial surgery alone with surgery combined with water shoot induction (mechanical trunk wounding to stimulate latent buds). Both approaches successfully restored canopy and yield over 10 years, but water shoot induction accelerated recovery by one year, though at increased labour cost.

More recently, Baumgartner et al. (2024) evaluated trunk renewal strategies for managing esca disease in California table grapes. Their approach involved cutting infected trunks back to the graft union and retraining new trunks from suckers. The study reported a 74% success rate (vines successfully retrained and productive) over a three-year period, though 25% of treated vines died despite the intervention. The authors noted that trunk renewal is most effective when implemented before vines show severe esca symptoms, suggesting that early detection and intervention are critical for success.

Several important considerations emerge from these remedial surgery studies. First, success rates are highly variable and depend on disease severity at the time of intervention, pathogen species involved, vine age and vigour, and environmental conditions during recovery. Second, remedial surgery represents a significant labour and short-term production cost, as retrained vines typically require 2-3 years to return to full productivity (or 1-2 years with water shoot induction; Sosnowski et al., 2021). Third, remedial surgery does not prevent reinfection, and treated vines remain susceptible to new infections through pruning wounds created during the retraining process. Therefore, remedial surgery should be viewed as part of an integrated management program that includes wound protection and other preventive measures.

Economic analyses of remedial surgery are limited but suggest that the practice may be cost-effective in high-value vineyards (e.g., premium wine grapes, table grapes) where vine replacement costs are substantial and where extending vine life by even a few years provides economic benefit. However, in lower-value production systems or in vineyards with very high disease incidence, complete replanting may be more economically rational than attempting to rehabilitate diseased vines.

An important research gap is the lack of standardized protocols for remedial surgery across different disease complexes, training systems, and regional conditions. Additionally, the long-term efficacy of remedial surgery (beyond 5-10 years) and the optimal timing and frequency of interventions remain poorly characterized.

5. Pruning Practices to Minimize GTDs

5.1. Pruning Tools and Cutting Quality

Mechanical transmission of GTD fungi via contaminated pruning tools is possible under experimental conditions, particularly after cutting infected perennial wood (Agustí-Brisach et al., 2015). However, the relevance of this pathway during routine dormant pruning appears limited because annual canes typically harbour low GTD inoculum (Martínez-Diz et al., 2020) and most new infections originate from airborne or rain-splashed propagules. Consistent with this, routine tool disinfection is generally not recommended in commercial pruning (Wine Australia, 2021). Targeted

hygiene may still be prudent during operations that cut into older or symptomatic wood (e.g., remedial surgery, spur renewal, reworking), where pathogen loads are higher and repeated cuts across vines could plausibly increase cross-contamination risk.

Evidence that cut “smoothness” materially reduces infection is also limited. Under artificial inoculation, spring shoot-thinning wounds created by tearing versus secateurs were similarly susceptible to *Da. seriata* and *Ea. lata* (Sosnowski and Ayres, 2022), suggesting that cut quality alone may not strongly restrict establishment when inoculum pressure is high. For dormant pruning, rigorous field comparisons of hand versus mechanical pruning (and the epidemiological significance of their contrasting cut profiles) remain scarce.

Overall, maintaining sharp tools remains good practice for vine health and worker safety, but GTD management should prioritize measures with stronger field support, region-adapted pruning timing, inoculum reduction, and timely wound protection, over routine tool disinfection or cut-quality interventions. This represents a shift from earlier recommendations and highlights how field evidence should override theoretical risk.

5.2. Cutting Method and Protective Wood Management

Traditional pruning schools emphasize leaving “protective wood” or “chicot”, managing desiccation cones within sacrificial tissue, and avoiding cuts that damage nodal structures, particularly the diaphragm, to preserve sap-flow continuity. These principles are widely promoted in viticulture, but direct evidence linking them to reduced GTD pathogen establishment under natural infection remains limited. Recent histological and field studies, however, provide mechanistic and experimental support for their biological plausibility.

Falsini et al. (2023) showed that retaining basal buds after pruning was associated with stronger tylosis formation in xylem vessels, whereas cuts removing basal buds showed weaker vessel occlusion; cuts on older, larger-diameter wood also produced deeper desiccation areas. Similarly, Bruez et al. (2025) reported in a 10-year field trial that “virtuous” pruning, based on leaving protective wood and preserving nodal structures, reduced internal desiccation, improved sap flow, and was associated with lower esca foliar expression and higher yield compared with flush cuts through the node. In the same system, preliminary microbiome evidence suggested that tissue type and tissue health status had stronger effects on fungal community structure than pruning method itself (Corrales-Adame et al., 2025). Together, these studies suggest that pruning cut placement may influence GTD outcomes mainly through wound defence, desiccation patterns and vascular function, rather than through large, immediate shifts in the established wood mycobiome.

More direct field evidence was recently provided by March et al. (2026), who showed that retaining stubs reduced internal staining and, in several comparisons, reduced recovery of *Ea. lata* compared with no-stub cuts. In cane-pruned vines, crown cuts that preserved basal buds and diaphragm tissue produced smaller wounds, shorter staining and lower *Ea. lata* colonization than flush cuts. These results provide direct support for the importance of cut position and nodal preservation in limiting pathogen advance from pruning wounds.

From a management perspective, protective wood, diaphragm preservation and sap-flow-oriented pruning can be considered low-risk practices that may improve vine functioning and potentially reduce long-term GTD impact. However, they should be framed as complements, not substitutes, for wound protection, sanitation and region-adapted pruning timing. Future work should validate these practices across regions under natural infection pressure, combining pathogen recovery, internal necrosis assessment, histological tracking of wound responses, sap-flow proxies and cost-benefit analyses.

5.3. Wound Size and Number

Although pruning wounds are central infection courts for GTD pathogens, relatively few studies have separated the effects of wound size, wound number and wound position. Larger wounds may provide greater surface area for spore deposition and pathogen entry, whereas vines with more

wounds have more potential infection courts. Henderson et al. (2021) showed that total pruning-wound surface area per vine was positively associated with subsequent GTD pathogen colonization; vines pruned to retain more buds, and therefore requiring more cuts, had higher infection rates than minimally pruned vines. This is consistent with histological evidence showing that cuts on older, larger-diameter wood generate deeper desiccation areas than cuts on younger canes (Falsini et al., 2023).

However, reducing wound number cannot be considered independently of agronomic objectives. Pruning regulates yield, fruit quality, canopy architecture and vine balance, so severe reduction of pruning cuts may be commercially unrealistic. A more practical objective is to avoid unnecessary cuts, particularly on permanent structures, and to ensure that wound protection strategies account for both wound number and wound size.

A key unresolved question is whether many small wounds pose less, equal or greater risk than fewer large wounds. Small wounds may be easier to protect thoroughly, whereas large wounds may remain physiologically altered for longer and could extend the period of vulnerability. Training systems that reduce annual wound load may therefore lower GTD risk, but this potential benefit must be evaluated together with other system-dependent factors, including retained dead wood, canopy density and microclimate. Future comparative studies should quantify total wound load, wound-size distribution, wound position and pathogen recovery to distinguish the effect of wounding from broader training-system effects.

5.4. Training Systems, Pruning Architecture and Sap-Flow Continuity

Vine training and pruning architecture can influence GTD impact by determining where wounds are placed, how frequently permanent structures are cut, how infections accumulate over time, and how well the vine maintains vascular continuity around necrotic tissues (Dumot et al., 2012; Travadon et al., 2016; Lecomte et al., 2018; Kraus et al., 2019, 2022) (Figure 3). Long-term observations in France indicate that systems with longer arms or more distributed woody structures tend to show lower Esca damage than simplified architectures with short or no arms, probably because annual wounds are kept farther from the trunk and functional redundancy is greater (Lecomte et al., 2018). However, annual foliar symptoms are unstable indicators of disease progression, whereas internal necrosis and vine mortality integrate cumulative damage over time. This distinction helps explain why results based only on symptom expression can appear inconsistent.

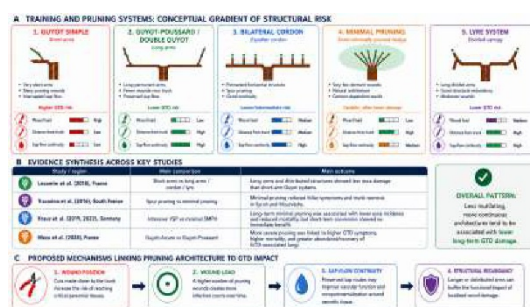


Figure 3. Training-system architecture and GTD outcomes across European vineyards. The figure summarizes how pruning architecture may influence GTD development through differences in wound load, wound position, arm length, sap-flow continuity and the spatial distribution of internal wood damage. The upper row illustrates five contrasting training or pruning systems: Guyot Simple with short arms, Guyot Double or “Guyot mixte Poussard” with longer arms, bilateral cordon or “Espalier cordon”, minimal pruning or SMPH, and the Lyre system with long divided arms. The lower panels synthesize evidence from key European studies, including long-term French surveys comparing short- versus long-arm Guyot, cordon and Lyre systems (Lecomte et al., 2018), minimal versus spur pruning effects on foliar symptoms, wood necrosis and fungal communities in southern France (Travadon et al., 2016), temporal patterns of GLSD incidence and mortality under intensive VSP and minimal SMPH pruning in Germany (Kraus et al., 2019, 2022), and recent pathobiome-based comparisons between Guyot-Arcure and Guyot-Poussard in France (Meza et al., 2024). Overall, the figure emphasizes that

training-system effects should be interpreted as long-term structural influences on vine resilience and disease expression rather than as short-term disease-control treatments.

Minimal or low-input pruning systems illustrate this context dependence. In southern France, minimally pruned vines showed reduced wood necrosis and lower Esca symptom expression relative to spur-pruned vines in some cultivars, but pathogen communities and cultivar effects complicated interpretation (Travadon et al., 2016). In Germany, comparisons between minimally pruned and intensively pruned systems showed strong year-to-year variability, with potential benefits becoming clearer only over longer periods and sometimes more evident in mortality or missing-vine metrics than in annual foliar symptoms (Kraus et al., 2019, 2022). Thus, training-system effects should be interpreted as long-term structural influences rather than short-term disease-control treatments.

Recent pathobiome-based evidence also supports this view. In adjacent 'Ugni Blanc' vineyards in France, Meza et al. (2024) found that Guyot-Arcure, a more severely pruned system with frequent renewal cuts and less controlled wound positioning, was associated with higher GTD symptom incidence and vine mortality than Guyot-Poussard. Although asymptomatic vines from both systems showed extensive internal necrosis, pruning strategy affected fungal richness and community composition, with greater representation of major GTD-associated groups in the more severely pruned vines. These findings reinforce the idea that pruning architecture can influence both disease expression and the wood pathobiome.

Mechanistically, several processes probably act together: repeated cuts on permanent wood may favour infection accumulation; longer arms or cordons may delay the progression of necroses into critical trunk sectors; and pruning architecture may affect sap flow and vine vigour. Recent work supports this physiological dimension. Bruez et al. (2025) reported that "virtuous" pruning improved sap flow and reduced esca expression compared with flush cuts through the node, whereas Galar-Martínez et al. (2024) showed that respectful pruning during vineyard establishment increased vegetative development and, in one site, yield in young 'Tempranillo' vineyards. Because the latter study did not quantify pathogen infection or internal necrosis, it should be interpreted as agronomic and physiological support for respectful pruning principles rather than direct evidence of GTD reduction.

From a management perspective, training and pruning architecture should be considered long-term decisions that influence vine resilience, wound exposure and the spatial distribution of internal damage. Current evidence supports minimizing unnecessary cuts on permanent structures, increasing the distance between annual wounds and the trunk where compatible with production goals, and preserving sap-flow continuity. Future studies should compare training systems across regions while jointly measuring wound load, internal necrosis, pathogen recovery, sap-flow proxies, foliar symptoms, mortality and economic costs.

6. Pruning Timing and Wound Susceptibility

6.1. How Long Are Pruning Wounds Susceptible and Why Does It Vary?

A central question in GTD epidemiology is the duration of pruning-wound susceptibility. Across studies, susceptibility typically declines with wound age, but reported "meaningful risk windows" range from ~2 weeks to >2 months, and in some cases low-level susceptibility has been detected up to ~4 months under artificial inoculation (Eskalen et al., 2007; Elena and Luque, 2016b; Díaz and Latorre, 2022; Sosnowski et al., 2023). A quantitative synthesis highlighted strong heterogeneity, with susceptibility half-lives spanning less than one week to more than eight weeks depending on study context (Rosace et al., 2023).

Several interacting factors likely drive this variability. (i) Pathogen biology: different GTD groups differ in their ability to colonize aging wounds and in seasonal activity patterns. (ii) Climate and wound healing: temperature and moisture conditions influence wound desiccation/callusing and the balance between host defenses and pathogen growth; warmer conditions may accelerate healing, but may also coincide with spore release depending on region. (iii) Inoculum pressure and

methodology: high-dose artificial inoculations can detect residual susceptibility that may be less relevant under natural infection, whereas high natural disease pressure can mask treatment effects and complicate interpretation. (iv) Assessment approach: outcomes differ when relying on culture-based recovery versus symptom incidence, and when measuring establishment versus downstream necrosis.

Given these uncertainties, the most robust practical message is that fresh wounds are consistently the highest-risk state, and management should prioritize rapid protection and region-adapted timing rather than assuming a universal susceptibility duration.

6.2. Early Versus Late Pruning: Why Recommendations Conflict Among Regions

Conflicting recommendations on early vs late pruning largely reflect genuine regional differences in inoculum phenology, rainfall-driven dispersal, and temperature-dependent wound healing (Luque et al., 2007; Serra et al., 2008; Úrbez-Torres and Gubler, 2011; Martínez-Diz et al., 2020; Sosnowski et al., 2023) (Figure 4). In some regions, delaying pruning can reduce infection risk because the high-inoculum period precedes late-winter pruning and/or warmer conditions shorten susceptibility (Úrbez-Torres and Gubler, 2011; Sosnowski et al., 2023). In other regions, pathogen detection and infection pressure may remain high later in winter, making early pruning preferable or making timing alone insufficient (Luque et al., 2014; Martínez-Diz et al., 2020). Moreover, pathogen groups differ: patterns observed for Botryosphaeriaceae may not transfer directly to Esca-associated pathogens, and year-to-year variability can be large (Serra et al., 2008). **A recent two-year, multi-site field study under natural infection in Spain and France further illustrates this context dependence: late pruning frequently increased pathogen recovery-based severity of Botryosphaeria dieback, Phomopsis dieback and Cytospora canker, but the magnitude and statistical significance of this effect varied among vineyards, seasons and pathogen groups (Ashley et al., 2026).**

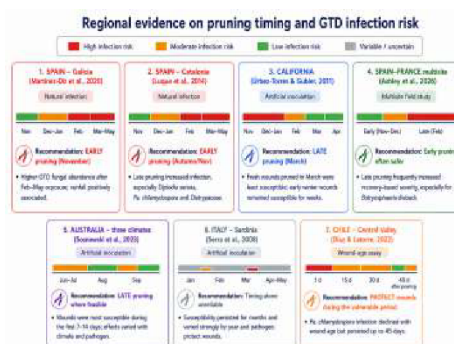


Figure 4. Regional pruning-time recommendations and infection-risk patterns for grapevine trunk disease management. The figure summarizes evidence from field studies conducted in California, Spain, Italy, Australia, Chile, together with a recent multi-site study in Spain and France. Each regional panel shows the pruning window evaluated, the relative infection-risk pattern, and the main practical recommendation derived from the corresponding study. Risk categories are indicated by colour: red, high infection risk; orange, moderate infection risk; green, low infection risk; and grey, variable or uncertain risk. The figure highlights that pruning-time recommendations are region-dependent: early dormant pruning was favoured in Galicia and Catalonia, late dormant pruning reduced infection risk in California and parts of Australia, whereas in Italy and Chile pruning time alone was less predictive and wound protection or short susceptibility windows were more relevant. The recent multi-site study in Spain and France further illustrates that late pruning can increase natural recovery of Botryosphaeriaceae, Diaporthe spp. and Cytospora spp. in some vineyards, but that the magnitude and consistency of this effect depend on site, season and pathogen group. Together, these studies show that pruning-time decisions should be adapted to local inoculum availability, rainfall patterns, temperature, wound-susceptibility duration and pathogen assemblages rather than generalized across viticultural regions.

Therefore, pruning-time decisions should be framed as a risk-management choice informed by local data: where spore release is strongly seasonal and predictable, timing can reduce exposure; where spores are broadly available or variability is high, wound protection becomes the dominant tool and timing should focus on operational feasibility and avoiding rain events when possible.

6.3. Double Pruning

Double pruning can reduce GTD risk by shifting the final, permanent wounds to a period with lower spore pressure and/or faster wound healing, while infections that establish on the initially cut long canes are removed during the finishing cut (Weber et al., 2007; Úrbez-Torres and Gubler, 2009). This strategy is most attractive where (i) there is a clear high-risk vs low-risk window, (ii) systems are compatible with mechanical pre-pruning, and (iii) vineyard value justifies additional costs (Hillis et al., 2016). In regions with extended or year-round inoculum availability, double pruning may provide less benefit unless combined with effective wound protection.

7. Pruning Wound Protection Strategies

7.1. Rationale and Long-Term Benefits

Applying protectants to pruning wounds is one of the most direct strategies to prevent GTD infections. By forming a physical, chemical and/or biological barrier on the wound surface, these products can inhibit spore germination, block pathogen entry, or exclude pathogens via rapid colonization by antagonistic microorganisms.

Evidence from long-term field trials indicates that repeated wound protection can reduce GTD incidence and severity. In a six-year trial in a California desert table grape vineyard, annual mechanical application of thiophanate-methyl reduced GTD incidence and vine mortality (approximately halving replanting rates) and increased marketable yield relative to untreated vines (Gispert et al., 2020). Multiple trunk pathogens were detected, including *Lasiodiplodia* spp., *Neoscytalidium dimidiatum*, *Eutypella* spp., *Phaeoacremonium* spp., and *Pa. chlamydospora*. However, the trial was conducted under atypically high disease pressure and largely preventive conditions (young vines; inoculum reservoirs such as old stumps; overhead irrigation), and therefore may overestimate benefits in lower-pressure vineyards or in blocks with established disease. Moreover, treating all wounds annually implies substantial recurring costs that must be considered in economic decision-making.

Because GTDs have long latency periods and infections accumulate over years, the benefits of wound protection are expected to accrue gradually. Accordingly, short-term trials may underestimate value, whereas multi-year studies better capture cumulative effects. Limited economic analyses suggest the practice is most cost-effective in high-value and/or young vineyards; in the Gispert et al. (2020) simulations, projected net present value gains over 25 years ranged from ~\$210,900 to \$313,100 per hectare (depending on control efficacy). As product availability and labels vary widely among regions, recommendations must also account for local regulatory constraints.

7.2. Application Methods and Timing

Wound protectants can be applied using various methods, each with advantages and limitations:

Paste application: Protectants formulated as thick pastes can be applied directly to individual pruning wounds using brushes, spatulas, or specialized applicators, ensuring thorough wound coverage. Ayres et al. (2022) and Díaz and Latorre (2013) found that paste application generally provided better disease control against trunk disease pathogens than spray application, likely due to more complete and persistent wound coverage. However, paste application is labour-intensive, requiring approximately 8-10 hours per hectare (Sosnowski and McCarthy, 2017), with costs estimated at NZ\$230/ha for cane-pruned and NZ\$460/ha for cordon-pruned vineyards, compared to approximately NZ\$120/ha for spray application.

Spray application: Protectants formulated as sprayable liquids can be applied using backpack or tractor-mounted sprayers. This method is faster and can more easily treat large numbers of wounds, though achieving complete coverage can be challenging, particularly for wounds on the underside of cordons. Despite generally lower efficacy than paste application, Sosnowski and McCarthy (2017) demonstrated through economic modelling that spray application would need to be only 15-45% less effective than hand painting to be economically equivalent, due to substantial cost savings. Water volume is critical: Ayres and Sosnowski (2022) found that application at low water rates (200 L/ha) resulted in poor wound coverage and control, emphasizing the importance of applying the recommended minimum of 600 L/ha.

Timing of application: Ayres et al. (2022) evaluated timing flexibility in field trials (2013–2015). Tebuconazole, fluazinam and pyraclostrobin showed curative activity against *Ea. lata* and *Nm. luteum* when applied up to 6 days after pruning/inoculation, substantially reducing pathogen recovery relative to untreated controls. Preventatively, the same fungicides protected wounds challenged up to 6 days after application for *Ea. lata* and up to 14 days for *Nm. luteum*. Overall, these results indicate that effective wound protection does not necessarily require treatment within 24 h: applications can be delayed (≤ 6 days post-pruning) while maintaining meaningful control, improving operational feasibility (e.g., avoiding spraying during pruning or under unsuitable weather). Consistent with this evidence, Australian label directions for tebuconazole were updated to allow application within 6 days of pruning. A recent Chilean field trial against *Botryosphaeriaceae* further showed that protection declined when pathogen challenge was delayed from 1 to 15 days after treatment, emphasizing that product persistence, wound age and the timing of pathogen exposure are critical components of pruning-wound protection (Hernández Del Amo et al., 2026).

Spray adjuvants: Ayres and Sosnowski (2022) found no benefit in adding spray adjuvants (wettors or stickers) to increase coverage and improve fungicide efficacy, suggesting that active ingredients are sufficiently effective when applied as labelled at recommended water volumes.

7.3. Chemical Fungicides: What Works Reliably and What Does Not

Recent field trials confirm that chemical wound protection can substantially reduce infection, but efficacy depends on pathogen group, year, and location (Brown et al., 2021; Martínez-Diz et al., 2021, Blundell and Eskalen, 2022; Baumgartner et al., 2023, 2025; Leal et al., 2024). Benzimidazoles (e.g., thiophanate-methyl/carbendazim where available) often provide the most consistent protection against several *Botryosphaeriaceae* and can be effective against *Eutypa* in some contexts, whereas performance against Esca-associated fungi (e.g., *Phaeoacremonium*/*Phaeoacremonium*) is frequently lower or variable. QoI/SDHI mixtures (e.g., pyraclostrobin + boscalid) can provide strong protection against *Botryosphaeriaceae* in some trials but are similarly inconsistent against Esca-associated pathogens. Typical efficacy patterns by pathogen group are summarized in Table 1.

Table 1. Chemical pruning-wound protectants in grapevine: key outcomes since 2018.

Reference	Location & system	Target pathogen(s)	Pruning time	Chemical product(s)	Key efficacy result
Sosnowski and Mundy (2019)	New Zealand (Marlborough and Hawke's Bay); DCAs + vineyard trials	<i>Ea. lata</i> , <i>Nm. luteum</i>	Dormant winter pruning; late July-August in vineyard trials. DCAs used dormant canes	Tebuconazole; carbendazim; fluzinam; mancozeb; flusilazole (various rates)	<i>Ea. lata</i> : Fungicides effective in vineyard; DCAs showed strong control <i>Nm. luteum</i> : Most fungicides effective in DCAs; field performance variable by year/rate.
Brown et al. (2021)	California, USA: Kingsburg; young table-grape vineyard; 3 seasons; protectants applied after pruning and pathogen challenge timed when rain was forecast	<i>Nm. parvum</i> , <i>De. ampelina</i> , <i>Ea. lata</i> , <i>Pa. chlamydospora</i>	Dormant winter pruning, January-early March, according to grower schedule	Pyraclostrobin-boscalid; thiophanate-methyl+myclobutanil; fluopyram+tebuconazole	<i>Nm. parvum</i> : Best performance with pyraclostrobin-boscalid and thiophanate-methyl+myclobutanil <i>De. ampelina</i> : Same two treatments generally among the lowest detection rates (significant reductions in 2019). <i>Ea. lata</i> : No protectant significantly reduced detection. <i>Pa. chlamydospora</i> : No consistent control across years.
Martinez-Diz et al. (2021)	Spain (Galicia); two commercial vineyards; 2 seasons; artificial inoculation 24 h after treatment	<i>Da. seriata</i> , <i>Pa. chlamydospora</i>	Dormant winter pruning; 19 February 2018 and 12 February 2019	Pyraclostrobin-boscalid; thiophanate-methyl; paste + tebuconazole	<i>Da. seriata</i> : High control in 2018-19 <i>Pa. chlamydospora</i> : Paste + tebuconazole and pyraclostrobin-boscalid effective
Reis et al. (2021)	Portugal (Lisbon); field trial; one season; post-harvest program; artificial inoculation	<i>La. theobromae</i> , <i>La. mediterranea</i>	Dormant winter pruning; 14 February 2019 and 20 February 2020	Pyraclostrobin-boscalid – LC2017 (Cu(II)+humic acids)	<i>La. theobromae</i> : Best control was generally with pyraclostrobin-boscalid or pyraclostrobin-boscalid + LC2017 <i>La. mediterranea</i> was best reduced by pyraclostrobin-boscalid in Cabernet Sauvignon in 2019 but more variably thereafter
Blundell and Eskalen (2022)	California (Sacramento); DCAs – 2 field sites	<i>Ea. lata</i> , <i>Nm. parvum</i>	Dormant pruning in February in field trials; DCAs used dormant canes collected in February	Fluopyram; trifloxystrobin; thiophanate-methyl+myclobutanil (plus other treatments in paper)	<i>Ea. lata</i> : Fluopyram and trifloxystrobin were the most effective in DCAs <i>Ea. lata</i> and <i>Nm. parvum</i> : Thiophanate-methyl + myclobutanil was the best chemical in Sacramento <i>Nm. parvum</i> : Thiophanate-methyl + myclobutanil reduced infection in Kern.
Baumgartner et al. (2023)	Washington (Prosser); 2 seasons; fungicide <3 days after pruning; inoculation ≤2 days later	<i>Cytospora</i> spp., <i>Ea. lata</i> ; <i>Pa. chlamydospora</i>	Late dormant pruning; 28 March 2019, 14 March 2020 and 22 March 2021	Pyraclostrobin-fluxapyroxad; thiophanate-methyl	<i>Cytospora</i> spp.: Thiophanate-methyl was the most effective. <i>Pa. chlamydospora</i> : Thiophanate-methyl was significant overall but highly year-dependent. <i>Ea. lata</i> : only 2021 showed a strong thiophanate-methyl effect.

Reference	Location & system	Target pathogen(s)	Pruning time	Chemical product(s)	Key efficacy result
Leal et al. (2024)	Spain (Álava) + France (Madiran); 3 seasons; natural infection	<i>Botryosphaeriaceae</i> spp.; esca-associated fungi; <i>Cytospora</i> canker; <i>Diaporthe</i> spp.	Dormant pruning; Álava: 21 February 2020, 10 February 2021 and 1 February 2022; Madiran: 2 March 2020, 3 March 2021 and 17 February 2022	Pyraclostrobin-boscalid	Across seasons, pyraclostrobin-boscalid showed intermediate and variable incidence reduction.
Baumgartner et al. (2025)	California (Earlham); 2 seasons; treatments + Pentra-bark adjuvant	<i>Ea. lata</i> , <i>Nm. parvum</i> ; <i>Pm. minimum</i>	Dormant pruning; 12 February 2020, 8 February 2021 and 27 January 2022.	Pyraclostrobin-boscalid ± Pentra-bark; thiophanate-methyl ± Pentra-bark	<i>Ea. lata</i> : in 2021, all fungicides reduced detection vs the control; in 2022, only pyraclostrobin + boscalid + Pentra-Bark was significant. <i>Nm. parvum</i> : thiophanate-methyl (– Pentra-Bark) was consistently significant; pyraclostrobin + boscalid + Pentra-Bark was also effective in 2020–2021
Hernández Del Amo et al. (2026)	Chile (Maule); 'Cabernet Sauvignon'; artificial inoculation with six <i>Botryosphaeriaceae</i> isolates at 1 and 15 days post-treatment	<i>Botryosphaeriaceae</i> spp.	Winter dormant pruning, July; treatments applied 2 h after pruning	Tetraconazole + thiophanate-methyl, fluxapyroxad pyraclostrobin, boscalid+pyraclostrobin	All products reduced lesion length and pathogen recovery compared with untreated controls. Efficacy was highest when inoculation occurred 1 day after treatment and declined markedly at 15 days. Tetraconazole + thiophanate-methyl was the most consistent chemical treatment.

Abbreviations: DCAs = detached cane assays; *Da* = *Diplodia*; *De* = *Diaporthe*; *Ea* = *Eutypa*; *Nm* = *Neofusicoccum*; *La* = *Lasiodiplodia*; *Pa* = *Phaeoamoniella*; *Pm* = *Phaeoacremonium*

Operational factors matter: coverage and water volume can strongly influence performance, and some fungicides show practical flexibility (effective when applied several days after pruning under trial conditions), which may improve real-world feasibility when immediate treatment is not possible (Ayres et al., 2022; Ayres and Sosnowski, 2022). Because product availability and labels vary greatly across regions (particularly under EU restrictions), management recommendations must be aligned with local regulatory frameworks.

7.4. Biological Control Agents: Promise, Variability, and the Winter-Temperature Bottleneck

BCAs, especially *Trichoderma*-based products, can provide high levels of pruning-wound protection in some regions and trials, but their efficacy remains highly variable across climates, seasons, pathogen groups and application contexts (Martínez-Diz et al., 2021; Reis et al., 2021; Blundell and Eskalen, 2022; Di Marco et al., 2022; Travadon et al., 2023; Leal et al., 2024) (Table 2). A key limitation is successful establishment on the wound surface before pathogen challenge. This partly explains why BCAs may perform poorly under cold dormant-pruning conditions, high inoculum pressure, repeated infection events or when bacterial formulations fail to persist on

exposed wood. Recent work with cold-adapted *Trichoderma* strains, such as *Ta. canadense*, illustrates a promising route to improve reliability by matching BCA ecology to local winter conditions (Pollard-Flamand et al., 2023).

Table 2. Biological control pruning-wound protectants in grapevine: key outcomes since 2018.

Reference	Location & system	Pruning time	Target pathogen(s)	BCA evaluated	Key efficacy result
Brown et al. (2021)	California (Kingsburg); 2 seasons; protectant then inoculation when rain forecast	Dormant winter pruning, January–early March, according to grower schedule	<i>Nm. parvum</i> , <i>De. ampelina</i> , <i>Ea. lata</i> , <i>Pa. chlamydospora</i>	Commercial <i>Bacillus amyloliquefaciens</i>	<i>Bacillus</i> was largely ineffective
Martínez-Diz et al. (2021)	Spain (Galicia); 2 seasons; artificial inoculation 24 h after treatment	Dormant winter pruning; 19 February 2018 and 12 February 2019	<i>Da. seriata</i> , <i>Pa. chlamydospora</i>	<i>Ta. atroviride</i> SC1; <i>Ta. atroviride</i> I-1237	Neither <i>Trichoderma</i> product significantly reduced pathogen recovery vs inoculated controls
Reis et al. (2021)	Portugal (Ísbon); field trial; one season; post-harvest program; artificial inoculation	Dormant winter pruning; 14 February 2019 and 20 February 2020	<i>Ia. theobromae</i> , <i>Ia. mediterranea</i>	<i>Ta. atroviride</i> I-1237	BCA antagonized <i>Lasiodiplodia</i> spp. in dual culture. Field efficacy depended on cultivar/year/isolate
Blundell and Eskalen (2022)	California (Sacramento); DCAs = 2 field sites (wine grape – table grape)	Dormant pruning in February in field trials; DCAs used dormant canes collected in February	<i>Ea. lata</i> , <i>Nm. parvum</i>	<i>Ta. atroviride</i> SC1; <i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080; <i>Am. pullulans</i> (DSM14940 + DSM14941); <i>Ta. hamatum</i> (UCD 8717); <i>Bs. subtilis</i> QST 713; <i>Bs. velezensis</i> (incl. UCD 8745)	<i>Ea. lata</i> : most consistent control came from UCD 8717 (<i>Ta. hamatum</i>) in the DCA and from <i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080/ <i>Am. pullulans</i> DSM strains <i>Nm. parvum</i> : strongest control was <i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080, with top field performance from <i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080 and <i>Bs. velezensis</i> in Elk Grove, and <i>Bs. subtilis</i> QST 713 in Delano. BCA applied 4 days before <i>Pa. chlamydospora</i> inoculation markedly reduced wood invasion and persisted well on wounds, and field monitoring showed reduced esca symptom incidence
Di Marco et al. (2022)	Italy; in-field cane inoculation in 20-yr vineyard (Florence) 9-year monitoring in young Guyot vineyards (Emilia-Romagna and Friuli)	Dormant winter pruning; artificial inoculation trial after late-February pre-pruning/fresh cut at treatment; long-term applications annually from late March to early April	Esca-associated fungi	<i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080	BCA applied 4 days before <i>Pa. chlamydospora</i> inoculation markedly reduced wood invasion and persisted well on wounds, and field monitoring showed reduced esca symptom incidence
Pollard-Flamand et al. (2023)	Canada, British Columbia; DCA and 2-year field trial; wounds challenged 1–21 d after treatment in greenhouse and 1–60 d in the field	Dormant pre-budbreak pruning; vines were pre-pruned, fresh wounds were made 1 d before treatment, and products were applied ≤3 h after pruning	<i>Da. seriata</i> , <i>Nm. parvum</i>	Local <i>Trichoderma</i> spp. combinations (<i>Ta. asperelloides</i> , <i>Ta. atroviride</i> , <i>Ta. canadense</i> ; commercial <i>Trichoderma</i> I-77)	DCA showed good control against both pathogens up to 21 d after treatment; field trials showed sustained control up to 60 d for several <i>Trichoderma</i> treatments, with high re-isolation indicating good persistence
Travadon et al. (2023) (grapevine subset)	California (UC Davis, Davis); 2 vineyard seasons on ~35-year-old spur-pruned vines; wounds sprayed to runoff and inoculated 24 h later	Dormant pruning; field trials established in February 2021 and January 2022, with treatments applied ≤2 h after pruning.	<i>Ea. lata</i> , <i>Nm. parvum</i>	<i>Ta. atroviride</i> SC1; <i>Cs. rosea</i> J1446; <i>Bs. amyloliquefaciens</i> MB1600; <i>Ss. lydicus</i> WYEC108	<i>Ta. atroviride</i> SC1 was the most effective and persistent treatment. <i>Bacillus</i> MB1600 reduced <i>Ea. lata</i> .
Leal et al. (2024)	Spain (Álava) + France (Madiran); 3 seasons; natural infection	Dormant pruning; Álava: 21 February 2020, 10 February 2021 and 1 February 2022; Madiran: 2 March 2020, 3 March 2021 and 17 February 2022	<i>Botryosphaeriaceae</i> spp.; Esca-associated fungi; <i>Cytospora</i> spp.; <i>Diaporthe</i> spp.	<i>Ta. atroviride</i> I-1237; <i>Ta. atroviride</i> SC1; <i>Ta. asperellum</i> ICC012 + <i>Ta. gamsii</i> ICC080	Site and season effects were strong, but <i>Ta. atroviride</i> I-1237 was the most consistently effective BCA, significantly reducing <i>Botryosphaeriaceae</i> incidence in most trials, whereas effects against esca-associated fungi and <i>Cytospora</i> spp. were more variable
García-García et al. (2026)	Spain (Extremadura); 3 adjacent vineyards with different training systems; late pruning; 2 seasons; natural infection + controlled <i>Pa. chlamydospora</i> assay	Late dormant pruning; <i>Ta. atroviride</i> SC1 applied within one week after pruning, from late February to early March	Natural infection by <i>Diatriypaceae</i> , <i>Botryosphaeriaceae</i> , <i>Pa. chlamydospora</i> , <i>Pm. minimum</i> and other GTD-associated fungi; controlled assay with <i>Pa. chlamydospora</i>	<i>Ta. atroviride</i> SC1	<i>Ta. atroviride</i> SC1 established well on treated wounds and reduced natural GTD infection under low disease pressure, although efficacy varied among vineyards/training systems and declined at 1 year post-treatment. Controlled assays showed BCA persistence near wounds and treatment-dependent shifts in the wood mycobiome
Hernández Del Armo et al. (2026)	Maule, Chile; 'Cabernet Sauvignon'; field trial with artificial inoculation	Winter dormant pruning, July; treatment applied 2 h after pruning	Artificial inoculation with six <i>Botryosphaeriaceae</i> isolates at 1 and 15 days post-treatment	Mamull WP: <i>Bionectria ochroleuca</i> Mitique + <i>Trichoderma gamsii</i> Volqui + <i>Hypocrea virens</i> Nire	Mamull WP reduced lesion length and mean percent infection compared with untreated controls. Efficacy was higher when inoculation occurred 1 day after treatment and declined at 15 days, indicating reduced persistence over time

Abbreviations: *Am* = *Aureobasidium*; *Bs* = *Bacillus*; *Cs* = *Clonostachys*; DCAs = detached cane assays; *Da* = *Diaporthe*; *Ea* = *Eutypa*; *Nm* = *Neofusicoccum*; *Ia* = *Lasiodiplodia*; *Pa* = *Phaeoaniella*; *Pm* = *Phaeoacremonium*; *Ss* = *Streptomyces*; *Ta* = *Trichoderma*

Recent evidence also indicates that BCA performance depends not only on the antagonist strain, but also on the wound environment and vineyard architecture. García-García et al. (2026) evaluated *Ta. atroviride* SC1 applied within one week after late pruning in three adjacent Spanish vineyards differing in training system. Under natural infection and low disease pressure, *Ta. atroviride* SC1 was consistently recovered from treated wounds and significantly reduced GTD pathogen infection, with mean disease control ranging from approximately 69% to 85% depending on the vineyard/training-system context, although disease control declined one year after treatment. Together, these findings support the use of BCAs as region-adapted tools within integrated pruning-wound protection programs, potentially combined with optimized pruning timing and/or reduced-risk chemical options where permitted, while highlighting the need for formulations and strains that establish rapidly and persist under commercial winter conditions.

7.5. Field Trial Synthesis and Comparative Efficacy

Recent field trials evaluating pruning-wound protectants under diverse conditions show that efficacy is highly context-dependent rather than product-universal (Tables 1 and 2). Chemical fungicides generally provide stronger and more consistent protection against *Botryosphaeriaceae*, and in some cases *Ea. lata*, than against esca-associated fungi such as *Pa. chlamydospora* and *Pm. minimum* (Brown et al., 2021; Martínez-Diz et al., 2021; Blundell and Eskalen, 2022; Baumgartner et al., 2023, 2025; Leal et al., 2024; Hernández Del Amo et al., 2026). BCAs show a similar context dependence: some *Trichoderma*-based treatments provide high protection when they establish effectively on wounds, whereas performance is weaker or inconsistent when establishment is poor, environmental conditions are unfavourable, or pathogen pressure is high (Di Marco et al., 2022; Pollard-Flamand et al., 2023; Travadon et al., 2023; García-García et al., 2026).

A second source of variability is experimental design. Artificial inoculation trials are useful for controlled comparisons among products and pathogens, but high inoculum doses may overestimate infection risk relative to commercial vineyards. Natural infection trials provide more realistic estimates of field performance, although infection rates can be low and strongly influenced by season, rainfall, temperature and local inoculum pressure (Leal et al., 2024). Consequently, single-year or single-site trials should be interpreted cautiously, and multi-year evaluations are needed to capture the cumulative and variable nature of GTD infection.

Operational factors are equally important. Paste applications can provide more complete wound coverage than sprays, but their labour cost limits adoption in many vineyards (Díaz and Latorre, 2013; Ayres et al., 2022). Spray treatments are more scalable, but efficacy depends strongly on coverage, water volume, wound age, application timing and product persistence (Ayres and Sosnowski, 2022; Ayres et al., 2022; Hernández Del Amo et al., 2026). Overall, current evidence does not support universal product rankings. Instead, product choice should be based on the dominant pathogen groups, local efficacy data, regulatory availability, vineyard value and the feasibility of repeated application under commercial pruning conditions.

8. Conclusions and Future Research Priorities

Pruning-related decisions influence GTD risk through three connected processes: the creation of susceptible wounds and their exposure to inoculum, the capacity of the vine to compartmentalize wounded tissues and maintain vascular function, and the feasibility of applying effective wound protection. The evidence reviewed here shows that pruning timing, wound number and size, cut position, training architecture, sanitation, remedial surgery and pruning-wound protectants can all contribute to GTD management. However, their effects are highly context-dependent. Climate, rainfall distribution, pathogen community, cultivar, vine vigour, water status, soil conditions, local inoculum pressure and regulatory constraints all determine whether a given practice reduces risk under commercial conditions.

The most robust practical implication is therefore not a universal pruning date, training system or product, but a region-adapted integrated strategy. In high-risk or high-value vineyards, management should prioritize reducing unnecessary wounds on permanent structures, maintaining protective wood and sap-flow continuity where feasible, avoiding pruning immediately before conducive rainfall events when local epidemiology supports this approach, reducing local inoculum sources, and protecting wounds with products that have shown efficacy under comparable regional conditions. Remedial surgery and trunk renewal can extend vineyard lifespan when applied early, but they should be considered complementary to preventive measures because retrained vines remain susceptible to new infections through pruning wounds.

Future research should focus on the mechanisms that explain the wide variability in pruning-wound susceptibility, the epidemiological importance of spring and summer wounds, and the field validation of protective wood, diaphragm preservation and sap-flow-oriented pruning under natural infection pressure. Additional priorities include improving BCA establishment under cold or variable

winter conditions, validating spore-dispersal and infection-risk models across regions, and evaluating integrated programs that combine pruning timing, wound protection, sanitation and training-system decisions. These studies should move beyond single-tactic assessments and jointly measure pathogen recovery, internal necrosis, wound healing, sap-flow proxies, foliar symptom expression, vine mortality and economic returns.

Although nursery infections and early-life management are important for long-term GTD prevention, they fall outside the main scope of this review unless directly linked to pruning-related infection processes. Overall, effective GTD management requires long-term implementation of locally adapted pruning and wound-protection strategies, supported by field evidence under realistic infection pressure and by economic analyses that help growers match management intensity to vineyard value and disease risk.

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