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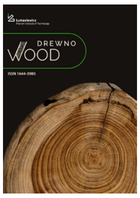

Managing the Invasive Tree-of-Heaven (*Ailanthus Altissima* (Mill.) Swingle) in Forest Ecosystems: An Adaptive, Integrated Approach to Ecological Complexity

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The tree-of-heaven (*Ailanthus altissima* (Mill.) Swingle) is one of the most aggressive arboreal invaders, threatening forest health and biodiversity across five continents. Given its rapid spread, severe ecological impact, and management difficulty, this paper (i) synthesises current knowledge of ecological factors driving its invasion in forest settings, (ii) critically evaluates available control methods, and (iii) proposes an integrated, evidence–based management framework suitable for forest ecosystems. Prevention strategies, such as legislation, vigilant monitoring, and the rapid removal of female trees, are essential first–line defences. For control, systemic herbicides applied via foliar sprays, basal bark, cut–stump, or stem injection methods provide the most effective long–term suppression. In contrast, mechanical or physical treatments alone often result in vigorous resprouting. Biological control agents show potential but remain purely experimental. However, the absence of approved biological agents and the limited availability of long–term cost–effectiveness data currently constrain management planning and large–scale implementation in forest ecosystems. This review presents a decision matrix that links control options to tree ontogenetic stages and site conditions, highlighting research needs that balance effectiveness, costs, and ecological safety. Overall, this synthesis offers a clear, evidence–based toolkit for managers and policymakers managing A. altissima in forest ecosystems.

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Introduction

The tree-of-heaven (*Ailanthus altissima* (Mill.) Swingle) (Fig. 1) is a fast–growing deciduous tree with shallow and wide-spread roots (Miller, 1990). Bark is smooth, grey, and becomes darker and fissured with age (DiTomaso & Healy, 2007). Pinnately compound, alternate leaves are up to 90 cm long, with 12–30 entire, lanceolate leaflets, each having 2–4 teeth with glands (Hunter, 1996). After the senescence, the twigs bear prominent

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Fig. 1. Morphological key features of *A. altissima*

heart–shaped leaf scars (Hu, 1979). The species is dioecious with inconspicuous green flowers clustered in terminal panicles; male flowers emit a strong foul odour resembling that of crushed foliage (Miller, 1990). Fruits are winged samaras, turning from green to yellow–brown colour as they ripen with one small, disc–like seed in the centre (DiTomaso & Healy, 2007). Native to the temperate regions of China (Praciak et al., 2003), it was introduced to Europe in the 18th century as an ornamental (Hu, 1979) and naturalised across all continents except Antarctica (Kowarik & Säumel, 2007).

Eco–physiologically, the species is an edaphically tolerant generalist that thrives under a wide array of climatic and edaphic conditions (Adamik & Brauns, 1957; Miller, 1990), but shows optimal performance in high–light, nitrogen–rich, moderately moist habitats subject to frequent disturbance (Landolt, 1977; Ellenberg et al., 1991). Exceptional phenotypic plasticity, manifested in rapid juvenile growth (Adamik, 1955), precocious maturity (Hunter, 1995), prolific seed production (Illick & Brouse, 1926), vigorous clonal sprouting (Singh et al., 1992), strong allelopathy (Gómez-Aparicio & Canham, 2008a), high photosynthetic efficiency (Marek, 1988), and significant tolerance to abiotic stress (Miller, 1990), has facilitated its spread across continents. As a result, *A. altissima* has colonised various natural, semi–natural, and anthropogenic habitats (Parsons & Cuthbertson, 2001; Boer, 2013).

Ecologically, *A. altissima* functions as an early-successional, gap-obligate species (Robinson & Handel, 1993; Knapp & Canham, 2000). Colonisation usually begins at forest edges, followed by gradual infiltration through abundant root suckering (Kowarik, 1995; Espenschield-Reilley & Runkle, 2008). Root suckers remain under shade, creating a dormant reservoir of vegetative propagules that quickly expand after canopy disturbance. Sexual reproduction starts at approximately 10 years and peaks between 12 and 20 years, but soil seed bank persistence is <1 year (Hunter, 1995; DiTomaso & Healy, 2007). Seedlings germinate under low light but rarely survive extended shade (Grime & Jeffrey, 1965; Forgione, 1993).

While largely absent from undisturbed, closed-canopy, late successional forest stands (Hull & Scott, 1982; Bertin et al., 2005), large–scale disturbances, namely silvicultural harvesting (Kasson et al., 2013), windthrow events (Xi & Peet, 2008), insect defoliation (Orwig & Foster, 1998), and, less frequently, fire (Beck & Van Horn, 2007), create canopy gaps and resource pulses that fosters the invasion (Barringer & Pannaman, 2003; Landenberger et al., 2007; Iverson et al., 2019). Once established in gaps, *A. altissima* often outpaces native tree species to canopy dominance (Knapp & Canham, 2000).

Today, it is recognised as one of the world's most aggressive arboreal invaders (Weber & Gut, 2004), exerting significant ecological pressure throughout its introduced range (Vilà et al., 2010; Štefanić et al., 2023; Lukačević & Štefanić, 2024). In North America, it directly competes with economically valuable native tree species (Badalamenti & LaMantia, 2013; Calin et al., 2021) and is spreading at approximately 435 hectares annually, now impacting over 98,000 hectares of forest land in the U.S. (Miller et al., 2013). In Virginia alone, live–stem volume increased from 67 million m^3 (0.20% of the state's total) in 2009 to 102 million m^3 (0.26%) in 2019 (Virginia Department of Forestry [VDF], 2009, 2019). This growth significantly alters forest composition by suppressing understory vegetation (Motard et al., 2011), diminishing faunal diversity (Gutiérrez-López et al., 2014), and altering soil chemical properties (Gómez-Aparicio & Canham, 2008b), thereby threatening the long-term resilience and functional integrity of forest ecosystems.

Regardless of extensive research on its ecology, managing *A. altissima* remains a challenging frontier in forestry due to its marked ecological plasticity and its ability to colonise both disturbed and intact forest sites. Consequently, there is a growing need for an integrated management framework that strategically combines control methods, rather than relying on isolated, one-time treatments. Therefore, the present study critically evaluates the effectiveness and limitations of available control methods and proposes an evidence-based management framework tailored for forest ecosystems.

Foundational considerations for *A. altissima* management in forest ecosystems

1. Management objectives

In forest ecosystems, management generally aims to achieve one or more strategic goals: (*i*) eradication, (*ii*) containment, (*iii*) reduction of infested areas, and (*iv*) decrease of individual tree density within established infestations (Dufour-Dror, 2013; United States Department of Agriculture [USDA], 2014; Brundu, 2017). Among these, eradication is rarely feasible due to topographical complexity, habitat heterogeneity, adjacent land-use constraints, and limited operational budgets (Boer, 2013; European and Mediterranean Plant Protection Organization [EPPO], 2020). For this reason, containment and density reduction are the most practical and cost–effective strategies in most forest environments.

2. Integrated strategy

Contemporary forest-based control programmes emphasise integration, i.e., pairing preventive measures with mechanical and chemical ones (Constán-Nava et al., 2010; Wunder et al., 2016). In practice, economic barriers remain a common challenge (Meloche & Murphy, 2006; Herrick et al., 2009; Salom et al., 2009), especially where repeated applications and long-term commitments are required. The overall effectiveness is highly dependent on interrelated factors, including infestation density, tree ontogenetic stages, site conditions, timing of interventions, and the capacity for follow-ups across multiple years (McGill &Tichner, 2010; USDA, 2014).

3. Monitoring, prioritisation, and detection

Sustained control depends on strong surveillance systems, especially in protected or ecologically sensitive forest areas (Hoshovsky, 1988; Enescu et al., 2016). Monitoring should prioritise the detection and geolocation of reproductive females, as they are the main source of long-distance dispersal (Baker et al., 2023). High-priority risk zones, such as riparian corridors, transportation infrastructure, and known former infestation sites, should be monitored more intensively because they play a key role in spreading propagules (USDA, 2014; EPPO, 2020).

Monitoring approaches may include remote sensing (e.g., aerial photography, high-resolution satellite imagery) for landscape-level surveillance (Rebbeck et al., 2015), as well as ground-based surveys for confirmation and fine-scale resolution (McAvoy et al., 2012). Method selection should reflect the scale of infestation, forest structure, and resource availability.

Control methods

Effective forest management of *A. altissima* requires a complementary approach, e.g., preventive regulation, sustained monitoring, and timely application of mechanical, physical, biological, and chemical treatments. The choice and timing of these measures should be tailored to local conditions (e.g., forest structure, invasion intensity, and operational constraints).

1. Preventive measures

1.1. Legislative framework

Preventing the spread of *A. altissima* in forest ecosystems remains the most cost-effective management strategy (Meloni et al., 2016). It is listed on the EPPO's List of Invasive Species (EPPO, n.d.) and the EU's Union List (Costello et al., 2022), requiring coordinated international and national efforts to limit its spread (Brundu et al., 2020; EPPO, 2020). Regulatory frameworks often include bans on the sale, transport, and planting (Sîrbu & Oprea, 2011; Crainic et al., 2019; EPPO, 2020). Yet, enforcement gaps remain, especially on vacant or legally disputed properties, which demand legal mandates for compulsory removal near protected areas and high-value forests (Meloche & Murphy, 2006; Ulus et al., 2021; Gavrilidis et al., 2023).

1.2. Hygiene protocols

The forest machinery and vehicles operating in areas infested with *A. altissima* can greatly increase its dispersal (Parsons & Cuthbertson, 2001; Fryer, 2010). Limiting vehicle access and cleaning tyres and undercarriages before leaving the site are low-cost measures that significantly lessen secondary spread and establishment in new areas (USDA, 2014; Brundu, 2017; EPPO, 2020).

1.3. Regulatory and educational outreach

Legal instruments alone are insufficient without stakeholder compliance (Marchante & Marchante, 2016; Başnou & Vilà, 2019; Urziceanu et al., 2020). Monitoring nursery trade activities, establishing national registries of ornamental imports, and mandating pre-import risk assessments can help close existing loopholes (Hulme et al., 2017; Başnou & Vilà, 2019). Public campaigns that discourage ornamental planting and promote native alternatives—especially along transport corridors—further limit its propagule pressure (Burrel, 2006; Swearingen et al., 2014; Brundu, 2017; EPPO, 2020).

1.4. Habitat preservation and restoration

Riparian corridors are highly vulnerable and can be easily colonised (Constán-Nava et al., 2014; Castro-Díez & Alonso, 2017) because water and wind disperse samaras over long distances (Lepart & Debussche, 1991; Planchuelo et al., 2016). Protecting fluvial integrity and reestablishing native vegetation buffers can intercept seeds and slow invasion along riparian gradients (Cabra-Rivas et al., 2014).

In closed-canopy forests, maintaining a dense overstory and healthy ground layer suppresses seedling recruitment (Hoshovsky, 1988; Swearingen et al., 2014). When canopy disturbance is unavoidable, rapid reforestation with competitive native species—such as *Liriodendron tulipifera*, *Liquidambar styraciflua*, or *Platanus occidentalis*—can prevent establishment, even though local performance varies (Kota et al., 2007; Moore & Lacy, 2009).

Current evidence remains limited, thus emphasising the need for comparative trials to identify regionally effective competitive species.

2. Mechanical control

Mechanical methods (e.g., hand pulling, digging, cutting, mowing, or girdling) are widely applied for initial suppression, particularly in low-budget contexts or ecologically sensitive areas (Fryer, 2010; VDF, 2019). For small-scale infestations, the so-called Bradley method, which involves staged removal from minimally to heavily infested zones, has been proposed as a low-impact, ecologically sound strategy (Fuller & Barbe, 1985; Hoshovsky, 1988; Boer, 2013). Applied as stand-alone treatments, however, they typically provoke vigorous stump and root resprouting, necessitating repeated follow-ups (Hunter, 2000; DiTomaso & Healy, 2007). Cutting before anthesis lowers seed production, and basal cuts suppress bole sprouts (Hunter, 2000). Most programmes, accordingly, pair mechanical measures with systemic herbicides to secure long-term control (DiTomaso & Kyser, 2007; Boer, 2013).

2.1. Manual removal

Hand pulling or digging effectively removes scattered seedlings and small saplings (Miller, 2006; Stalter et al., 2009; USDA, 2014). It is important to distinguish seedlings—characterised by slender stems and cotyledons—from saplings (Hunter, 2000; DiTomaso & Healy, 2007). Extraction should be done in moist soil to ensure complete root removal (Hoshovsky, 1988; Chafin, 2007). While weed wrenches can assist with larger plants, removing the entire root system is crucial to prevent regrowth (Kaufman & Kaufman, 2023).

2.2. Cutting or mowing

Single or irregular cuts stimulate vigorous resprouting, whereas repeated mowing over multiple growing seasons can exhaust root reserves (Czarapata, 2005; Chace, 2013; Yonebayashi et al., 2016). Early-summer cutting yields the greatest depletion effect (Hunter, 1996; Wright, 2009; VDF, 2019). Even so, long–term studies by ConstánNava et al. (2010) reported limited suppression after annual cutting alone. A recent innovation—covering freshly cut stumps with biodegradable black mulch—effectively inhibited resprouting in Italian trials (Arduini et al., 2024). Equipment choice ranges from brush cutters to tractor–mounted mowers; still, terrain complexity and compaction risk must be weighed (Hoshovsky, 1988; EPPO, 2020). Post-cut herbicide follow-ups are mandatory (Olson et al., 2004; Northam & Meyer, 2009).

2.3. Girdling

Girdling severs phloem continuity by removing a complete ring of bark and cambium, gradually starving the crown (Hunter, 2000; EPPO, 2020). Conducted with an axe or hatchet in spring, it is inexpensive but often triggers basal sprouting unless the girdled zone is immediately treated with a systemic herbicide (Olson et al., 2004; DiTomaso & Healy, 2007; Meloni et al., 2016). As reported by the EPPO (2020), groove dimensions should scale with tree diameter, i.e., three narrow rings for older trees and one wide ring for younger trees. Girdling is especially useful for eliminating seed-bearing female trees (VDF, 2019), and any resprouts require subsequent chemical or mechanical follow-ups (Hunter, 2000).

3. Physical control

3.1. Prescribed fire

Current evidence shows that prescribed fire offers little to no long-term suppression and can even promote further invasion (Lewis, 2007; Fryer, 2010; Rebbeck, 2012).

Experimental burns (>150 °C) effectively kill stems and destroy exposed samaras, but those buried in soil evade thermal damage (Meggaro & Vilà, 2002; Guthrie et al., 2016). By obliterating forest litter, fire creates bare, high-light microsites that encourage seedling recruitment from off-site seed sources, if present (Rebbeck & Jolliff, 2018; Iverson et al., 2019; Cruz et al., 2021).

Post-burn monitoring reveals vigorous stump and root resprouting, leading to stem densities exceeding pre-fire levels (Marsh, 2005; Pomp, 2008; Rebbeck et al., 2014, 2017). Thick bark further boosts its fire tolerance (Lambert et al., 2010; Dey & Kabrick, 2016). Given this, prescribed fire alone is viewed as ineffective and potentially counterproductive as a control measure (Bryant & Held, 2004; Yonebayashi et al., 2016).

Forest managers are therefore advised to avoid using prescribed fire as a stand-alone treatment in favour of alternative control methods (Evans et al., 2006; Lewis, 2007; Rebbeck, 2012).

4. Biological control

4.1. Classical biological control

Although *A. altissima* was long considered pest-tolerant (Goor & Barney, 1968), recent studies have identified several host-specific pathogens and herbivores with potential for biological control (Ding et al., 2006a, 2006b).

Among the most promising are three pathogenic fungi (e.g., *Verticillium albo-atrum*, *V. dahliae*, and *V. nonalfalfae*) which induce vascular wilt symptoms including chlorosis, premature leaf drop, crown dieback, and xylem discolouration (Schall & Davis, 2009; Rebbeck et al., 2013; Kasson et al., 2014, 2015). These fungi have demonstrated high virulence against *A. altissima* in both North America and Europe, with minimal non-target effects on native woody species (Maschek & Halmschlager, 2018; Lechner et al., 2023). In parallel, two host-specific weevils (e.g., *Eucryptorrhynchus brandti* and *E. chinensis*) have been identified as potential agents due to their combined foliar and stem-boring activity (Kok et al., 2008; McAvoy et al., 2014, 2023). The adults defoliate trees, while larvae tunnel through the cambium and xylem, disrupting vascular flow (Ding et al., 2006a, 2006b). These weevils have undergone quarantine evaluation in the U.S. (Herrick et al., 2009; Salom et al., 2009), and they facilitate secondary spread of *Verticillium* spp. in natural populations (Snyder et al., 2012).

Despite their promise, no fungal or insect agents have yet received regulatory approval for commercial release in either the U.S. (USDA, 2014) or Europe (EPPO, 2020).

4.2. Prescribed grazing

Browsing by domestic herbivores has been tested as a supplemental control strategy, particularly in early-stage infestations (Hoshovsky, 1988; Burch & Zedaker, 2003). While *A. altissima* leaves offer moderate nutritional value (Azim et al., 2002), their high concentration of bitter terpenoid ailanthone deters most grazers (Heisey, 1997; Meloni et al., 2016). Goats and sheep have been observed feeding on seedlings and sprouts, whereas cattle consistently avoid the plants (Simmonds et al., 2000; Nota et al., 2024). More importantly, Bourke (1996) observed no signs of toxicity in goats following repeated ingestion of *A. altissima* foliage. Nonetheless, grazing pressure must be maintained to effectively deplete resprouting capacity (Hoshovsky, 1988; VDF, 2019).

Wildlife interactions are limited: granivorous rodents rarely eat seeds (Manson & Stiles, 1998), and although meadow voles browse seedlings occasionally (Ostfeld et al., 1997; Cadenasso & Pickett, 2000), only a few bird species (e.g., pine grosbeak and crossbills) are known to consume the seeds (Vines, 2004). In forests with high deer densities, saplings may be heavily browsed in shaded areas (Pannill, 2000; Mátrai et al., 2004; Carter & Fredricksen, 2007), potentially giving native species that tolerate browsing less effectively a competitive advantage (Knapp & Canham, 2000).

Despite some efficacy in sprout suppression, prescribed grazing lacks the consistency and durability required for long-term control and should be considered only as part of an integrated management framework (Burch & Zedaker, 2003; Meloni et al., 2016; VDF, 2019).

5. Chemical control

Chemical treatments remain the most reliable means of suppressing *A. altissima*, routinely outperforming mechanical treatments in both efficacy and longevity (Burch & Zedaker, 2003; ConstánNava et al., 2010; Fogliatto et al., 2020). Nevertheless, single applications often yield short-term density reductions, so repeated treatment and rigorous post-application monitoring are essential (Meloche & Murphy, 2006; Herrick et al., 2009; Salom et al., 2009). Failure to manage resprouting stems following initial treatment often leads to a swift resurgence of *A. altissima* populations, returning them to pre-treatment density levels (Parson & Cuthbertson, 2001; McGill & Tichner, 2010; USDA, 2014).

Water- or oil-soluble dyes help field operators verify coverage and identify drift (USDA, 2014; Miller et al., 2015). Extra caution is needed near high-value native trees because soil-mobile herbicides, especially imazapyr, have caused root-graft injury up to 3 m from treated *A. altissima* stems (Eck, 2005; Lewis & McCarthy, 2008). In such cases, triclopyr or picloram are safer alternatives (Eck & McGill, 2007). Ester formulations should be avoided in riparian zones due to their high aquatic toxicity; instead, water-soluble products are recommended (DiTomaso & Kyser, 2007).

Chemical control is applied either as (*i*) broadcast foliar sprays or (*ii*) individual–plant treatments, such as basal bark, cut-stump, or stem injection (USDA, 2014; EPPO, 2020; Soler & Izquierdo, 2024). Systemic suppression relies on high-phloem mobile herbicides capable of translocating through the root system (Badalamenti et al., 2015). Glyphosate, triclopyr, picloram, imazapyr, and 2,4–D consistently achieve >70% mortality with well-timed foliar or basal applications (Bovey, 2001; Bowker & Stringer, 2011). Other formulations of 2,4–D and 2,4,5–T show variable results and significant regrowth (Parsons & Cuthbertson, 2001). Recent trials point to additional effective herbicides, including fluroxypyr, clopyralid, metsulfuron-methyl, and flazasulfuron, while terbacil appears promising; diuron and simazine remain mostly ineffective (Tworkoski et al., 2000; Soler & Izquierdo, 2024).

5.1. Broadcast foliar sprays

Foliar herbicide application is the most common method for controlling *A. altissima*, especially in the early stages of infestation. Treatments work best when applied in spring during the active growth period, after leaves are fully expanded and shoots are <2 meters tall (Hunter, 2000; Czarapata, 2005; Calin et al., 2021). This timing maximises herbicide absorption and systemic translocation through the root system while reducing off-target drift (USDA, 2014; Swearingen et al., 2014; EPPO, 2020). As noted by Hoshovsky (1988), herbicide applications conducted before full leaf expansion significantly reduce treatment efficacy.

Commonly used herbicides, such as glyphosate, triclopyr, fosamine, and metsulfuron–methyl, are applied with a non-ionic surfactant to improve leaf penetration and decrease ecological toxicity (Evans et al., 2006; Dufour-Dror, 2013). Although dicamba and imazapyr are also effective, their persistence and high soil mobility make them unsuitable in environmentally sensitive areas (USDA, 2014).

Application techniques range from hand-held or backpack sprayers for small-scale infestation to mechanised and aerial systems for larger or inaccessible sites (McGill & Tichner, 2010; EPPO, 2020). Ground-based treatments can be limited by canopy structure and stem height (Parsons & Cuthbertson, 2001), while aerial delivery is advantageous in rugged terrain or continuous infestations (Bovey, 2001; Miller et al., 2015). Optimal conditions include ambient temperatures of ≈18 °C and wind speeds between 8–10 mph, which promote uptake and reduce drift risk (Swearingen et al., 2014; Calin et al., 2020, 2021). This method is relatively low-cost, with expenses typically ranging from US$150 to US$200 per acre (Kochenderfer et al., 2012).

5.2. Basal bark application

Basal bark application is a direct, minimally invasive chemical method for controlling *A. altissima*, especially suited for small-scale infestations and scattered trees (USDA, 2014). Unlike cut–stump or injection methods, it requires no mechanical cutting and can be used year-round (Swearingen et al., 2014). This method involves applying highly concentrated systemic herbicides, usually in an oil-based carrier or with an oil–soluble adjuvant, along the lower 30–45 cm of the trunk using a low-pressure backpack sprayer. The herbicide penetrates the bark and is readily absorbed into the phloem, enabling systemic translocation to the root system (Hoshovsky, 1988; Burch & Zedaker, 2006; DiTomaso & Kyser, 2007).

Thorough application to the point of runoff is critical to ensure full uptake (Hoshovsky, 1988; Burch & Zedaker, 2006). Treatments are most effective in the autumn, when foliage loss facilitates access and downward phloem flow enhances herbicide movement to the roots (DiTomaso & Kyser, 2007; USDA, 2014). According to Swearingen et al. (2014), full circumferential coverage is essential; for stems under 15 cm in diameter, a continuous 30 cm band is required, whereas larger stems demand a 60 cm band. The bark must be dry and free of any moisture to allow proper adhesion and absorption (Hoshovsky, 1988).

Efficacy declines with increasing stem diameter, primarily due to limited herbicide penetration through thicker bark layers (Peugh et al., 2013; USDA, 2014). While stems <10 cm are consistently well controlled (Eck & McGill, 2007; Bowker & Stinger, 2010), treatments can remain effective on stems up to 30 cm when appropriate oil–based carriers are used (Peugh et al., 2013). Brundu et al. (2020) identify basal bark treatments as the most effective method for mature trees under certain field conditions.

Triclopyr, either alone or in combination with picloram, is the most widely used active ingredient in basal bark treatment, offering high efficacy with relatively low phytotoxicity risk to non-target vegetation compared to imazapyr (Eck, 2005; Eck & McGill, 2007; DiTomaso & Kyser, 2007). Trials have shown that triclopyr + picloram mixtures outperform those of triclopyr + imazapyr (Burch & Zedaker, 2006). Additional herbicide evaluations indicate strong performance from aminopyralid and triclopyr combinations with fluroxypyr (Fogliatto et al., 2020). Glyphosate, due to its poor lipophilicity, is largely ineffective when applied via this method (DiTomaso & Kyser, 2007). More recently, Soler and Izquierdo

(2024) reported near–complete control with 2,4–D + triclopyr and triclopyr + aminopyralid mixtures, while fluroxypyr + metsulfuron–methyl yielded moderate suppression. No control was achieved with isoxaflutole + thiencarbazone–methyl.

Despite its simplicity, basal bark application is labour–intensive and best suited for localised infestations or trees with a diameter from 5 to 20 cm, i.e., conditions that allow for high absorption efficiency (USDA, 2014; EPPO, 2020). Reported treatment costs range from US$80 to US$125 per acre (Kochenderfer et al., 2012).

5.3. Cut–stump application

The cut–stump method is a targeted control strategy that involves felling trees as close to the ground as possible, preferably below the lowest branches, to limit the resprouting potential (Dufour-Dror, 2013; USDA, 2014; Fogliatto et al., 2020). Immediately after cutting, systemic herbicides, either undiluted or properly diluted, must be applied to the cambial zone using a paintbrush, handheld sprayer, or backpack sprayer (Hoshovsky, 1988; USDA, 2014). For optimal efficacy, application should occur within 20 minutes of felling; however, triclopyr and imazapyr have shown continued effectiveness when applied up to one hour post–cut (DiTomaso & Kyser, 2007; Miller et al., 2015).

Treatment time is a critical factor. EPPO (2020) recommends late summer (e.g., August–September) as the ideal window period, when carbohydrate translocation to the roots improves herbicide effectiveness. For stumps <10 cm in diameter, thorough surface coverage is essential, whereas for larger stumps, the herbicide should be applied to the outer ⅓ of the cut surface, i.e., cambial tissue layer (McGill & Tichner, 2010; Swearingen et al., 2014; USDA, 2014).

This method is particularly advantageous in dense infestations or where terrain, access, or proximity to non-target vegetation preclude broadcast treatments (DiTomaso & Kyser, 2007; USDA, 2014). Still, caution is warranted when applying this technique to reproductive female trees, as cutting may facilitate seed dispersal (Dufour-Dror, 2013).

The most commonly used systemic herbicides are glyphosate and triclopyr, both of which have demonstrated high efficacy in field settings (Meloche & Murphy, 2006; Constán-Nava et al., 2010). Trials in Cyprus have shown comparable suppression rates between the two compounds (Dufour-Dror, 2013). When applied correctly, cut-stump treatments with triclopyr and imazapyr have consistently achieved control rates over 90% (DiTomaso & Kyser, 2007).

More recent evaluations have expanded the spectrum of effective active ingredients. Soler and Izquierdo (2024) report strong performance from a wide range of compounds, including fluroxypyr, flazasulfuron, metsulfuron-methyl, metribuzin, and several mixtures such as 2,4–D + triclopyr, clopyralid + triclopyr, and triclopyr + aminopyralid, all of which have been successfully administered via cut–stump injection. Notably, combinations such as triclopyr + fluroxypyr and aminopyralid + fluroxypyr yielded high suppression levels in multi–year trials (Constán-Nava et al., 2010; Fogliatto et al., 2020). Reported treatment costs, including both chemical and labour inputs, range from US$40 to US$60 per acre (Kochenderfer et al., 2012).

5.4. Stem injection

Stem injection delivers water-soluble herbicide directly into the cambium, ensuring systemic translocation to roots and minimising spray drift (Hoshovsky, 1988; McGill & Tichner, 2010). The technique is reserved for mature stems >5 cm diameter at breast height, especially for seed-bearing females, where broadcast or basal-bark treatments are impractical (Meloche & Murphy, 2006; Dufour-Dror, 2013). Several stem injection techniques are used.

1. **Hack–and–squirt:** using a hatchet, downward-angled cuts of 4–8 cm are made around the trunk at 5–10 cm intervals—one hack per 8 cm of diameter—leaving a flap of bark to retain solution (USDA, 2014). Each cut receives 1 mL of concentrated herbicide within 10 seconds of wounding. Triclopyr remains the primary active substance, but imazapyr, dicamba, and 2,4–D + picloram also provide >95% canopy reduction when applied during the summer growth period; glyphosate performs poorly (Swearingen et al., 2014; VDF, 2019).
2. **Drill–fill:** holes at a 45° angle and a depth of 5 cm are drilled around the lower stem and filled with undiluted herbicide via syringe (Badalamenti & La Mantia, 2013; Dufour-Dror, 2013). Field trials in Sicily achieved 90–95% mortality with 1–2 mL glyphosate per hole (Badalamenti & La Mantia, 2013). The late–summer application maximises vascular flow and efficacy (Constán-Nava et al., 2010; Soler & Izquierdo, 2024). Recent Spanish work reported 98–100% control with triclopyr + aminopyralid, 2,4–D + triclopyr, fluroxypyr, or flazasulfuron; metsulfuron-methyl and isoxaflutole + thiencarbazone-methyl were less effective (86–100%; Soler & Izquierdo, 2024).
3. **Capsule–injecting systems:** a spring-loaded lance inserts pre-measured imazapyr or triclopyr capsules through the bark at one capsule per 10 cm circumference (Eck, 2005; Eck & McGill, 2007). Imazapyr capsules routinely exceed 95% of control; triclopyr capsules are less consistent. The higher

capital cost is justified when multiple invasive tree species are treated across large infested areas (Meloche & Murphy, 2007).

As indicated by VDF (2019), treatments achieve maximum efficacy in late summer to early autumn, coinciding with peak downward phloem translocation; applications outside the active growing season are less effective and may stimulate increased root suckering. Because mortality is delayed, injected trees should remain standing until fully dead, and the method should be avoided near roads, trails, or public areas where falling limbs pose a hazard (EPPO, 2020). Post-treatment monitoring is essential, with follow-up foliar sprayings to control any basal sprouts or root suckers that emerge the following year. Estimated implementation costs, encompassing herbicide application and labour, range from US$50 to US$75 per acre (Kochenderfer et al., 2012).

Towards the forest-focused integrated management framework for *A. altissima*

Due to its high reproductive plasticity, rapid vegetative regeneration, and remarkable ecological resilience, *A. altissima* poses a formidable and persistent challenge to forest managers. As a result, its control within forest ecosystems cannot depend on isolated or inflexible strategies. Instead, long-term suppression requires the development and implementation of a context-sensitive, ecologically grounded, and adaptive integrated management framework, one that accounts for the species' ecological resilience and reproductive adaptability. Table 1 synthesises current scientific knowledge into a decision matrix, aligning specific control methods with tree ontogenetic stages, site conditions, operational constraints, and identified research gaps. Each technique is evaluated based on five main criteria: (*i*) effectiveness, (*ii*) timing, (*iii*) site conditions, (*iv*) costs, and (*v*) ecological risk.

The evaluation criteria were derived from a qualitative synthesis of peer-reviewed studies, forestry agency guidance documents, and documented management outcomes from field trials. Because quantitative, standardised comparisons among control methods for *A. altissima* remain limited, each grading score represents relative performance trends and ecological risk inferred from consistent patterns reported across multiple literature sources, rather than an absolute measure of efficiency. Hence, this matrix serves as a decision-support tool, not a directive standard. This tool aims to support forest managers in selecting

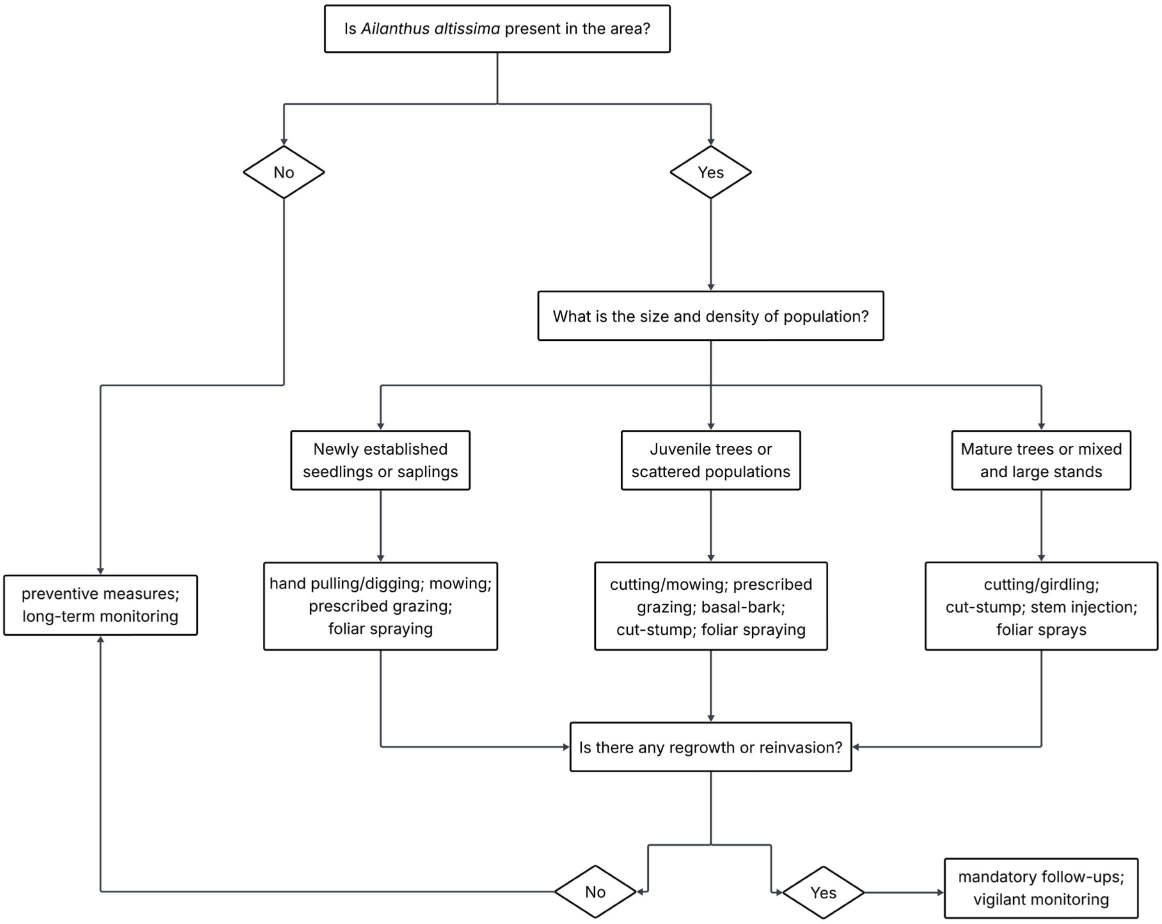

Fig. 2. Decision–support flowchart outlining control methods for *A. altissima* in forest ecosystems

the most appropriate combinations of control measures based on both ecological context and implementation capacity. From a practical standpoint, forest managers should follow the operational management guidelines outlined in Fig. 2.

Currently, systemic herbicide applications—particularly via cut–stump, basal bark, and stem injection methods—demonstrate high to very high effectiveness across most tree size classes, especially during the late summer to early autumn, when downward phloem translocation maximises root kill. Although associated with moderate operational costs, these methods have low to moderate ecological risk when carefully timed and spatially restricted, making them a reliable intervention for long-term control. Alternatively, foliar sprays offer moderate effectiveness, are highly dependent on seasonal timing and leaf expansion, and pose a higher ecological risk. Nevertheless, they are best suited for managing high-density monoculture stands where the risk to native species is minimal. By contrast, mechanical methods such as hand pulling, cutting, or girdling offer only low to moderate effectiveness as standalone treatments and often stimulate prolific resprouting. Their ecological risk is generally low, but cost and labour intensity can be significant, especially when applied across large infestations. Consequently, these techniques are best suited for early-stage or low-density infestation, when immediately followed by herbicide application.

Notwithstanding emerging interest, biological control remains underrepresented in the literature and lacks sufficient empirical data to allow rigorous evaluation across the five decision matrix criteria. Existing knowledge is largely derived from small–scale trials, anecdotal observations, or experimental quarantine studies, thereby limiting current assessments to qualitative assumptions rather than evidence-based scoring. This underscores the urgent need for robust, long-term, replicated field studies to clarify the efficacy, timing, ecological suitability, and potential non-target risks within integrated forest management frameworks. Until such data becomes available, the application of these should be considered exploratory and implemented cautiously. Irrespective of advances in control techniques, critical knowledge gaps persist, thus limiting the scalability and long-term resilience of an integrated management framework. To support the continued development and effective implementation of such a framework, the following recommendations are presented.

1. Strengthening prevention and regulatory protocols

A coordinated and robust legislative and institutional response is urgently needed at both national and regional levels to effectively reduce the ecological impact and ongoing spread of *A. altissima*. Each country should enact and enforce binding legal frameworks that explicitly prohibit the sale, transport, propagation, and ornamental use of *A. altissima*. National authorities should implement routine inspection and monitoring protocols to complement these prohibitions. These should prioritise the geospatial detection and mapping of existing populations, specifically female seed-bearing trees. A national registry of infested zones, updated annually, should be maintained and made publicly accessible to support rapid response strategies, coordinated regional actions, and public awareness. Additionally, countries should publish yearly reports summarising infestation trends, control efforts, comparative efficacy of different management techniques, and ecological outcomes. Such annual reports will serve as vital tools for refining best strategies and allocating resources more efficiently. Furthermore, cross-border collaboration and shared databases will be instrumental in responding to the transboundary nature of *A. altissima* spread and ensuring harmonised containment efforts between countries. Forest management enterprises must be held to strict operational hygiene standards. Mandatory hygiene protocols must be enforced across all silvicultural operations. Forest machinery must undergo thorough cleaning and decontamination before exiting infested areas. Soil removal and high-pressure washing should be standard practices to prevent accidental spread of seeds or root fragments. This is especially critical when the machinery is moved between forest stands, conservation zones, or regions of differing infestation severity.

2. Enhancing mechanical and physical control strategies

Mechanical control techniques are commonly used during early infestations or in environmentally sensitive areas. They should not be used as a stand-alone treatment because their effectiveness is limited by quick and vigorous resprouting, which can often worsen the infestation density. For this reason, they need to be followed by a suitable herbicide application to achieve the best suppression. Future research should focus on evaluating different combinations of mechanical methods with systemic herbicides to identify the most effective and site-specific pairing, considering factors such as active ingredients, concentrations, application methods, seasonal timing, ontogenetic stages, and tree size classes.

Prescribed fire, although historically utilised in forest management, is not a recommended approach for controlling *A. altissima*, as it often encourages root sucker growth due to its high fire tolerance and thick bark insulation. When prescribed fire is used for silvicultural purposes (e.g., fuel load reduction), it must be

Table 1. Decision matrix for integrated management of *A. altissima* in forest ecosystems[§]

Ontogenetic stage	Recommended control methods	Decision matrix criteria[*]					Research gaps
		Effectiveness	**Timing**	**Site conditions**	**Costs**	**Ecological risk**	
Seedlings or saplings (<2 m)	Hand pulling or digging	+/++	Spring (post–rain)	Moist soil, shaded or semi–open sites, limited access	+	+ (minimal disturbance)	Limited data on root removal completeness and seedling identification.
	Foliar sprays (*glyphosate*)	++	Late spring to summer	Open and accessible sites	++	++ (risk of non–target vegetation contact)	Lack of field trials on foliar suppression thresholds under overstory mixed vegetation across different forest types.
Juvenile trees (2–10 cm DBH[†])	Basal bark (*triclopyr*; *imazapyr*[‡])	+++	Autumn	Dry bark conditions	++	+ (targeted application, potential for leaching)	Knowledge gaps in bark thickness response and herbicide uptake efficacy, resprouting effects, and herbicide leaching.
	Cut–stump (*triclopyr*; *imazapyr*[‡]) or Foliar sprays of resprouts (*glyphosate*)	+++	Late summer to autumn	Accessible sites	+/++	+/++ (targeted application, potential for leaching and drift)	Limited long–term studies on different herbicides and stump size interactions, resprouting effects, and herbicide leaching.
	Prescribed grazing	+/++	Spring to summer	Early infestations, open or lightly wooded areas	+	+ (minimal disturbance, potential for herbicide intoxication)	Lack of grazing protocol data in forest settings (e.g., animal species, grazing duration, and stocking rates).
Mature trees (>20 cm DBH)	Stem injection (*triclopyr*; *imazapyr*[‡])	+++	Late summer to autumn	Dense infestations, scattered female trees	++	+ (targeted application, potential for leaching)	Few limited studies on delayed mortality, resprouting effects, and herbicide leaching.
	Cut–stump (*triclopyr*; *imazapyr*[‡]) or Foliar sprays of resprouts (*glyphosate*)	+++	Late summer to autumn	Dense infestations, scattered female trees	++	+/++ (targeted application, potential for leaching and drift)	Limited long–term studies comparing herbicides and stump size interactions, resprouting effects, and herbicide leaching.
	Girdling and/or Foliar sprays of resprouts (*glyphosate*)	++/+++	Spring to summer	Stands where cutting and other methods are restricted	+	+/++ (if herbicide is applied properly in grooves, potential for drift)	Knowledge gaps in optimal groove dimensions and resprout suppression timing.

Multi–stage infestations	Aerial foliar spray	++	Late spring to summer	Broad–scale monocultures, open canopy	++/+++	+++/++++ (high drift potential)	Insufficient landscape–scale efficacy comparison trials across different forest types.
	Mechanical mowing	+	Multiple passes/year	Flat terrains, open access	++	+ (minimal disturbance)	Lack of data on mowing timing and frequency needed for total root exhaustion.
	Biological control	?	?	Site–independent	?	?	No field–approved agents; host–specificity and ecosystem effects still unverified.
	Restoration planting	~	Post–removal	All sites (particularly riparian zones and disturbed forests)	?	+ (supports ecological function)	Need for trait–based species selection trials for reinvasion resistance and ecological recovery across different forest settings.

Notes.

[§] In this decision matrix, the higher effectiveness grading scores reflect a greater likelihood of long–term suppression, whereas the higher ecological–risk grading scores indicate an increased probability of non–target impacts or site–level disturbance, and vice versa. The mixed grading scores of effectiveness and ecological risks indicate variation in outcomes across site conditions and/or tree ontogenetic stages. Cost estimates, drawn primarily from Kochenderfer et al. (2012), reflect chemical control only; quantitative data for mechanical or integrated methods are lacking. Given the lack of empirical cost assessment data for mechanical and integrated control methods, relative costs were inferred qualitatively from typical field operations, accounting for potential mowing frequency, fuel consumption, labour inputs, and, where applicable, stocking rates under standard forestry maintenance practices.

[*] Grading scores: + = *low*, ++ = *moderate*, +++ = *high*, ++++ = *very high*, ? = *insufficient empirical evidence*, ~ = *variable outcomes reported*

[**] Mixed grading scores: +/++ = *low to moderate*, ++/+++ = *moderate to high*, +++/++++ = *high to very high*

[†] DBH = diameter at breast height, measured 1.3 m above the ground

[‡] Ester–based formulations of imazapyr and triclopyr are recommended in riparian zones

accompanied by an integrated strategy that includes mechanical suppression of resprouts, following immediate herbicide application, and reforestation with competitive native tree species. Controlled field trials should investigate optimal post-burn intervention sequences, timing, and verify long-term success rates.

3. Advancing biological control and prescribed grazing

Biological control remains an underexplored, yet promising frontier. Even though some progress has been made over the years, there are currently no approved biological control agents for widespread release in Europe or the U.S. Hence, national biocontrol programs should prioritise the identification and isolation of native antagonists, tailored to each country's ecological and regulatory context, followed by rigorous host-specificity testing preceding any release to safeguard native flora and fauna. In addition, novel trials should evaluate the compatibility of releasing biocontrol agents with simultaneous herbicide application. Since the synergistic or antagonistic interactions between the two remain poorly understood and may influence overall efficacy in an integrated management framework, these trials are needed to elucidate potential antagonistic interactions and maximise long-term suppression.

Prescribed grazing may serve as a complementary management option, particularly in early or small-scale infestations where seedling suppression can be achieved. Even then, extreme caution is necessary; that is, grazing schedules should be coordinated promptly to avoid coinciding with herbicide application and livestock ingestion of treated foliage. Forest managers should enforce withholding periods, livestock exclusion zones, and rotational schemes to closely monitor the regrowth dynamics of *A. altissima* before reintroducing livestock. Likewise, large field trials are of utmost importance to determine the best practices regarding the animal species used, stocking rates, and grazing periods for operational feasibility and integration into multi-year control regimes in forest settings.

4. Refining chemical control

Chemical control remains the cornerstone of *A. altissima* management. Nonetheless, the variability of treatment success highlights the need for comprehensive field trials that test combinations of herbicide formulations, concentrations, application methods, and seasonal timing. National and regional forest enterprises must establish coordinated field experiments to screen for the most effective herbicide-application pairings. These trials should account for phenological timing, herbicide mobility, persistence, translocation properties, formulations, and degradation rates. Nevertheless, ecotoxicological research remains a critical gap. Given this, further investigation into potential leaching, residual soil activity, and ecotoxicological effects is of paramount importance to minimise unintended impacts on native species and soil health across different forest types.

5. Supporting ecological restoration

Since promoting native canopy closure and vigorous ground-layer vegetation may provide durable biotic resistance against reinvasion, ecological restoration is essential to ensure long-term resilience in forest ecosystems following *A. altissima* removal. Restoration programmes should prioritise selecting native species capable of outcompeting *A. altissima* under local conditions. Species with high competitive ability should be identified, trialled, and used to reestablish canopy cover and suppress reinvasion. Trials should examine traits such as shade tolerance, root architecture, allelopathic resistance, and nutrient uptake to guide species selection. Restoration efforts must aim not only to replace biomass but also to reconstitute ecosystem functions and resistance pathways in disturbed forests. In this regard, ecological modelling and site-specific experiments are needed to fully address the optimal assemblages of native flora capable of suppressing and resisting the reinvasion of *A. altissima*, while restoring forest function.

Conclusive remarks

The sustainable management of *A. altissima* in forest ecosystems requires an ecologically grounded and adaptive framework tailored to site conditions, forest structure, and tree ontogenetic stages. As synthesised in Table 1, systemic herbicide applications remain the most effective interventions, especially when properly applied, with moderate costs and manageable ecological risks. In contrast, mechanical methods provide limited efficacy when used alone due to vigorous resprouting but can substantially improve outcomes when combined with timely herbicide application. Prescribed fire poses a high ecological risk and should not be used in isolation; its role is restricted to integrated post-fire strategies that include chemical follow-ups. Aerial sprays are most suitable in dense monocultures lacking native vegetation but carry significant off-target risks in diverse forest settings. Biological control and prescribed grazing, while emerging as promising tools, remain underrepresented in the literature. Due to a lack of empirical research, their role in integrated management remains exploratory and should be implemented with extreme caution. Similarly, comparative cost-benefit analyses for all major treatment strategies remain scarce and should be prioritised to inform decision-making under constrained resource conditions. Further research is urgently needed to evaluate ecotoxicological risks of herbicide use and identify competitive native species for post-removal restoration. Ultimately, safeguarding forest ecosystem function, resilience, and biodiversity against the escalating threat of *A. altissima* depends not only on refining available control methods but also on embedding them within an adaptive forest-focused management framework grounded in experimental validation, institutional coordination, and long-term ecological monitoring.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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