



Integrated Weed Management in Eucalyptus Plantations: A Review

Úrsula Ramos Zaidan^{1,*} , Wendel Magno de Souza² , Gerson dos Santos Lisboa¹ 

Abstract

Weed management in *Eucalyptus* plantations should not be an ancillary silvicultural operation, but rather a component that influences establishment, plant development, stand operational management, and vegetation conditions under the canopy throughout the cycle. This review examines the management of spontaneous vegetation in *Eucalyptus* plantations, from establishment to understory dynamics, with an emphasis on how operational control practices can be reorganized within an integrated weed management (IWM) framework. The literature shows that interference is most critical at planting and during early growth, when seedlings still exhibit low competitive ability and high exposure to competition for water, nutrients, light, and space. However, its effects are not restricted to establishment, as weed coexistence can alter crop development, nutrient use, biomass accumulation, and wood production for several years. Operational studies indicate that weed competition responses depend on the duration, intensity, and spatial arrangement of control, including strip width, timing of intervention, and suppression persistence. Chemical control remains the dominant foundation of management, but its performance depends on dose, clone, application conditions, straw residue, reinfestation pattern, and light availability. The article also discusses the limitations of the herbicide-centered model, elements of IWM, ecological implications of the understory, and research gaps, advocating for management protocols based on coexistence periods that are spatially explicit and tailored to the production context.

Keywords

Weed competition — Herbicide selectivity — Weed resistance — Forest understory — Precision silviculture

¹ Federal University of Goiás

² Suzano S.A., Brazil

*Corresponding author: ursula.zaidan@gmail.com

1. Introduction

Weed management in *Eucalyptus* sp. plantations becomes decisive at the moment the seedling needs to establish itself rapidly in the field, when it faces high exposure to competition and has a low capacity to occupy the site. At this stage, delays in weed control compromise not only the initial start-up but also the uptake of growth resources and the uniform performance of the stand. Brazilian experimental literature consistently shows that weed interference during the first year alters eucalyptus development and requires specific attention during the establishment period (Tarouco et al., 2009; Medeiros et al., 2016). In parallel, technical documents focused on crop management highlight that the presence of weeds reduces growth and timber increment while also hindering subsequent silvicultural operations, increasing overall system costs (Goulart et al., 2015; Avisar et al., 2023; Melo et al., 2020). Thus, treating weed management merely as an ancillary operation oversimplifies the problem, as it forms part of the silvicultural foundation for stand performance.

The technical and scientific literature on this topic is extensive, but its conceptual organization remains uneven. There is abundant material on interference, herbicides, application technology, weeding, control strips, and the response of *Eucalyptus* to coexistence with weed species, which shows that the theme of "weed control" is well represented in the literature. The issue is that this body of work does not always appear explicitly structured as Integrated Weed Management (IWM) in planted forests. Even the reference work on IWM in *Eucalyptus* brings together methods, interference factors, and application technology under the same analytical framework, indicating that this integration is both possible and necessary (Ferreira et al., 2010). Meanwhile, a review on reforestation in Brazil notes that while various techniques exist, the isolated use of any single method is not recommended, requiring a tailored choice based on the planting scenario and operational costs (Santos & Silva, 2018). This gap between technical knowledge and the explicit structuring of IWM justifies the proposed review.

This review focuses on *Eucalyptus* spp. plantations, with an emphasis on establishment, initial growth, weed



management practices, herbicide selectivity, resistance, the understory, and management implications throughout the stand lifecycle. The goal is neither to generically review weeds in forest systems nor to automatically extrapolate results from other tree species to eucalyptus. Nevertheless, selected studies conducted in other geographical contexts or specific silvicultural settings will be considered when they help interpret mechanisms or decisions relevant to this genus. Works on growth response to weed competition control in *Eucalyptus pellita* F.Muell. contribute to discussing the intensity and duration of management across contrasting sites (Inail et al., 2021). Studies on understory diversity in *Eucalyptus benthamii* Maiden & Cabbage help frame vegetation under the canopy as an ecological component of the system (Stefano et al., 2020). Similarly, research on selective herbicides for establishment expands the operational understanding of the topic (Minogue et al., 2018).

Based on this background, this article aims to critically synthesize what is already consolidated in weed management in *Eucalyptus* sp. plantations, identify what is being tested as a technical adjustment or new tool, and point out what is still missing to consolidate an integrated approach to weed management in planted forests. This includes considering both operational practices already adopted and emerging solutions incorporated into the recent debate. Among them are glyphosate-tolerant genetically modified materials, proposed as a tool to improve management without dispensing with safety evaluations and integration into the silvicultural system (Avisar et al., 2023). It also includes reviews highlighting the need for site-specific management and the adjustment of practices to local conditions, a perspective close to precision forestry, where management decisions are adjusted spatially rather than uniformed across the entire area (Hutapea et al., 2023).

2. Weed interference and effects on stand development

During the establishment phase, weed interference arises from the overlap between the high physiological demand of the seedlings and their low capacity to occupy the site. At this stage, eucalyptus explores a limited volume of soil and intercepts little light, which increases competition for water, nutrients, light, and physical space with grasses and other spontaneous species (Santos & Silva, 2018). In clones of *Eucalyptus urophylla* S.T.Blake × *Eucalyptus grandis* W.Hill ex Maiden, coexistence with weeds altered initial growth and nutrient concentrations, indicating that competition is not limited to biomass reduction but also affects the nutritional status of the seedlings

(Medeiros et al., 2016). When coexisting with *Urochloa* spp., growth was lower even when the weed was at a certain distance, and interference increased as it moved closer to the seedling, demonstrating a spatial component to this competition (Graat et al., 2015). Response also varied with density and developmental stage in the case of *Commelina benghalensis* L. (Costa et al., 2021).

The most immediate effects of this interference appear in stand establishment, initial growth, and shoot architecture. In a review of reforestation in Brazil, it was highlighted that weed competition can compromise the growth and survival of forest species, especially in areas converted from pasture. In a field experiment with *Urochloa decumbens* (Stapf) R.D. Webster and *Spermacoce latifolia* Aubl., young eucalyptus seedlings showed high susceptibility to interference and required 140 weed-free days to maintain normal development after transplanting (Toledo et al., 2000). In another study, competition reduced stem and branch diameter and dry mass, with the period prior to interference estimated at 107 days after transplanting, reinforcing that the first year concentrates much of the stand's vulnerability (Tarouco et al., 2009). Furthermore, when planting occurred immediately after the desiccation of *Urochloa decumbens*, initial development was worse compared to intervals longer than 14 days, suggesting that delays in initial establishment can impact canopy architecture and closure speed (Graat et al., 2018).

Coexistence with weeds does not merely cause temporary losses during establishment; in many cases, it alters the growth trajectory of the stand for several years. In an *E. grandis* × *E. urophylla* hybrid evaluated at 4.5 years, the continuous presence of weeds reduced wood production and total biomass, in addition to modifying nutrient stocks and the use efficiency of these elements across different tree compartments (Momolli et al., 2023). On a seven-year scale, the width of the weed control strip maintained for only the first six months still influenced final performance, with a 1.25 m strip on each side of the row resulting in a 61.8% gain compared to the infested control (Tiburcio et al., 2023). In *Eucalyptus globulus* Labill., the timing of weed control throughout the rotation increased productivity by the end of the study, showing that the effect of the weed community can persist beyond the period conventionally treated as establishment (Corticeiro et al., 2023). These results shift the discussion from initial growth loss to the complete production trajectory of the stand.

Therefore, stand response should not be interpreted simply as the presence or absence of weed competition. The period of coexistence alters the level of damage, and trials with increasing periods of control and coexistence have shown that the control window needs to be suffi-



ciently long to prevent cumulative losses in the first year (Toledo et al., 2000). The local intensity of the interference also matters: in coexistence with *Urochloa* spp., reductions in height, diameter, dry mass, and leaf area became more severe when the weed grew closer to the seedling, even without changing the identity of the weed species (Graat et al., 2015). Furthermore, the spatial distribution of management modifies the yield outcome over longer horizons, as side strips of different widths produced distinct responses in diameter, height, volume, and mean annual increment, with better performance from constant 1.00 m strips on each side of the row or equivalent progressive schemes (Toledo et al., 2003).

3. Operational weed management practices in *Eucalyptus* plantations

In operational management of *Eucalyptus* spp. plantations, the most common pattern combines chemical control concentrated in the initial phase, maintaining weed-free strips along the planting line, and additional interventions until canopy closure. Under Brazilian conditions, using herbicide-treated strips along the planting row has been a conventional practice, often in standardized widths, although stand performance shows that this standardization is not always sufficient (Silva et al., 2012). Field trials with constant and progressive strips showed that spatially organized control throughout the first 12 months impacts height, diameter, volume, and mean annual increment, indicating that the initial operation defines part of the stand's future performance (Toledo et al., 2003). In clonal planting, combining herbicides with a reapplication of pre-emergents at 120 days maintained control until the end of the study, with emphasis on glyphosate + isoxaflutole + reapplication in the planting row and inter-row (Schetz et al., 2021).

The logic of these interventions can be summarized as an operational sequence linked to stand development, rather than a fixed set of independent applications. Figure 1 organizes this progression into five phases, from site preparation to the understory condition in a structured stand, showing that the target of management changes over time. In the initial phases, the priority is to reduce pre-planting competition and protect young seedlings that are not yet competitive; next, the focus shifts to maintaining weed-free rows during establishment and initial growth. With canopy expansion, the need for complete suppression tends to decrease, creating room for more selective control of reinfestation and, later on, localized management of understory vegetation. In row-based perennial systems, such as *Coffea arabica* L., vegetation management in inter-rows can alter aboveground

biomass and is associated with crop performance (Zaidan et al., 2022).

In Phase I, management focuses on preparing the area for planting by reducing pre-existing vegetation and organizing the operational strip where the seedling will be inserted. In Phase II, the priority shifts to the direct protection of the newly planted seedling, a stage where small reinfestations near the planting row can already compromise survival and uniformity. Phase III corresponds to the period when eucalyptus begins canopy expansion but still coexists with open spaces, requiring more continuous control maintenance around the row. In Phase IV, increased shading and site occupancy alter the pattern of interference, so control tends to become more selective and driven by localized reinfestation. Finally, in Phase V, the operational challenge is no longer crop establishment, but rather managing the vegetation under the canopy, considering access, fire risk (including the accumulation of dry litter mass), and the need for intervention in an already established understory.

This temporal progression should also guide the remote sensing monitoring of competing vegetation. In the initial phases, when soil, rows, and inter-rows are still exposed, optical sensors can support the separation between seedling canopy, bare soil, and patches of spontaneous vegetation. Under these conditions, the most useful operational information is not necessarily the taxonomic identification of the weeds, but the quantification of coverage and the spatial intensity of the infestation. As a result, vegetation maps can be converted into weed competition pressure classes, location of patches, control failures, post-application escapes, and priority areas for reapplication or directed mowing, within a workflow that connects optical acquisition, patch detection, and spatial prescription of management (Figure 2).

Once this diagnosis is spatialized, chemical interventions can be positioned with greater clarity within the stand's operational sequence. In this arrangement, post-emergent and residual herbicides fulfill distinct and complementary roles. The Embrapa technical document on herbicides registered for eucalyptus crops compiles and systematizes the main information regarding recommended products and their respective usage instructions (Goulart et al., 2015). Among the herbicides used in pre-emergence, flumioxazin, isoxaflutole, sulfentrazone, and indaziflam stand out, being employed to reduce weed reinfestation after planting. However, the selectivity of these products depends on the molecule used, the applied dose, and the form of contact with the seedlings (Araujo Neto et al., 2020). In this context, Tiburcio et al. (2012) found that flumioxazin was selective to eucalyptus at doses up to 125 g ha⁻¹, showing greater efficacy in weed control when associated with isoxaflutole and

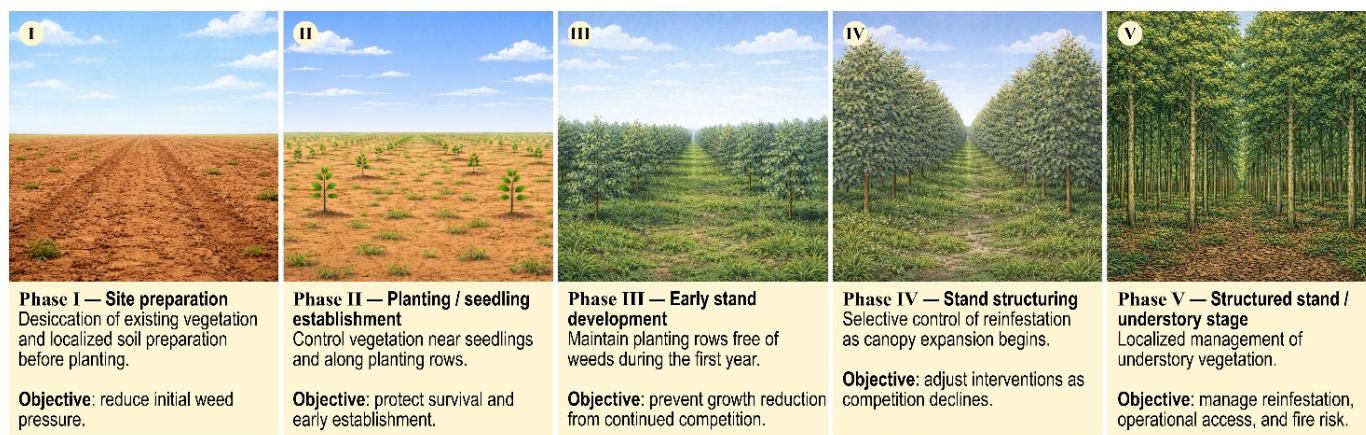


Figure 1. Operational phases of vegetation management in *Eucalyptus* plantations, from site preparation to the understory stage in a structured stand. The figure illustrates how the focus of weed management shifts along stand development: from desiccation and localized soil preparation before planting (Phase I), to protection of seedlings during establishment (Phase II), maintenance of weed-free planting rows during early stand development (Phase III), selective control of reinfestation as canopy expansion begins (Phase IV), and localized management of understory vegetation in later stages (Phase V). Together, these phases summarize the temporal and operational progression of weed management in commercial *Eucalyptus* plantations. Source: the authors, assisted by ChatGPT 5.5.

sulfentrazone. In a study with indaziflam applied in weed pre-emergence and crop post-emergence, the control of *Brachiaria plantaginea* (Link) Hitchc. and *Ipomoea grandifolia* (Dammer) O'Donnell was classified as very good to excellent throughout the evaluations (Pires et al., 2023). Meanwhile, in hybrid clones of *E. grandis* × *E. urophylla*, pre-emergent applications tended to be more effective than post-emergent ones in promoting initial growth (Minogue & Osiecka, 2015).

The width of the treated strip, the timing of application, and control efficiency alter stand performance over both short and long terms. At two locations in the state of São Paulo, treated strips of at least 0.75 m on each side of the row were necessary to minimize interference and sustain better initial development of *Eucalyptus grandis* (Silva et al., 2012). Over a longer horizon, the response was non-linear: in a commercial area in Bahia, strips maintained for only the first six months produced detectable differences at seven years, with better stand performance in wider control widths around the planting row (Tiburcio et al., 2023). Control persistence also depends on the reapplication strategy. In *Eucalyptus benthamii*, two sequential applications of sulfometuron methyl, at 14 and 56 days after planting, resulted in more bare soil and lower grass and vine coverage than a single application, although seedling response varied across sites (Osiecka & Minogue, 2015). Herbicide selectivity in eucalyptus plantations must be treated as a conditional attribute rather than a fixed property of the product. The response to glyphosate varies among clones, with differences in growth, shikimic acid accumulation, gas

exchange, and sensitivity to low and high doses, showing that distinct genetic materials can react differently to the same active ingredient (Cerqueira Junior et al., 2020). In post-emergent applications combined with foliar fertilizer, the response was also clone-dependent: indaziflam and glyphosate + S-metolachlor were the most damaging treatments, whereas the fertilizer reduced intoxication in one clone while intensifying symptoms in others (Barroso et al., 2022). Not every operational condition, however, alters this pattern. For the herbicides oxyfluorfen and saflufenacil, XR 110.02 and TTI 110.02 nozzles did not modify the selectivity observed in seedlings (Silva et al., 2019). Even so, drift and herbicide application positioning remain determining factors, as glyphosate caused greater phytotoxicity when applied directly onto leaves or when hitting a higher proportion of the canopy, especially in young plants (Costa et al., 2012; Santos Junior et al., 2015).

The efficiency of chemical control also depends on factors in the immediate environment of the stand and the biological condition of the infestation. In the presence of eucalyptus straw, the S-metolachlor + glyphosate mixture lost efficiency, and greater control was obtained in plots without straw, even though the mulch alone reduced grass biomass; in this study, simulated rainfall of 25 or 50 mm did not alter the control results (Duque et al., 2023). Light incidence modifies the susceptibility of target species. In *Digitaria insularis*, shading increased sensitivity to glyphosate alone and in combination with carfentrazone-ethyl, whereas under full sun none of the tested doses were efficient (Ferreira et al., 2024). A

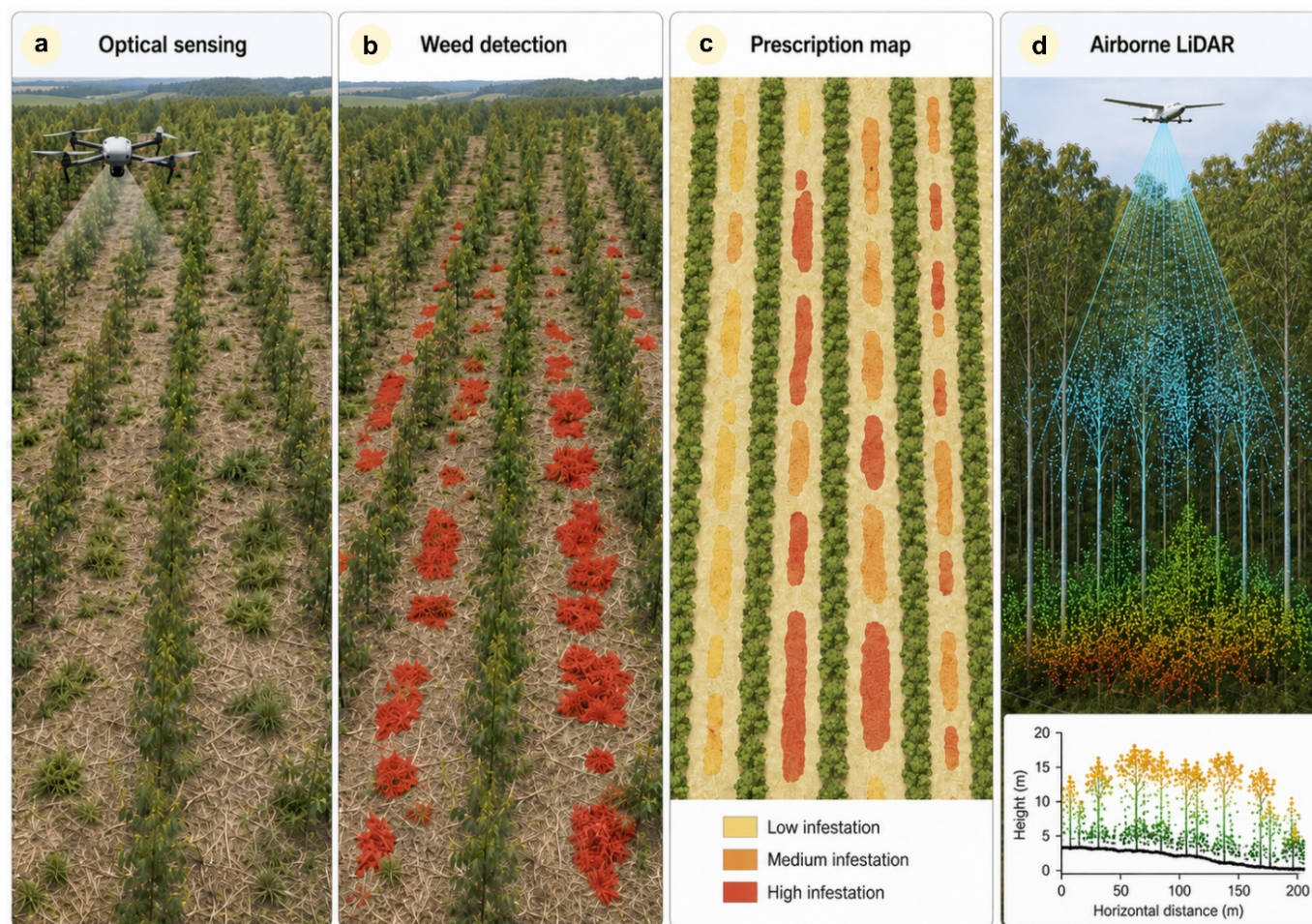


Figure 2. Remote sensing-supported weed management in Eucalyptus plantations. The workflow illustrates how spatial monitoring can support integrated weed management across stand development: (a) optical sensing in young plantations before canopy closure, when planting rows, inter-row soil and weed patches are still visible; (b) image-based weed detection, separating spontaneous vegetation from Eucalyptus rows; (c) conversion of detected patches into an operational prescription map with low, medium and high infestation classes for site-specific management; and (d) airborne LiDAR monitoring in more developed stands, where the focus shifts from direct optical detection of weeds to structural characterization of understory vegetation beneath the canopy. Source: the authors, assisted by ChatGPT 5.5.

similar response occurred in *Commelina benghalensis*, whose tolerance to saflufenacil was higher without shade and lower under 40% and 55% shading, due to shifts in biomass allocation and a larger contact area with the herbicide (Santos Junior et al., 2019).

4. Limits of the herbicide-centered model and the risk of management simplification

In many forest systems with *Eucalyptus* spp., weed management is still practically organized around the choice of active ingredients, product combinations, and reapplication schedules, while placing other management strategies in the background. This clearly appears in

operational studies comparing systems with and without pre-emergent reapplication and measuring the efficiency of herbicide mixtures over time, as in the clonal planting study conducted by Schetz et al. (2021). At the same time, the IWM literature on eucalyptus itself devotes substantial attention to available herbicides, application technology, and the operational efficiency of these products, highlighting that the practical foundation of the system remains heavily anchored in chemical control (Ferreira et al., 2010).

The problem is that this centrality is often accompanied by the repetition of a few modes of action, especially in areas where glyphosate plays a recurring role in managing the row, inter-row, or renovation vegetation. The



expected consequence is an increased selection pressure on the weed community. Guidugli et al. (2024) directly state that repeated use of herbicides with the same mode of action has led to the selection of resistant weeds, most notably glyphosate-resistant *Digitaria insularis* (L.) Fedde. In a similar scenario, Santos Junior et al. (2019) report that the repetitive use of glyphosate in eucalyptus plantations selected tolerant species such as *Commelina benghalensis* L., requiring rotation or combination with saflufenacil. The fact that spatiotemporal risk analyses targeting the selection of resistant *D. insularis* biotypes in eucalyptus areas already exist shows that this process is not merely potential, but is already part of the sector's operational diagnosis (Barroso et al., 2021).

Problem species make this limitation even more evident, as they illustrate scenarios where exclusively chemical management loses biological and operational predictability. In the case of glyphosate-resistant *D. insularis*, coexistence with eucalyptus seedlings reduced leaf and stem dry matter, and regrowth interfered more aggressively than plants originating from seeds, regardless of density and distance (Guidugli et al., 2024). For *C. benghalensis*, losses in initial eucalyptus growth have been observed starting at just 4 plants m⁻², with a more pronounced effect during summer, demonstrating that the operational relevance of the species depends not only on formal resistance, but also on its competitive capacity in the field (Costa et al., 2021). Furthermore, the response of *D. insularis* to chemical control varied with light incidence, indicating that the susceptibility of the species also depends on system shading (Ferreira et al., 2024). In this context, risk maps for selecting resistant biotypes gain practical value in planning infested areas (Barroso et al., 2021).

There is also a framing effect within this herbicide-centered model: the problem becomes primarily defined by the choice of product, dose, and reapplication, while making it less explicit at what point, for how long, and with what intensity the vegetation truly needs to be suppressed to meet the silvicultural objective. Consequently, decisions tend to rely on application schedules and immediate control metrics, without necessarily monitoring actual vegetation cover over time. Long-term trials with *E. globulus* show that vegetation management must be adjusted to understory coverage throughout the rotation, rather than being restricted to the initial establishment period (Corticeiro et al., 2023). The limitation of the herbicide-centered model, therefore, lies not only in resistance or selectivity, but also in its tendency to reduce an ecological and silvicultural decision to a mere choice of input.

5. Elements for integrated weed management in planted forests

In plantation stands, integrated weed management (IWM) should not be understood as a mere sum of control operations, but as a planned combination of chemical, mechanical, cultural, silvicultural, and ecological strategies, tailored to the production system and the stand's stage of growth. The reference manual on the subject itself organizes management based on interference, the factors that modulate this interference, control methods, and application technology, indicating that the concept involves coordinating tools rather than relying on a single practice (Ferreira et al., 2010). The review on weeds in reforestation areas in Brazil also shows that the weed community in these systems is diverse and requires a broader approach than simply eliminating vegetative cover immediately (Santos & Silva, 2018). Even recent tools, such as glyphosate-tolerant eucalyptus, have been proposed as a resource to improve management, rather than a replacement for an integrated decision strategy (Avisar et al., 2023).

The adoption of IWM presupposes prevention, monitoring, and diagnosis of the weed community before choosing interventions. This includes recognizing the presence of understory or reinfestation, its distribution, and the associated productive or operational risk. In eucalyptus plantations, the understory can increase fire risk, hinder forestry operations, and reduce yield through competition, so its detection must be integrated into the decision-making process (Melo et al., 2020). In this context, the use of airborne laser scanning to discriminate the presence and absence of understory shows that the diagnosis can be spatialized and incorporated into planning before field intervention (Melo et al., 2020). This logic is compatible with precision silviculture, where spatial and temporal data begin to support localized decisions throughout the rotation, rather than uniform prescriptions for the entire area (Gavilan-Acuna et al., 2025). Thus, prevention and monitoring cease to be merely descriptive stages and begin to produce decision layers, such as reinfestation maps, control strips, intervention patches, and stand prioritization (Figure 2).

Among non-strictly chemical management components, the spatial arrangement of control, ground cover, straw residue, and stand shading can help suppress infestations. Trials with control strips show that the width and distribution of the weed-free area around the planting row alter the intensity of interference and, therefore, should be treated as a silvicultural decision rather than a mere operational detail (Toledo et al., 2003). In coexistence with *Urochloa* spp., both chemical and mechanical control, with or without removal of the weeded shoots,



were effective in curbing interference with initial growth, indicating that different management strategies can serve a similar function when applied at the appropriate time (Ferreira et al., 2016). Eucalyptus straw residue also modifies the system's response to the herbicide (Duque et al., 2023), and the interval between desiccation of *U. decumbens* and planting influences the early development of eucalyptus (Graat et al., 2018). Operationally, this body of evidence opens up possibilities for adjustments at the sub-stand scale, aligning with precision silviculture applications (Cohrs et al., 2025).

The diversification of modes of action and the rotation of strategies must be treated as part of resistance management and not merely as a technical choice of product. The array of herbicides registered for the crop shows that the system has access to different active ingredients and application methods, which allows for programs that are less dependent on a single molecule (Goulart et al., 2015). This diversification is necessary because the risk of selection already needs to be incorporated preventively into the planning of eucalyptus control programs (Barroso et al., 2021). This type of process reinforces the need for rotating modes of action and using programs that rely less on a single molecule, including the use of alternative herbicides such as saflufenacil (Santos Junior et al., 2019). The presence of selective pre-emergent alternatives, such as flumioxazin, expands precisely this margin of diversification within control programs (Tiburcio et al., 2012).

As synthesized in Figure 1, weed community management in *Eucalyptus* sp. plantations should not be treated as a uniform practice throughout stand development, because the objective of the intervention changes from protecting early establishment to more selective management of reinfestation and understory vegetation. Management decisions need to be tailored to the stand stage, infestation pressure, floristic composition, and the silvicultural goal of each area. In *E. pellita*, total weed competition control throughout the rotation increased wood volume in a low-productivity site, whereas in other situations, competition-free management before canopy closure sustained the adopted operational pattern, demonstrating that control intensity varies with the productive context (Inail et al., 2021). Furthermore, during weed coexistence, higher topdress fertilization did not substantially alter growth, indicating direct competition for the applied resource (Pereira et al., 2012). Similarly, site-specific practices have been highlighted as necessary to optimize growth and yield in tropical environments (Hutapea et al., 2023).

6. Understory, vegetation ecology, and management implications

In forest plantations, the understory cannot be treated merely as an unwanted fraction of the stand's vegetation. It forms a biologically active layer, with its own richness, diversity, and structure shaped by tree canopy cover and site conditions. In *E. benthamii* plantations, understory species richness decreased over time, and the eucalyptus stand displayed an intermediate condition between young and old *Pinus elliottii* Engelm. stands, suggesting that canopy closure and environmental modification act as filters on the present flora (Stefano et al., 2020). On another scale, a survey in eucalyptus plantations on Hainan Island, southern China (a humid tropical climate region comparable to areas of the Brazilian Amazon and Northeastern coast), recorded 124 species in the understory, with differences between shrub and herbaceous layers and among locations, highlighting variation in the composition of this vegetation (Chen et al., 2024). Furthermore, the type of weed community management alters the associated fauna, as observed for ants in *E. grandis* (Boscardin et al., 2016).

The composition and structure of the understory respond to the management adopted in the stand, as well as to how this management interacts with climate, soil, topography, and canopy development. The diversity of shrub and herbaceous layers can vary between areas, and the factors associated with this variation are not necessarily the same: climatic and topographic variables tend to show a stronger relationship with the shrub layer, whereas soil attributes and light conditions may have a greater relationship with the herbaceous layer (Chen et al., 2024). This shows that the vegetation response under the canopy depends on multiple environmental filters, rather than merely on the decision to control or not control. From an operational standpoint, this heterogeneity must be observed prior to intervention. In young stands, optical sensors may suffice to map visible spontaneous vegetation in the row and inter-row; however, with canopy closure, direct detection of the ground and weed competition tends to lose efficiency. At this stage, sensors providing structural information, such as airborne laser scanning, become more suitable for locating and classifying understory vegetation during management planning (Melo et al., 2020), shifting monitoring from optical detection of visible weeds to the structural characterization of the understory (Figure 2d).

The implications of vegetation management extend beyond tree growth, encompassing changes in the structure and ecological dynamics of the environment beneath the canopy. The presence of an understory reorganizes biomass in the lower strata and influences vertical fuel



continuity within the stand. This vegetation close to the ground can facilitate the connection between surface fuels and upper forest layers, a condition associated with fire propagation and severity in forest systems. Recent studies show that vertical continuity metrics, such as the presence of "ladder fuels," are among the structural factors that best explain fire severity in forest landscapes (Hakkenberg et al., 2024). Consequently, the understory ceases to be merely a component of weed competition and becomes integral to the stand's ecological functioning. This ecological dimension also includes changes in soil microbiological indicators linked to weed management in perennial systems (Zaidan et al., 2023). At the same time, different control methods do not yield the same level of ecological simplification. In *E. grandis*, the indirect effect of herbicides was more pronounced on the local composition of ant species than on total richness, suggesting shifts in the associated biota as well (Boscardin et al., 2016).

An integrated approach needs to distinguish situations where total suppression of the weed community is necessary from those where selective or contextualized management is more coherent with system objectives. In environments where competition severely compromises tree growth, more intense interventions may be justified; in others, the complete elimination of vegetation should not be taken as a rule. In *E. benthamii*, stand structure and soil attributes directly influenced understory richness and diversity, showing that suppressing the weed community also reshapes the stand's ecological environment (Stefano et al., 2020). In this framework, selective management becomes a technical decision rather than an operational concession (Boscardin et al., 2016).

7. Gaps in the literature and research agenda

The available literature on weeds in eucalyptus plantations has advanced further in describing interference, evaluating chemical control, and defining strip widths than in comparing complete IWM systems. The review of Brazilian research highlights weed species diversity, negative effects on growth and survival, and the need to combine methods, but it also reveals that many studies remain centered on isolated techniques rather than integrated decision frameworks (Santos & Silva, 2018). There is also evidence that weed coexistence has repercussions up to mid-rotation, affecting biomass, nutrients, and yield (Momolli et al., 2023). Even so, studies comparing complete IWM programs under operational conditions remain rare.

The definition of the stand's most vulnerable stages still needs to better incorporate the variability imposed by weed flora composition, genetic material, and establishment context. Interference does not manifest in the same way across clones or weed species, and its effects can simultaneously impact seedling growth and nutritional status. This indicates that fixed management windows, while useful as an initial baseline, are insufficient to represent the diversity of field conditions. Further progress is needed toward comparable decision-making criteria that account for floristic composition, the degree of competition intensity between weeds and the crop, and the differential response of the planted materials.

Another gap lies in the absence of experimental designs that integrate, within the same study, stand yield, crop selectivity, resistance risk, understory response, and operational costs. Today, these components appear in a fragmented manner. Post-emergence selectivity associated with foliar fertilizer was evaluated in distinct clones, revealing differential responses among genetic materials and herbicide treatments (Barroso et al., 2022). The influence of nozzle type on the selectivity of oxyfluorfen and saflufenacil was also addressed separately, without connecting it to long-term yield performance or weed community composition (Silva et al., 2019). Simulated drift studies examined damage from triclopyr and fluroxypyr + triclopyr in eucalyptus clones (Carvalho et al., 2014) and glyphosate effects on leaves, stems, and the whole plant (Costa et al., 2012). Meanwhile, the cost and operational choice dimension appears primarily in reviews, rather than integrated into these trials (Santos & Silva, 2018).

A more useful research agenda for tropical planted forests must combine the coexistence period, floristic composition, and spatial monitoring of the weed community. Long-term trials indicate that the effects of weed management can extend throughout the rotation, depending on the intensity, spatial configuration, and timing of weed control (Corticeiro et al., 2023; Tiburcio et al., 2023). At the same time, understory vegetation composition responds to climate, soil, and topography, reinforcing the need for multi-environment approaches rather than isolated local trials (Chen et al., 2024). Monitoring tools, such as airborne laser scanning, already allow for discriminating the presence and absence of understory with good accuracy and can serve as a foundation for spatial decision protocols (Melo et al., 2020). The next step is to translate this evidence into IWM protocols tailored to stand age, infestation pressure, and silvicultural objectives, establishing operational thresholds to convert vegetation maps into control decisions—such as maintaining, reapplying, mowing, widening control strips, or prioritizing stands.



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- ✓ There is no evidence of plagiarism in this article.

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