

Systematic Review

Sustainable Management of *Leucaena leucocephala* in Wetland and Riparian Ecosystems: A Systematic Review of Ecological Impacts and Control Strategies

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Abstract

Leucaena leucocephala is a nitrogen-fixing legume widely used in agroforestry systems, although its invasive potential poses increasing risks to wetlands and riparian ecosystems. This systematic review synthesizes current knowledge on the ecological mechanisms, environmental stressors, and management strategies associated with the invasion of *L. leucocephala* in humid tropical environments. Following PRISMA guidelines, 60 studies retrieved from Scopus, Web of Science, and Consensus were qualitatively analyzed. The results indicate that invasion success is strongly associated with environmental disturbances and stress conditions, particularly drought stress, altered hydrological regimes, fire occurrence, and land-use change, which reduce ecosystem resistance and facilitate species establishment. Key invasion mechanisms include high seed production, persistent soil seed banks, rapid growth, allelopathic effects, and strong resprouting capacity, leading to suppression of native vegetation and structural simplification of plant communities. Integrated management strategies combining mechanical and chemical control with active revegetation consistently showed higher effectiveness than isolated approaches. The evidence further suggests that climate-related stressors may intensify invasion dynamics and increase ecosystem vulnerability under future climate scenarios. Despite recent advances, important knowledge gaps remain regarding long-term ecosystem functioning, hydrological feedback, and adaptive management in invaded wetlands.

Keywords: biological invasion; ecological restoration; invasive species management; agroforestry systems



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1. Introduction

Leucaena leucocephala, native to southern Mexico and Central America (Belize and Guatemala), is considered one of the most problematic invasive plant species in tropical and subtropical regions. In wetland and riparian ecosystems, its management is particularly challenging, as isolated control methods are often ineffective and may even exacerbate invasion processes [1]. The species is widely recognized for its rapid growth and high capacity for biological nitrogen fixation. Although these characteristics led to its extensive use in restoration programs and agroforestry, they also underpin its invasive success and

capacity to alter ecosystem structure and functioning, raising significant concerns for native biodiversity [2].

In these ecosystems, *Leucaena leucocephala* has demonstrated the ability to colonize riverbanks, floodplains, and forest edges, where it may suppress native vegetation and alter ecosystem functioning [3,4]. In the Pantanal wetland, for example, areas experiencing prolonged dry periods and increased fire frequency tend to exhibit higher densities of *Leucaena leucocephala* regeneration, accompanied by reductions in native species richness. Climate projections further indicate that intensification of drought events and increased fire frequency may facilitate the continued expansion of this species in the region [5].

Despite its invasive potential, *L. leucocephala* may provide ecological benefits in certain managed contexts. The species has been reported to improve soil properties, stabilize slopes, and assist in soil recovery in degraded agricultural or urban landscapes [6–9]. However, such benefits are typically observed in agricultural or silvopastoral systems rather than in natural wetland ecosystems, where the ecological risks associated with biological invasion and biodiversity loss are considerably higher [3,5,10,11].

Given these contrasting roles, a better understanding of the ecological drivers, impacts, and management strategies associated with *L. leucocephala* invasion in wetlands is needed. Therefore, this study aims to conduct a systematic review of the scientific literature addressing the invasion ecology and management strategies of *Leucaena leucocephala* in wetland and riparian ecosystems. Specifically, this study seeks to: (1) synthesize current knowledge on the ecological and ecophysiological mechanisms that facilitate the establishment and spread of the species in these environments; (2) evaluate its impacts on vegetation structure, biodiversity, and soil properties in invaded ecosystems; (3) identify and compare the effectiveness of different management strategies used to control the species, including mechanical, chemical, and biological approaches; and (4) analyze the role of environmental factors, particularly hydrological regimes and drought events, in the invasion dynamics of the species.

Based on existing literature, we hypothesize that the invasion of *L. leucocephala* in wetland ecosystems is facilitated by alterations in hydrological regimes, particularly reductions in flood duration and intensity. Furthermore, we propose that: (i) the presence of the species promotes structural and functional simplification of plant communities, reducing native species richness and altering ecological processes related to nutrient cycling and soil properties; (ii) integrated management strategies are more effective than isolated control approaches; and (iii) ecological restoration following species removal often requires active reintroduction of native vegetation due to ecological legacies left by the invasion in soil conditions and seed banks.

2. Materials and Methods

This systematic review was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility in the identification, selection, and synthesis of scientific evidence regarding the management of *Leucaena leucocephala*.

2.1. Search Strategy and Databases

The literature search was conducted using major scientific databases, including Scopus, Web of Science, and the Consensus academic search engine, which aggregates more than 170 million scientific publications. The search strategy was structured around three main thematic axes: Species, Environment, and Process, using Boolean operators (AND, OR) and truncation where appropriate to maximize the retrieval of relevant studies. The following descriptors were used:

1. Species: "*Leucaena leucocephala*"
2. Environment: wetland, riparian zone, floodplain, river bank, flooded forest
3. Process: management, sustainable management, restoration, control, invasion

The complete Boolean search strings were as follows: ("*Leucaena leucocephala*") AND ("wetland" OR "riparian zone" OR "floodplain" OR "river bank" OR "flooded forest") AND ("management" OR "sustainable management" OR "restoration" OR "control" OR "invasion").

Only peer-reviewed articles published between 2010 and 2025, in Portuguese, English, or Spanish, were considered for inclusion to ensure the incorporation of the most recent scientific evidence and regional perspectives.

The last search was conducted in February 2026.

2.2. Study Selection and Eligibility Criteria

The study selection process followed four main stages (Figure 1):

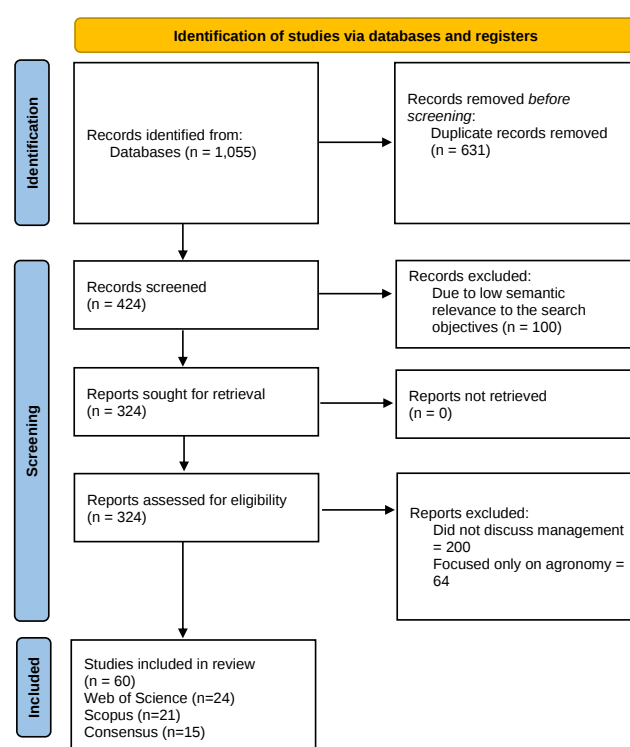


Figure 1. PRISMA flow diagram of the study selection process. The diagram illustrates the stages of identification, screening, eligibility, and inclusion of studies regarding the invasion ecology, management, and restoration strategies associated with *Leucaena leucocephala*. A total of 1055 records were initially identified, resulting in a final selection of 60 high-quality papers for qualitative synthesis.

Identification: A total of 1055 potentially relevant records were initially identified across the selected databases.

Screening: After removing duplicates and records with missing abstracts, 424 unique studies remained. These were screened based on titles and abstracts, resulting in the exclusion of 100 records due to low semantic relevance to the research objectives. The screening process was conducted by two independent reviewers. Discrepancies were resolved through consensus.

Eligibility: A total of 324 full-text articles were sought for retrieval and assessed for eligibility. At this stage, 264 articles were excluded. The main reasons for exclusion are detailed in Figure 1 and included: (i) lack of focus on invasion ecology, (ii) absence of management or restoration analysis, and (iii) purely agronomic or physiological studies.

Physiological studies were excluded when not linked to invasion or management. However, ecophysiological traits reported in the selected literature (e.g., photosynthetic efficiency, nitrogen fixation capacity, and drought tolerance) were considered when they contributed to explaining invasion mechanisms or management responses. This approach ensured that physiological evidence was incorporated in an applied ecological context, avoiding the inclusion of purely experimental studies without direct relevance to invasion dynamics or control strategies.

Inclusion: Following this rigorous assessment, 60 studies met all eligibility criteria and were included in the qualitative synthesis. These studies provide the basis for the analysis of invasion ecology, management, and restoration approaches associated with *Leucaena leucocephala* in wetland and riparian ecosystems.

2.3. Data Extraction and Evidence Synthesis

Data extraction was performed independently by two reviewers using a standardized form. To synthesize the main patterns reported in the literature regarding the management of *Leucaena leucocephala*, a qualitative evidence synthesis was conducted based on the studies included in the review (Supplementary Table S1). Each article was examined to identify statements or findings related to invasion drivers, control methods, ecological responses to management, and restoration strategies.

During the analysis, recurring management-related claims were identified, such as the effectiveness of integrated control methods, the limitations of mechanical removal, the role of revegetation with native species, and the influence of environmental disturbances on reinvasion processes. Each occurrence in which a study provided empirical results or explicit discussion supporting a given claim was recorded as an evidence occurrence.

In total, 60 evidence occurrences ($n = 60$) were identified across the analyzed studies. Each study contributed at least one evidence occurrence, resulting in a total of 60 evidence occurrences across the dataset. These occurrences were grouped into thematic categories representing the main management-related claims found in the literature. The proportion of evidence for each category was calculated by dividing the number of occurrences supporting a given claim by the total number of evidence occurrences identified in the dataset.

For each category, a reasoning statement was elaborated to summarize the ecological or management mechanisms explaining the observed pattern, based on the findings reported by the cited studies.

Variability among studies was explored qualitatively considering differences in ecosystems, climatic conditions, geographic regions, and management approaches. This approach allowed the identification of consistent patterns and divergences across the analyzed literature.

The overall certainty of evidence was qualitatively assessed considering consistency, number of studies, and agreement among findings.

Heterogeneity among studies was explored qualitatively by comparing differences in ecosystem type, geographic region, disturbance regimes, and management strategies. Due to the absence of quantitative synthesis, no formal subgroup analysis or meta-regression was conducted.

No formal sensitivity analyses were performed; however, robustness of the findings was inferred based on consistency of evidence across independent studies and contexts.

Potential reporting bias was qualitatively assessed considering the likelihood that studies reporting significant ecological impacts or successful management outcomes are more frequently published.

The certainty of evidence for each identified claim was qualitatively evaluated based on consistency of findings, number of supporting studies, and agreement among results, following an adapted evidence synthesis approach.

2.4. Risk of Bias Assessment

The risk of bias of the included studies was qualitatively assessed based on criteria adapted for ecological and environmental studies, including: (i) study design, (ii) sample size and representativeness, (iii) clarity of methodological description, and (iv) consistency between results and conclusions.

Each study was classified as having low, moderate, or high risk of bias. The assessment was conducted by two independent reviewers, and disagreements were resolved through discussion.

Overall, most studies presented moderate risk of bias, mainly due to observational designs and limited replication.

Potential reporting bias was considered qualitatively, given the absence of quantitative synthesis. The possibility that studies with positive or significant results are more likely to be published was acknowledged.

3. Results and Discussion

The overall risk of bias among the included studies was predominantly moderate, mainly due to the prevalence of observational designs and limited experimental replication. A smaller proportion of studies were classified as low risk, typically those with controlled experimental designs, while a few studies presented high risk of bias due to insufficient methodological detail.

3.1. Geographic Distribution, Ecosystems, and Associated Disturbances

The analyzed studies show a broad geographic distribution, with a strong concentration in tropical regions. Approximately 34% of the studies were conducted in Brazil, particularly within the Atlantic Forest, Cerrado, and Pantanal biomes. Around 23% were carried out in Asia (mainly China, India, Thailand, and Indonesia), while 13% were conducted in Africa (South Africa, Congo, and Mozambique). Studies from Latin America outside Brazil accounted for approximately 8%, including Mexico, Colombia, and Argentina. Research conducted in tropical islands or coastal regions (such as Hawaii, Jamaica, and Sri Lanka) represented about 6%, while 16% consisted of global reviews or meta-analyses addressing multiple biomes. This distribution confirms that most research on *Leucaena leucocephala* is concentrated in tropical and subtropical regions, where the species is widely naturalized or used in productive systems (Figure 2).

Regarding the ecosystems investigated, dry systems or tropical savannas were the most frequently studied environments ($\approx 36\%$), including grasslands, savannas, and seasonal tropical forests. Riparian environments or slopes associated with watercourses represented approximately 24% of the studies, while wetlands accounted for around 18%, including research conducted in the Pantanal and coastal wetland zones. Agroecosystems and silvopastoral systems represented about 14%, whereas laboratory studies or controlled experiments accounted for approximately 8%. These results demonstrate that the species occurs across a wide range of environments but is particularly frequent in dry ecosystems, riparian zones, and productive landscapes (Figure 3).

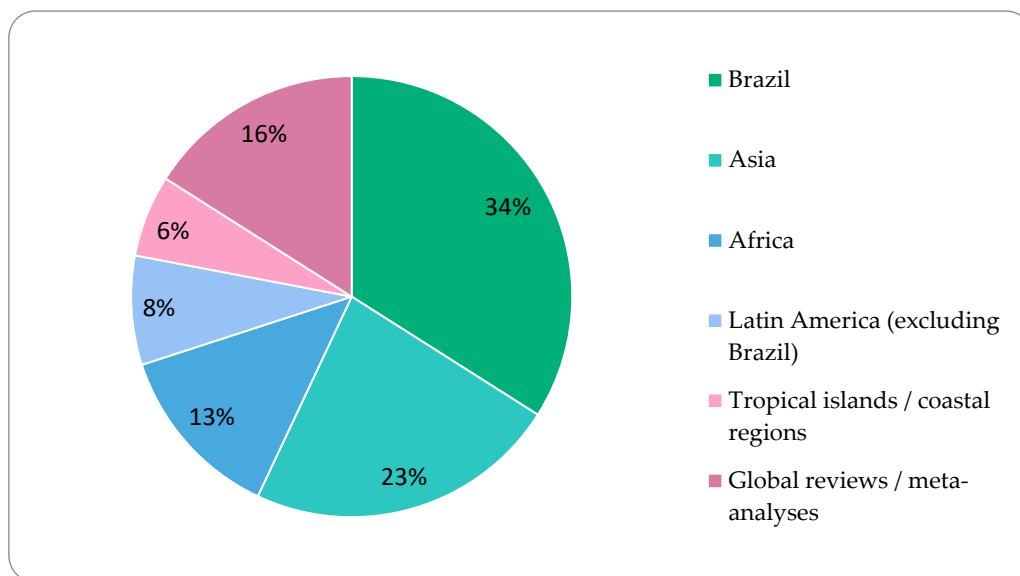


Figure 2. Geographic distribution of the 60 studies included in the systematic review addressing the ecology and management of *Leucaena leucocephala*.

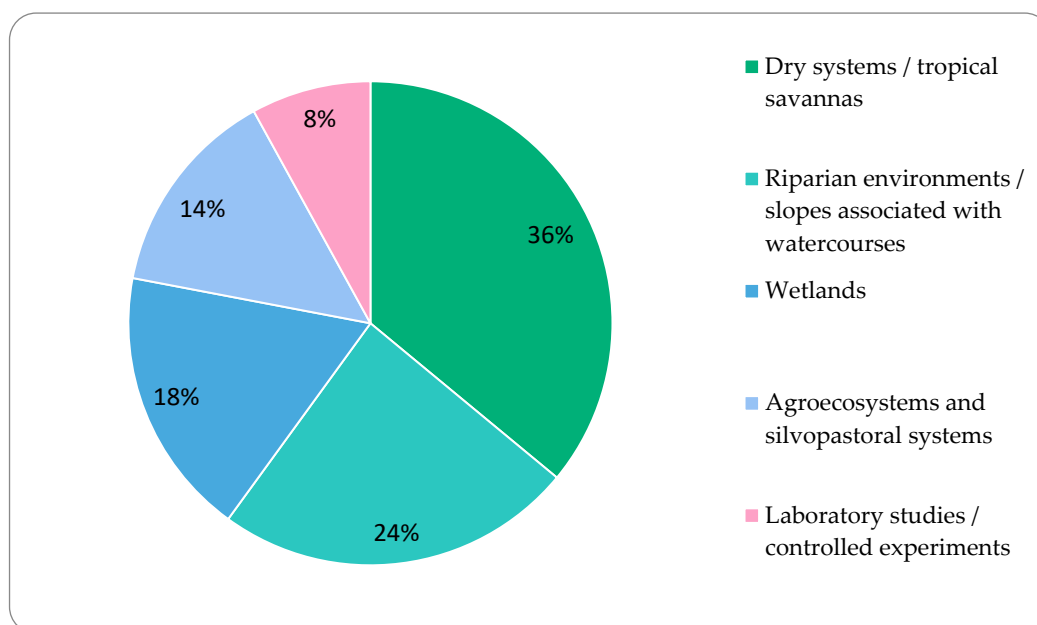


Figure 3. Distribution of ecosystem types represented in the studies included in the systematic review on *Leucaena leucocephala*.

Among the environmental disturbance factors associated with invasion, drought or water deficit was the most frequently reported, appearing in approximately 30% of the studies, especially in savannas and seasonal forests. Anthropogenic disturbances, including urbanization, mining, agriculture, and pasture abandonment, were cited in about 28% of the cases. Fire events were mentioned in approximately 18% of the studies, while alterations in flooding regimes or hydrological pulses accounted for around 14%, particularly in tropical wetlands. Other factors, such as metal contamination, climate change, and land-use change, were reported less frequently. Overall, these results indicate that *L. leucocephala* tends to establish preferentially in disturbed environments or areas subject to extreme climatic events (Figure 4).

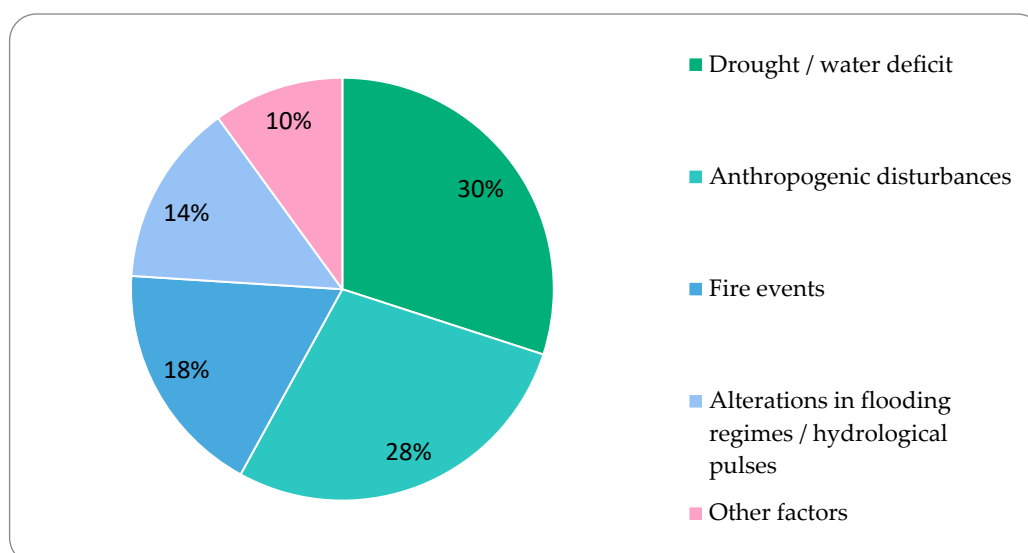


Figure 4. Main environmental disturbance factors associated with the invasion of *Leucaena leucocephala* based on the analyzed studies.

3.2. Ecological Mechanisms Associated with Invasive Success

Among the most frequently reported mechanisms, high seed production stands out, being mentioned in approximately 32% of the studies. The species produces a large number of seeds throughout the year and exhibits early reproductive maturity, being able to flower only a few months after germination [3,12]. Seeds exhibit physical dormancy due to an impermeable seed coat, allowing the formation of persistent soil seed banks that may last for more than a decade [13,14].

Another important factor is rapid growth associated with high physiological plasticity, cited in about 28% of the studies. The species exhibits high physiological efficiency, including elevated photosynthetic performance and optimized resource use, which enhances its competitive advantage in disturbed environments [15–17]. Additionally, its deep root system allows access to water in deeper soil layers, contributing to its tolerance to drought conditions [18].

The ability to resprout vigorously after disturbances also represents an important mechanism of population persistence, being reported in approximately 22% of the studies. Following cutting, fire, or mechanical damage, the species can produce multiple shoots from the stump or root system, making its control more difficult [12,19].

In addition, its ecophysiological traits, particularly nitrogen fixation and metabolic efficiency, facilitate establishment in nutrient-poor or degraded soils [3,20]. Furthermore, the allelopathic activity of the plant associated with the release of the amino acid mimosine may inhibit the germination and growth of neighboring species [3,21].

On the other hand, under the influence of abiotic dynamics, the species shows low tolerance to prolonged flooding, establishing preferentially in higher areas where inundation is less frequent [5,22]. Under climate change scenarios characterized by prolonged droughts, *Leucaena* may expand its distribution into wetland areas undergoing drying processes [5].

The species also shows relevant interactions with fire regimes. Heat generated by fires can break seed dormancy, stimulating mass germination after fire events [23]. In addition, its rapid biomass production may increase fuel loads in the ecosystem, potentially intensifying future fire events [5,24].

The dominance of *L. leucocephala* across different habitats, from well-drained sandy soils to riverbanks, is associated with its high physiological plasticity [25]. The species

exhibits high drought tolerance, mainly due to its root system accessing deeper soil layers than many native herbaceous or shrub species [18,26]. Although it prefers neutral to alkaline soils, it can also survive in acidic soils with pH as low as 4.1, although its performance is reduced under high aluminum saturation, a common condition in many tropical wetland areas [27,28].

Wetlands, riverbanks, and swamp areas represent high-risk environments for species proliferation. *L. leucocephala* is considered a significant invader in semi-natural or natural habitats of conservation interest, particularly in fluvial and coastal ecosystems [29]. Its ability to form dense monospecific stands leads to the exclusion of native species, altering ecosystem structure and limiting access for both wildlife and humans [30].

Finally, invasion may generate impacts on fauna and ecosystem services. The replacement of native vegetation alters the availability of shelter and food resources for fauna, particularly birds [31]. The reduction of animal-dispersed species may trigger cascading effects on ecological interaction networks. Furthermore, the formation of dense vegetation stands may render riparian and recreational areas inaccessible, reducing their social use [30,32].

3.3. Ecological Impacts on Natural Ecosystems and Wetlands

The ecological impacts of invasion are also widely documented. Many studies report that *Leucaena leucocephala* forms dense and often monodominant populations, significantly reducing native species diversity and hindering understory regeneration [33–35]. This process results in structural and functional simplification of plant communities, often described as the formation of “green deserts,” where few species are able to establish under the invasive canopy [12,15]. In some cases, these effects may facilitate the establishment of other exotic species or alter successional trajectories, compromising the natural recovery of native vegetation [36,37] (Table 1).

Table 1. Main ecological impacts relevant to wetland ecosystems.

Aspect	Effect of <i>L. leucocephala</i>	Implications for Restoration	Sources
Plant diversity	Decline in species richness and dominance of a single species	Leads to community impoverishment rather than ecosystem recovery	[3,5,10,11]
Invasion dynamics	High seed production and persistent soil seed bank	Increases risk of reinvasion and requires continuous and costly control	[3,5,11]
Riparian/wetland zones	Colonizes riverbanks and areas with variable flooding regimes	Competes with natural regeneration of floodplain species	[3,5,11]

As a result of its compact growth, one of the most frequently reported impacts of *L. leucocephala* is the suppression of plant biodiversity. By forming dense monospecific stands, the plant alters habitat structure and significantly reduces light availability in the understory [38]. This reduction in incident radiation may inhibit the germination and establishment of native tree and herbaceous species, impairing natural vegetation regeneration [11,30]. Additionally, as a nitrogen-fixing legume with high biomass production [39–41], *L. leucocephala* can also significantly modify nutrient availability dynamics, promoting nitrogen enrichment in the soil altering soil physicochemical properties. This process may alter biogeochemical cycles and favor the expansion of other invasive species

adapted to nutrient-rich environments [7,10,42]. Therefore, the dominance of the species can lead to biotic homogenization and structural simplification of plant communities. In some cases, native species are replaced by invasive or ruderal species that are more tolerant to shade and disturbance [43].

Interaction with the hydrological regime also plays a relevant role in invasion dynamics. The species exhibits low tolerance to prolonged flooding and tends to establish preferentially in areas of intermediate elevation or along riverbanks, where flooding is less frequent [22] (Figure 5). However, alterations in hydrological regimes or prolonged drought periods may favor its expansion into areas previously protected by flood pulses [5]. These ecological impacts become particularly relevant in riparian zones and wetlands, where invasion may compromise native species regeneration and alter ecological processes associated with ecosystem hydrodynamics (Table 1).



Figure 5. *Leucaena leucocephala* occurring in (A) riparian vegetation and (B) wetland environments in Paraná State, Brazil, illustrating its establishment and dominance in disturbed humid ecosystems. Photos: Maria de los Angeles Perez Lizama.

The presence of *L. leucocephala* in wetlands can trigger ecological changes that affect processes ranging from soil microclimate to broader biogeochemical dynamics. By forming a continuous and dense canopy, the species drastically reduces the amount of photosynthetically active radiation reaching the soil. Studies on forest regeneration have shown that *L. leucocephala* can reduce light intensity to less than 19% of external levels, creating deep shade conditions that inhibit the germination and establishment of both pioneer and late-successional native species [35,44].

Despite eventual agronomic benefits of the species, several studies highlight its negative effects and reinforce the need for rigorous monitoring and the implementation of preventive strategies to avoid ecological imbalances in wetland ecosystems.

3.4. Management and Control Strategies for *Leucaena leucocephala*

Regarding management, most studies indicate that isolated control strategies are rarely sufficient to sustainably reduce populations of *Leucaena leucocephala* (Supplementary Table S2). Simple mechanical methods, such as cutting or mowing, tend to be ineffective due to the species' strong resprouting capacity [12,45]. For this reason, several authors recommend

integrated management strategies combining mechanical, chemical, and, in some cases, biological methods to reduce both adult individuals and the soil seed bank [13,39]. However, even when invasive populations are successfully controlled, ecosystem recovery does not always occur naturally, as ecological legacies in the soil and seed bank may limit natural regeneration [1,40].

In this context, several studies highlight the importance of integrating species control with active restoration strategies, such as planting competitive native species, forest enrichment, or assisted natural regeneration [2,33]. The introduction of native species with similar functional traits or competitive abilities for resources can accelerate the recovery of vegetation structure and diversity [1,15].

The literature consistently demonstrates that effective management of *L. leucocephala* depends on integrated strategies combining mechanical removal, targeted herbicide application, and active revegetation with native species [3,5,12,33].

These approaches frequently achieve high control efficiency (80–100% mortality) by simultaneously reducing resprouting and limiting reinvasion from persistent seed banks. In contrast, isolated methods, particularly mechanical removal, are generally insufficient, as rapid regeneration from root systems often results in reinfestation [12,19,46].

Among the analyzed studies, different approaches related to management or use of *L. leucocephala* were identified. Approximately 32% of the studies evaluated control or eradication methods (mechanical, chemical, or combined). Another 26% investigated ecological functions or impacts of the species on ecosystems, including effects on vegetation structure, invasion dynamics, and carbon cycling. About 21% of the studies analyzed the productive use of the species in agroforestry or silvopastoral systems, focusing on biomass or forage production. The remaining 21% consisted of observational studies on invasion processes or natural regeneration. These results indicate a relatively balanced distribution between management-focused and ecological studies, although there are still relatively few experiments specifically designed to evaluate control strategies (Supplementary Table S2).

The use of herbicides in riparian or wet environments requires particular caution to avoid contamination of water bodies and impacts on non-target species. Recent techniques, such as herbicide capsule implantation directly into the stem (“stem implant”), have been proposed as safer alternatives for selective control in environmentally sensitive areas [30]. These techniques allow herbicides to be applied directly into the plant vascular system, reducing the risk of chemical drift and impacts on adjacent native vegetation.

Sustainable management of *Leucaena leucocephala* requires a gradual, priority-based approach, as recommended for invasive species in riparian and wetland environments. Complete eradication is generally feasible only in early-stage invasions, when affected areas are small and control costs remain relatively low [47]. In already established invasions, management strategies tend to focus on containment, preventing spread to new areas, or population suppression, reducing abundance to levels compatible with native ecosystem functioning [48,49].

The most common approaches involve integrated soil and water management, including practices such as organic fertilization and the introduction of beneficial microorganisms, as well as the reintroduction of native species to promote biodiversity restoration and adaptive control of invasive species [2]. In productive contexts, the use of *L. leucocephala* also stands out for its ability to improve soil fertility through biological nitrogen fixation [7].

Although these management steps are widely recognized in invasion ecology, their effectiveness in wetland systems depends on the integration of ecological, hydrological, and socio-institutional factors. In particular, community engagement, land-use governance, and long-term monitoring capacity play a critical role in determining the success of management

interventions. In this context, an effective management plan should consider the following structured steps:

Goal setting—Clearly define whether the objective is full ecological restoration, river-bank stabilization, or risk reduction (e.g., erosion or fire) [50].

Prioritization—Focus efforts on satellite populations or high-conservation-value areas where invasion is still incipient [51].

Site-specific planning—Select appropriate tools (mechanical, chemical, or biological), used individually or in combination, considering factors such as proximity to water bodies and sensitivity of local fauna [30].

Implementation—Carry out control actions using appropriate personal protective equipment, considering the potential toxicity of the plant [32].

Monitoring and evaluation—Monitor the area over long periods, particularly the seed bank and resprouting, often for more than a decade, to assess intervention effectiveness [52].

3.4.1. Mechanical Control

Mechanical control involves the physical removal of plants through techniques such as cutting, mowing, thinning, or uprooting. These approaches are commonly used in small areas or during the early stages of invasion. However, *Leucaena leucocephala* limits the effectiveness of mechanical control when applied in isolation due to its high resprouting capacity [53].

In many cases, simple cutting results in rapid regeneration, requiring repeated interventions over time. Methods such as soil scarification or the use of machinery for root removal may increase effectiveness but often involve high operational costs and can cause significant soil disturbance.

Additional strategies include the use of artificial shading or soil cover to limit the germination of seeds present in the soil seed bank. However, these methods have limited applicability and are generally restricted to experimental settings or small-scale interventions.

3.4.2. Chemical Control

Chemical control is widely used in the management of the species, especially in areas with dense populations. Systemic herbicides applied directly to cut stumps have been reported as one of the most effective strategies, significantly reducing resprouting capacity [32] (Table 2).

Table 2. Effectiveness trial results in riparian zones and roadside environments.

Chemical Treatment	Dose/Method	Mortality (24 Months)	Speed of Action
Aminopyralid + Metsulfuron	Capsule	100%	High (complete mortality within 12 months) [30]
Picloram	Capsule	100%	Moderate to slow [30]
Clopyralid	Capsule	98.3%	Moderate [30]
Glyphosate	Capsule	56.7%	Inconsistent [30]
Triclopyr + Picloram	Liquid (Drill & Fill)	100%	High [30]

Among the compounds used, herbicides such as glyphosate, triclopyr, and mixtures containing picloram and 2,4-D stand out. These are typically applied via foliar spraying or directly to the stem after cutting. Several studies report high mortality rates when

these herbicides are applied correctly, particularly when combined with prior mechanical removal [42].

Despite their effectiveness, herbicide use may present limitations in sensitive environments such as riparian areas and wetlands, due to the risk of chemical drift and water contamination. In such cases, more targeted application methods have been proposed to minimize environmental impacts.

3.4.3. Combined Mechanical and Chemical Control

Among the studies analyzed that evaluated direct control strategies, 30% reported complete mortality (100%), mainly when chemical control was combined with mechanical cutting. Another 40% of the studies reported mortality rates between 80% and 90%, indicating high effectiveness of chemical methods applied either alone or in combination. In contrast, low mortality (approximately 17%) was observed in 30% of the studies, generally in productive contexts or experiments where eradication was not the primary objective.

Overall, the results indicate that integrated methods, particularly the combination of mechanical cutting and herbicide application, are the most effective, frequently achieving control rates between 80% and 100%. In contrast, purely mechanical approaches or those associated with productive systems tend to result in significantly lower mortality ($\approx 17\%$), allowing persistence or regeneration of the species after management.

Clear-cutting combined with localized herbicide application (especially picloram + 2,4-D) to freshly cut stumps has proven to be the most effective method for reducing resprouting and controlling established populations, achieving up to 80% control after one year [12,19,46]. Mechanical removal alone typically results in intense resprouting due to the vigor of the root system [3,19].

Therefore, cutting alone is rarely sufficient to eliminate populations and is usually combined with complementary treatments:

Stump treatment—Immediate application of herbicides such as triclopyr to freshly cut stumps is commonly recommended to prevent regeneration [54].

Frequent mowing—In pasture systems, repeated cutting can maintain plants in a juvenile stage and reduce seed production, although it rarely eliminates populations if the root system remains intact [18,26,55].

Fire management—Fire may have ambiguous effects. Low-intensity fires can stimulate germination by breaking seed dormancy, whereas high-intensity fires may eliminate adult individuals but often create favorable conditions for recolonization [23,24].

The use of herbicides in wetland and riparian environments presents challenges due to the risk of water contamination and impacts on non-target species. Traditional methods such as high-volume foliar spraying or basal bark application with diesel carriers are increasingly discouraged in ecologically sensitive environments [30].

3.4.4. Innovative Chemical Methods in Sensitive Areas

A recent innovation for management in riparian corridors is the stem-implant method using biodegradable herbicide capsules. This technique involves drilling into the trunk and inserting a capsule containing dry granular herbicide, which is then sealed with a wooden plug [30].

The main advantages of this method include:

Environmental safety—The herbicide remains confined within the vascular system of the target plant, reducing risks of drift and water contamination [30].

Selectivity—Allows individual control of *Leucaena leucocephala* trees within native vegetation without affecting surrounding plants [30].

Operator safety—Reduces direct exposure to chemicals and eliminates the need to transport large volumes of water or diesel [30].

The “drill and fill” technique, although effective, requires greater care to avoid spills, whereas encapsulation offers greater safety and portability for management teams working in difficult-to-access environments such as riverbanks [30].

3.4.5. Biological Control

Biological control represents a complementary strategy but still lacks sufficient evidence of effectiveness as a standalone solution [56,57]. It may offer a low-cost alternative for managing wild populations of *Leucaena leucocephala*. Among the studied agents are specialized herbivorous insects, such as the psyllid *Heteropsylla cubana* and the beetle *Acanthoscelides macrophthalmus*, which can cause significant damage to leaves and seeds [42].

The use of *Acanthoscelides macrophthalmus* has potential to reduce viable seed production; however, its isolated impact is limited and should be integrated with other management practices [56–58]. Continuous monitoring is essential due to the long-term persistence of the seed bank [3,59]. Although rarely causing mortality in adult trees, infestation by *Heteropsylla cubana* can significantly reduce seed production and growth rates, decreasing the species’ competitiveness relative to native vegetation regeneration [29].

In addition to insect-based biological control, the strategic use of goats has also been reported as an effective management tool in dense *L. leucocephala* stands. These animals preferentially browse the foliage and can strip bark from trunks, leading to tree mortality through girdling [29].

3.4.6. Revegetation and Enrichment with Native Species

Following the initial control of *Leucaena leucocephala*, planting or stimulating natural regeneration of native species is essential to prevent reinvasion. Thinning followed by enrichment planting significantly increases growth and survival of native species under the residual canopy of *L. leucocephala* [33]. Dense revegetation reduces light availability at the soil surface, limiting the germination of invasive seeds from the soil seed bank [1,33].

3.4.7. Management Through Productive Use

The analyzed literature reveals a biological and ecological complexity that positions *L. leucocephala* as both a valuable productive resource and a potential ecological threat to the integrity of natural ecosystems. In agro-silvopastoral systems, the species is often described as a “miracle tree” due to its high productivity and forage value. In contrast, in biodiversity conservation contexts, it is frequently considered a “green pest” due to its high invasive potential.

This duality highlights the need for management strategies that go beyond the dichotomy between economic utility and ecological risk. The challenge is particularly evident in wetlands, riparian zones, and coastal ecosystems, where hydrological dynamics may facilitate dispersal and establishment, compromising native biodiversity and ecosystem services [29,60].

In some regions, management strategies based on productive use have been proposed as a way to reduce species expansion. *Leucaena leucocephala* has high value as a forage plant and is widely used in silvopastoral systems due to its high protein content [42]. Grazing by goats and cattle can help reduce seedling regeneration and limit the growth of young populations. Additionally, the species has been explored for biomass and bioenergy production in some agricultural systems. However, if not properly managed, these practices may also facilitate the spread of the species into new areas.

3.4.8. Adaptive Management and the “Code of Practice”

In contexts where *Leucaena leucocephala* still holds economic value, particularly in silvopastoral systems, sustainability depends on the implementation of strict containment measures. The Leucaena Code of Practice, for example, recommends avoiding planting within 100–200 m of watercourses to reduce the risk of hydrological seed dispersal [61].

Long-term monitoring of cultivated areas is also recommended, often exceeding a decade, to gradually deplete the persistent seed bank, which can remain viable for up to 20 years [13].

Key recommended management practices include:

Spacing and competition—Row planting combined with competitive grasses can reduce the establishment of spontaneous *L. leucocephala* seedlings [55].

Height management—Controlling plant height through intensive grazing or pruning prevents individuals from reaching reproductive maturity and reduces seed production [18, 55].

Rumen inoculation—The introduction of the bacterium *Synergistes jonesii* into the rumen of ruminants enables the degradation of dihydroxypyridine—DHP (a mimosine-derived compound), preventing animal toxicity and allowing livestock to efficiently consume the plant, thereby acting as a biological control agent [18,55].

3.5. Synthesis of Evidence on Management Strategies

The following sections provide an integrative interpretation of the synthesized evidence, emphasizing key ecological mechanisms, management implications, and critical knowledge gaps that remain insufficiently addressed in the current literature.

The synthesis includes studies with predominantly moderate risk of bias, which should be considered when interpreting the consistency of the reported patterns.

The overall analysis indicates that integrated management strategies are the most effective for controlling *Leucaena leucocephala*. The combination of mechanical cutting and herbicide application frequently results in control rates exceeding 80%, whereas purely mechanical methods tend to exhibit lower effectiveness due to the species’ strong resprouting capacity.

In addition, the studies highlight that environmental disturbances can facilitate reinvasion processes, particularly when the soil seed bank remains active. In this context, management strategies must consider not only the removal of adult plants but also the control of regeneration and the restoration of native vegetation.

Among the evaluated approaches, integrated management combining mechanical and chemical control shows the highest effectiveness, while purely mechanical methods often lead to intense resprouting. Revegetation and enrichment with native species also emerge as critical tools to reduce reinvasion risk following removal of the invasive species.

Conversely, the use of fire as a control strategy is generally discouraged, as heat can break seed dormancy and trigger germination pulses. Biological control, although promising in certain contexts, tends to have limited effectiveness when used in isolation and is more effective when integrated with other management strategies. A synthesis of these findings is presented in Table 3.

Table 3. Evidence on *Leucaena leucocephala* management strategies and proportion of evidence ($n = 60$).

Key Finding	Proportion of Evidence	Ecological Rationale	References
Large disturbances facilitate reinvasion	25%	Disturbances such as pasture abandonment, urban development, extreme droughts, or hydrological alterations create open niches that favor <i>Leucaena</i> colonization from persistent seed banks. These environments often exhibit degraded soils and increased connectivity with propagule sources.	[3,11,14,16,20,35,36,41,62–68]
Integrated control (cutting + herbicide) is the most effective method	20%	Mechanical clearing followed by application of systemic herbicides to the stump (e.g., glyphosate, triclopyr, or picloram) drastically reduces resprouting and can achieve 80–90% effectiveness. Integration with revegetation, soil management, and grazing reduces the seed bank and prevents reinvasion. Modeling studies indicate that combining strategies reduces the need for repeated treatments.	[1,2,6,12,13,46,69–74]
Mechanical removal alone leads to intense resprouting	20%	Due to its deep root system and stored nutrient reserves, <i>Leucaena</i> exhibits strong regeneration capacity after cutting. Mechanical removal alone often results in multiple shoots per stump and rapid canopy recovery, requiring chemical control or complementary management.	[8,13,16,17,19,45,64,75–80]
Revegetation or enrichment with native species reduces reinvasion	13%	Dense planting or assisted regeneration of native species creates shading and competition for resources, limiting <i>Leucaena</i> germination and growth. Niche occupation following invasive removal reduces reinvasion risk and promotes ecosystem recovery.	[1,10,15,17,33,35,37,81]
Fire should not be used as a control tool	12%	Fire acts as a thermal scarification agent, breaking seed dormancy and increasing germination rates. Surface fires may trigger massive regeneration pulses and promote <i>Leucaena</i> dominance over native vegetation.	[5,13,16,82–85]
Biological control has limited effect when used alone	8%	The seed-feeding beetle <i>Acanthoscelides macrophthalmus</i> reduces seed viability and the seed bank but does not eliminate established adult trees. Psyllid infestation causes severe defoliation, yet the species rapidly resprouts. In regions such as Hawaii and other tropical islands, biocontrol reduced productive use but did not prevent naturalization, indicating the need for complementary management.	[13,56,86–88]

Table 3. Cont.

Key Finding	Proportion of Evidence	Ecological Rationale	References
Management through utilization (forage/bioenergy) as control	5%	Utilizing <i>Leucaena</i> biomass for forage, timber, or bioenergy can reduce seed production and gradually decrease population density in invaded areas. Although rarely sufficient alone, it may lower management costs and create economic incentives for continuous removal.	[13,16,89]

Note: Proportion of evidence represents the relative frequency of studies supporting each claim within the analyzed dataset ($n = 60$).

In contrast, lower certainty was associated with biological control and management through utilization, due to fewer studies and greater variability in reported outcomes. The qualitative nature of the synthesis and the predominance of observational studies also contribute to moderate levels of confidence in the overall evidence.

The variability observed among studies reflects differences in environmental conditions, disturbance regimes, and management contexts, highlighting the context-dependent nature of invasion dynamics and management effectiveness.

Overall, the certainty of evidence was considered moderate for most findings, as multiple studies consistently supported the main management strategies and ecological patterns identified. Higher certainty was observed for claims related to integrated management effectiveness and the role of disturbances in facilitating reinvasion, which were supported by a larger proportion of studies (Table 3).

Potential reporting bias should be considered when interpreting these findings, as studies reporting significant ecological impacts or successful management strategies are more likely to be published, which may influence the overall synthesis.

To provide an integrated synthesis of the main findings, a conceptual framework linking invasion drivers, ecological mechanisms, management strategies, and ecosystem responses is presented in Figure 6.

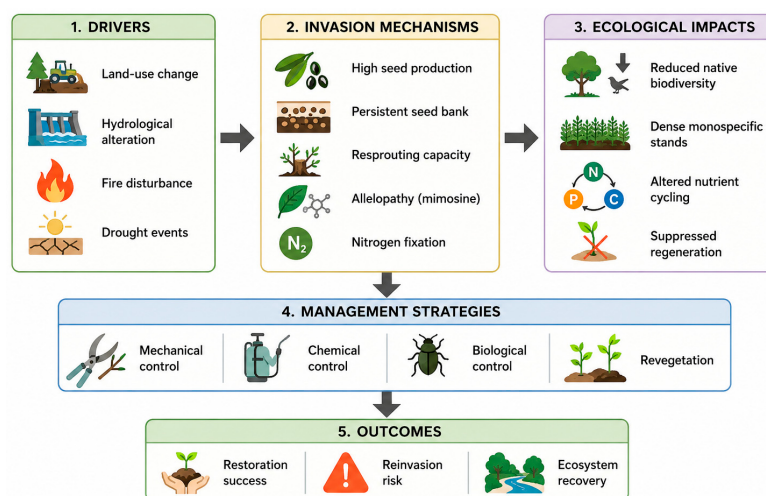


Figure 6. Conceptual framework illustrating the relationships among invasion drivers, ecological mechanisms, management strategies, and ecosystem responses associated with *Leucaena leucocephala* in wetland and riparian ecosystems.

3.6. Ecosystem Recovery and Functional Impacts

The recovery of wetlands invaded by *Leucaena leucocephala* does not end with the removal of adult individuals. Soil chemical alterations and the persistence of viable seeds can promote reinvasion processes [35,90]. Restoration projects conducted in the Atlantic Forest and Southeast Asia indicate that removal alone often results in rapid reinvasion when not followed by revegetation strategies using native secondary and late-successional species [35,44].

In addition, invasion profoundly alters ecosystem functioning. *L. leucocephala* forms dense monospecific stands that significantly reduce light availability in the understory, suppressing the natural regeneration of native tree species [13,35]. This dominance promotes biotic homogenization and a marked reduction in species richness, particularly among animal-dispersed species [5,35].

At the soil level, its capacity for biological nitrogen fixation can increase nitrification and mineralization rates, thereby altering long-term biogeochemical cycles [3,9].

3.7. Critical Success Factors

The success of management initiatives strongly depends on understanding local ecological processes, long-term community engagement, and the adaptation of practices to specific environmental conditions [55]. However, institutional aspects and the role of public policies remain underexplored in the literature as either enabling or limiting factors.

Controlling *L. leucocephala* is challenging due to its high resilience. Mechanical methods based solely on clear-cutting are considered ineffective, as they tend to stimulate multiple resprouts from the stump. In this context, the use of blade plows to remove root systems or shading stumps with black plastic to inhibit resprouting has been recommended [12,19].

For chemical control, trunk injection of glyphosate during the dry season is considered one of the most effective methods for eliminating adult individuals [19]. Additionally, immediate stump treatment after cutting with herbicides such as picloram combined with 2,4-D has demonstrated control rates of up to 80% [12].

Biological control has also been investigated. The seed-feeding beetle *Acanthoscelides macrophthalmus* has been introduced in some management programs to reduce the species' seed bank. However, its effectiveness in isolation is limited and is generally recommended as part of an integrated control strategy [3,56].

The use of fire as a management tool is discouraged, as frequent fires favor regeneration of the species and further reduce native biodiversity in wetlands [5,59]. Large-scale mechanical disturbances (e.g., bulldozers) may also stimulate massive resprouting [3].

3.8. Interdisciplinary Applications

The integration of *Leucaena leucocephala* into agroforestry systems has been identified as a growing trend, promoting socioeconomic benefits for local communities through increased agricultural productivity and soil restoration [7,55]. However, studies evaluating its direct impacts on aquatic biodiversity and ecosystem services associated with wetlands remain scarce.

Successful adoption also depends on community involvement and the adaptation of management practices to local conditions. Long-term ecological impacts and the role of public policies in managing this species in wetland ecosystems remain insufficiently explored.

3.9. Challenges Under Climate Change

Climate projections for ecosystems such as the Pantanal suggest a high vulnerability of areas historically protected by seasonal flooding, making these specific habitats increasingly

susceptible to invasion [5]. Under this scenario, sustainable management must adopt a proactive approach, prioritizing the maintenance of natural hydrological flows and preserving flood regimes as ecological barriers against species establishment [5].

Management of *L. leucocephala* in wetlands should therefore be grounded in technical precision and the integration of ecological knowledge. The use of improved herbicide application technologies, combined with continuous monitoring and a better understanding of interactions among fire, hydrology, and soil characteristics, may help balance the species' productive potential with the need to conserve biodiversity [5,30,35].

3.10. Research Gaps and Futures Directions

The dual role of *Leucaena leucocephala* as both a productive resource and an invasive species can be conceptualized as a trade-off between ecological risks and economic benefits across different land-use contexts (Figure 7).

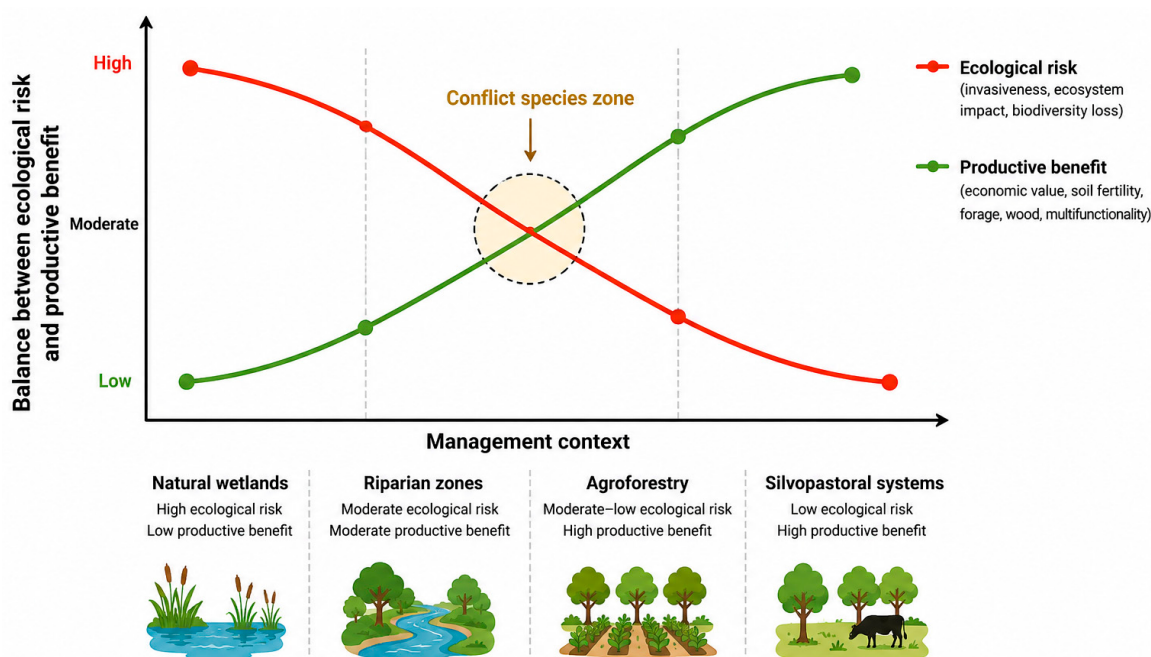


Figure 7. Conceptual trade-off between ecological risks and productive benefits of *Leucaena leucocephala* across different land-use contexts.

Although the literature on *Leucaena leucocephala* highlights its agronomic benefits and invasive potential, critical gaps remain regarding its ecological and institutional implications in wetland ecosystems (Table 4). Most studies focus on soil fertility effects and biological nitrogen fixation [7,9], whereas relatively few address impacts on native biodiversity and the governance frameworks required for long-term management [3,59].

Table 4. Matrix of studies addressing management strategies across environmental contexts.

Topic	Integrated Physical-chemical Control	Revegetation/Enrichment with Natives	Biological Control	Fire Use
Tropical wetlands	7	4	3	2
Urban riparian areas	2	2	2	1
Silvopastoral systems	3	6	4	4

Studies evaluating the species' contribution to the recovery of degraded soils are relatively common; however, assessments of its ecological legacy, such as soil phytotoxicity and persistent alterations in the soil seed bank in wetlands, remain limited [21,90]. Likewise, the role of public policies and socioeconomic factors in shaping management outcomes remains poorly documented in the biological invasions literature [49,61].

In tropical wetlands, physical–chemical control is reported by [1,13,33,35,36,62]. Revegetation/enrichment emerges as the central strategy to overcome invasion legacy in wetlands [1,33,35]. Biological control and fire are less frequently addressed, with [13] detailing the use of *Acanthoscelides macrophthalmus* and the limitations of fire in these environments.

In urban riparian areas, physical–chemical control and revegetation are consistently identified as necessary to contain expansion [16]. Biological control is supported by studies such as [87] (psyllids in urban environments) and [56] (seed beetles in urban phytophysiology). Fire use is rarely addressed, with [82] examining thermal germination in disturbed urban settings.

In silvopastoral systems, physical–chemical control is reported by [13,64,81]. Revegetation/enrichment is more prominent, supported by studies such as [2,6,10,77,78,81], which focus on integrating native species and soil recovery. Biological control is documented by [10,56,74,88], ranging from insect predation to grazing-based management. Fire is also discussed in these systems [82,84–86], mainly as a tool for dormancy breaking or resilience assessment.

Overall, the literature highlights *Leucaena leucocephala* as a “conflict species.” While strict control and removal are prioritized in wetlands and urban areas, silvopastoral systems show a shift toward integrated management approaches, combining productive use with active revegetation to enhance biodiversity without compromising forage value.

Based on the identified gaps, several priority questions emerge for future research:

Hydrological dynamics and climate change: One key issue concerns the long-term ecological impacts, in particular, how reduced flood duration, intensified by climate change, may facilitate species expansion into areas previously protected by seasonal inundation [5]. Spatially explicit projections remain critically absent for vulnerable biomes such as Pantanal, Amazon floodplain forests, and coastal wetlands.

Landscape-Level Governance and Resource Conflict: Future studies should evaluate how local community engagement, combined with institutional support, can reduce the high costs associated with large-scale control and monitoring [48].

Restoration Strategies and Ecological Legacy: It is essential to determine which functional groups of native species are most capable of competing with *Leucaena leucocephala* regeneration after mechanical and chemical control interventions [36].

Addressing these gaps requires interdisciplinary approaches integrating ecology, hydrology, and social sciences to ensure that management strategies are not only technically effective but also institutionally viable and sustainable in the long term [3,61].

Based on the synthesized evidence, an integrated management framework considering invasion stage and ecosystem context is proposed (Figure 8), highlighting adaptive strategies for effective long-term control and ecosystem recovery.

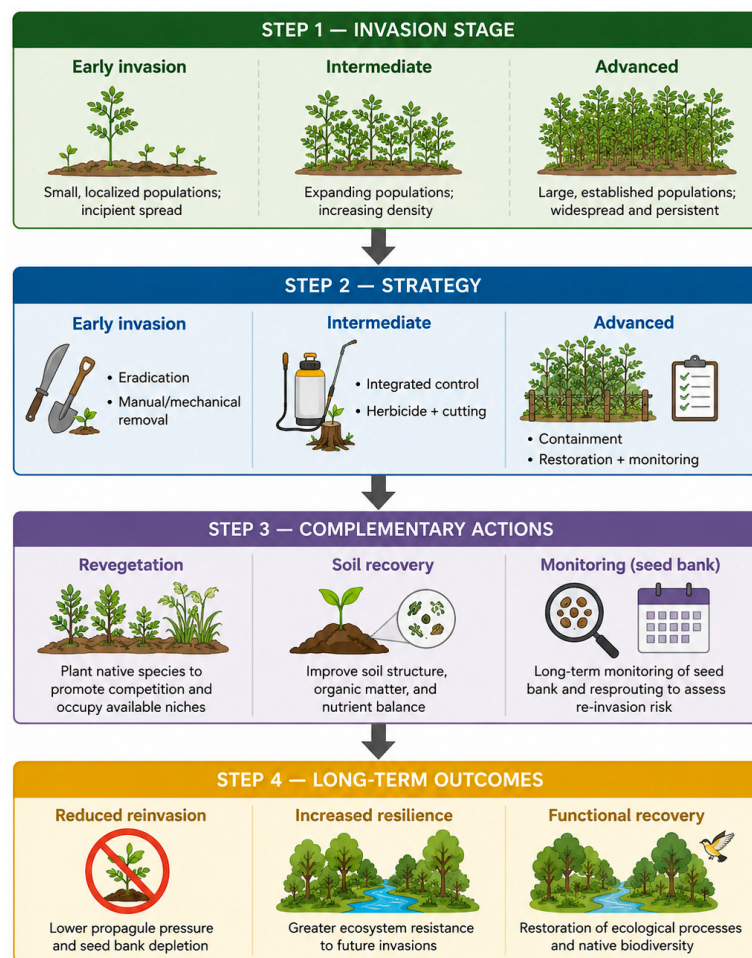


Figure 8. Integrated management framework for *Leucaena leucocephala* based on invasion stage and ecosystem context.

4. Conclusions

This systematic review synthesizes current knowledge on the invasion ecology and management strategies of *Leucaena leucocephala* in wetlands and riparian zones. Overall, the analyzed studies indicate that the success of this species is driven both by intrinsic biological traits, such as rapid growth, high seed production, and strong resprouting capacity, and by environmental changes that reduce ecosystem resistance.

Environmental stressors, particularly drought stress, hydrological instability, fire occurrence, and anthropogenic disturbances, appear to play a central role in facilitating invasion processes and increasing ecosystem susceptibility to species establishment.

Alterations in hydrological regimes, especially reductions in flood frequency and duration, may further facilitate the establishment and expansion of *L. leucocephala* in riparian environments. In addition, several studies indicate that the species promotes structural simplification of plant communities, reducing native regeneration through dense canopy formation and potential allelopathic effects.

Regarding management, integrated strategies consistently outperform isolated approaches. The combination of mechanical and chemical control, coupled with continuous monitoring and active restoration using native species, emerges as a promising pathway to reduce species persistence and restore ecosystem functionality.

Under ongoing climate change scenarios, increasing environmental stress may further compromise the resilience of wetlands and riparian ecosystems, reinforcing the urgency of adaptive and integrated management strategies.

Despite advances in understanding invasion dynamics and control strategies, significant uncertainties remain regarding long-term ecosystem responses, particularly under changing hydrological regimes and climate scenarios.

5. Limitations of the Review Process

This review has methodological limitations, including restriction to three databases, inclusion of studies published in only three languages, and the absence of quantitative meta-analysis. In addition, although screening and data extraction were conducted by independent reviewers, the qualitative synthesis approach may introduce subjectivity in the interpretation of results. These factors may limit the comprehensiveness and reproducibility of the review.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/stresses6020031/s1>, Table S1: Characterization of the studies included in the review on *Leucaena leucocephala*, including geographic location, ecosystem type, environmental factors, and main mechanisms associated with invasion; Table S2: Synthesis of the literature on ecological mechanisms, ecosystem impacts, management strategies, and restoration implications associated with the invasion of *Leucaena leucocephala*.

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