

Review

Tree Components in Integrated Crop–Livestock–Forest Systems: Silvicultural Management, Wood Production, Timber Quality, and Greenhouse Gas Mitigation

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Abstract

Integrated Crop–Livestock–Forest (ICLF) systems have emerged as a key strategy for sustainable agricultural intensification by simultaneously enhancing productivity, ecosystem services, and climate resilience in tropical environments. This review synthesizes current knowledge on the role of the tree component in ICLF systems, with emphasis on wood production, timber quality, greenhouse gas (GHG) mitigation, and ecosystem functioning. We discuss the conceptual basis and typologies of ICLF systems, the influence of spatial and temporal arrangements, and the biotic and abiotic factors regulating tree growth and productivity. The review further examines management practices—including species selection, tree density, thinning, and pruning—and their implications for wood yield, timber quality, and overall system performance. Evidence demonstrates that appropriately managed tree components enhance nutrient cycling, soil quality, biodiversity, animal welfare, and farm profitability while increasing carbon sequestration in aboveground biomass and soils. Trees also contribute to offsetting methane (CH₄) and nitrous oxide (N₂O) emissions, reinforcing the climate mitigation potential of ICLF systems. Despite these benefits, adoption remains constrained by technical, economic, and regional challenges, highlighting the need for site-specific recommendations and improved silvicultural management. Overall, optimizing the tree component can maximize the multifunctionality of ICLF systems, supporting sustainable wood production, ecosystem restoration, the implementation of Brazil’s ABC+



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Plan, and the achievement of the country's Nationally Determined Contributions (NDCs) under the Paris Agreement.

Keywords: carbon sequestration; ecosystem services; nature-based solutions; silvicultural management; tree-based systems

1. Introduction

Population growth and the increasing global demand for food impose the challenge of sustainably expanding agricultural and livestock production, particularly in the face of extreme climate change scenarios [1]. Historically, conventional systems based on monocultures or extensive pasturelands have been associated with soil degradation, biodiversity loss, and high greenhouse gas (GHG) emissions [2]. As a viable alternative for sustainable land-use intensification, Integrated Crop–Livestock–Forest (ICLF) systems have emerged as one of the leading modern agricultural strategies. In this context, the Brazilian Low Carbon Emission in Agriculture Plan (ABC+ Plan) has updated its target for the recovery of degraded pastures to 30 million hectares by 2030, prioritizing the adoption of ICLF systems [3]. Beyond supporting domestic low-carbon agriculture policies, ICLF systems are also recognized as a key nature-based solution for achieving Brazil's Nationally Determined Contributions (NDCs) under the Paris Agreement by promoting carbon sequestration, restoring degraded lands, enhancing climate resilience, and reducing greenhouse gas emissions from agricultural production.

By reconciling the production of grains, meat, and forest products within the same area—whether through rotation, intercropping, or succession—these production systems maximize resource-use efficiency and confer resilience against climate variability and economic fluctuations that affect tropical and subtropical regions [4]. These systems are based on the functional integration between crop, livestock, and forestry components, promoting ecological synergies that result in greater resource-use efficiency, the recovery of degraded areas, the intensification of nutrient cycling, and an increase in soil carbon stocks [5,6].

Within ICLF systems, the tree component plays a central role in the provision of ecosystem services and the economic viability of the system (Figure 1). The inclusion of trees significantly alters the local microclimate by attenuating the incidence of direct solar radiation and reducing the radiant heat load, thereby providing an environment with greater thermal comfort and enhancing animal welfare [7,8]. Furthermore, trees perform key ecological functions in improving edaphic conditions, favoring nutrient cycling through litterfall and exploring deeper horizons via their root systems, which subsequently reduces erosion and improves water infiltration [9,10]. From an environmental perspective, trees act as a carbon sink, mitigating GHG emissions from the agricultural and livestock phases through the continuous storage of carbon in aboveground biomass, roots, and the soil profile [11–13]. Economically, the harvested timber ensures a valuable diversification of income for farmers at the end of the production cycle.

Ultimately, the coherence of examining these diverse disciplines—spanning from silviculture and wood quality to biogeochemical soil dynamics and animal physiology—rests on the recognition that the tree component plays a central role in modulating solar radiation, temperature, water fluxes, microclimatic conditions, nutrient cycling and carbon sink. Aboveground, its canopy intercepts solar radiation, modulating the understory microclimate to improve animal welfare [10,11] and conserve biodiversity, while altering light availability and initiating resource competition with companion crops. Belowground,

its deep and extensive root systems redistribute water and nutrients through hydraulic lift and continuous organic inputs, which reorganizes the soil microbiome and stabilizes organic carbon in deep pedological pools [7,9]. Simultaneously, the biological accumulation of woody biomass serves as the principal sink for climate mitigation, where silvicultural decisions directly determine both the technical properties of the harvested timber and the net greenhouse gas balance of the system [11–13]. Therefore, the tree component constitutes the unifying regulatory lever through which all productive, competitive, ecosystemic, and biogeochemical interactions are dynamically governed.

Despite the ecosystemic and economic benefits of ICLF systems, the forestry component frequently remains the most challenging aspect for farmers to adopt [14]. The design of integrated agricultural systems involves complex ecological interactions—such as competition for light, water, and nutrients—requiring specialized silvicultural technical knowledge that differs from conventional agriculture [15]. Moreover, although the literature reports the general advantages of ICLF, a gap remains in systematizing how tree management decisions (e.g., density, thinning, pruning, and species selection) concomitantly affect final timber quality and the system’s actual capacity to offset specific emissions (such as enteric methane and nitrous oxide) in tropical environments.

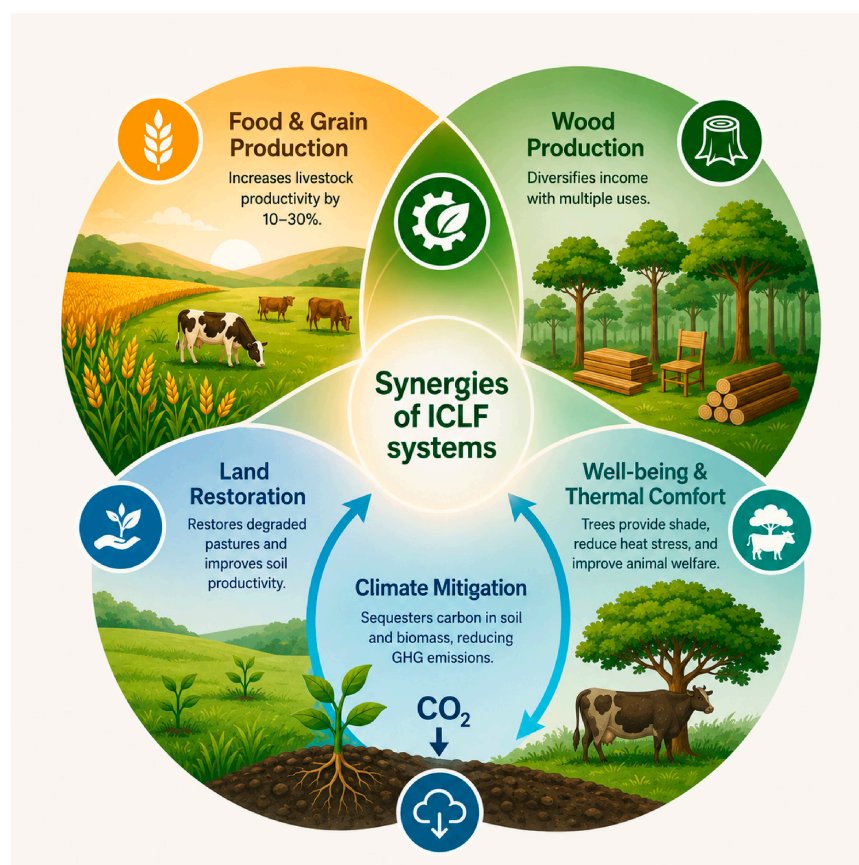


Figure 1. Conceptual diagram illustrating the synergies of integrated crop–livestock–forest (ICLF) systems. The model highlights five key interconnected benefits: food and grain production [2,4], wood production [16,17], animal well-being and thermal comfort [7,8], climate change mitigation [11,12,18], and land restoration [6,19]. Note: Figure generated using Artificial Intelligence (Google NotebookLM, version Google AI Pro 2026), based on the authors’ conceptual design.

Within this context, this review aimed to synthesize the available evidence regarding the role of the tree component in ICLF systems concerning timber production and quality, ecosystem services (soil, livestock, and microclimate), and GHG mitigation (CO₂, CH₄, and N₂O), while simultaneously highlighting the primary management bottlenecks and

diversification opportunities. Accordingly, the review was structured around four main themes: (i) describing the design of integrated agricultural systems and the ecological functions of the tree component under contrasting edaphoclimatic conditions; (ii) evaluating how biotic and abiotic factors, combined with management practices, influence tree growth, wood production, and timber quality in ICLFs; (iii) discussing the contribution of the tree component to GHG mitigation, particularly through carbon sequestration in the aboveground biomass, roots, and soil, as well as its indirect effects on CH₄ and N₂O emissions; and (iv) identifying the main technical bottlenecks—including management practices, genetic material, and system design—as well as economic opportunities, such as the production of high-value-added timber and the generation of carbon credits.

2. Literature Search and Study Selection

2.1. Search Strategy and Databases

To address the procedures undertaken for this broad review, a structured literature search was conducted across two major international multidisciplinary databases, Web of Science and Scopus, complemented by searches in Google Scholar. The search was designed to identify peer-reviewed research papers, technical communications, chapters or scientific books addressing the following key topics: “ICLF systems”, “tree component”, “agroforestry”, “silvicultural management”, “wood production”, “timber quality”, “carbon sequestration”, “greenhouse gas mitigation”, “ecosystem services”, “tropical environments”.

The search string was constructed using five main thematic blocks of keywords, directly reflecting the core subjects of this manuscript. Keywords within each thematic block were combined using the Boolean operator OR, whereas the thematic blocks were combined using AND:

1. Integrated Systems, Typologies, and Arrangements: “integrated crop-livestock-forest”, “ICLF”, “iLPF”, “ILPF”, “silvopastoral”, “silvipastoral”, “agrosilvopastoral”, “agrosilvopastoral”, “agroforestry”, “crop-livestock-forestry”, “crop-forest”, “integrated crop-livestock”.
2. Silvicultural Management, Wood Production, and Timber Quality: “wood quality”, “timber quality”, “wood yield”, “basic density”, “mechanical properties”, “heartwood”, “sapwood”, “stem form”, “thinning”, “pruning”, “tree density”, “spacing”.
3. Soil Health, Carbon Stabilization, and Physical Fractionation: “soil organic matter”, “soil health”, “soil organic carbon”, “carbon stock”, “physical fractionation”, “particulate organic matter”, “particulate organic carbon”, “mineral-associated organic matter”, “biogeochemical hotspots”, “soil microbiota”, “microbial biomass”, “nutrient cycling”.
4. Animal Welfare, Microclimatic Modulation and Livestock Performance: “animal welfare”, “thermal comfort”, “shading”, “microclimate”, “heat stress”, “forage quality”.
5. Greenhouse Gas Mitigation and Carbon Offsetting: “greenhouse gas mitigation”, “carbon sequestration”, “carbon neutral”, “carbon sink”, “ABC+ Plan”, “Carbon Neutral Brazilian Beef”, “adoption bottlenecks”, “implementation barriers”.

The temporal scope of the search was restricted to studies published between 1993 and 2026 to capture the evolution of research on tropical integration and soil carbon dynamics. This starting threshold of 1993 was selected to align with the publication of foundational conceptual and structural frameworks for modern agroforestry [20], which represented an important milestone in the development and consolidation of integrated and ecologically based production systems. This 33-year window encompasses the scientific and policy evolution of tropical integrated systems: spanning from early, pioneering agrosilvopastoral models in the 1990s and the experimental applications of soil organic matter physical

fractionation protocols to the modern era of institutionalized low-carbon agricultural policies and emerging decarbonization market initiatives. The search was limited to peer-reviewed journal articles written in English, Spanish and Portuguese.

2.2. Study Selection Process and Flow

To address the comprehensive scope of this review (covering silviculture, wood properties, microclimate, animal welfare, and biogeochemical interactions), the screening and selection of retrieved literature followed a structured, multi-stage hierarchical workflow:

1. Identification: The initial systematic search across databases using the five primary thematic blocks yielded a robust set of raw bibliographic records. Duplicate records identified across databases were subsequently removed.
2. Screening: At this stage, papers were categorized according to their primary contribution to the core themes of the manuscript (e.g., microclimatic buffering, animal physiology, wood quality, GHG mitigation, and soil health). Publications that did not address tropical or subtropical integrated production systems, or that did not provide evidence related to the thematic scope of the review, were excluded. The remaining publications were categorized according to their primary thematic contribution, including silvicultural management and wood properties, soil organic carbon dynamics, microclimatic regulation and animal welfare, and greenhouse gas mitigation and carbon sequestration. Relevant publications within these thematic categories were retained for the subsequent eligibility assessment and synthesis.
3. Eligibility Assessment: The full texts of the remaining candidate publications were independently evaluated against predefined eligibility criteria specifically designed for the tree components in ICLF systems and their potential for wood production, timber quality, and greenhouse gas mitigation in tropical environments. Discrepancies during this stage were resolved through consensus.
4. Inclusion: A final set of 207 publications met the predefined eligibility criteria and constituted the core evidence base for the qualitative and comparative synthesis of tree-based components within integrated and agroforestry systems. Additional relevant literature was used, when appropriate, to provide conceptual background and support the thematic narrative discussion.

2.3. Literature Eligibility and Selection Criteria

To ensure methodological comparability, reproducibility, and geographic specificity across both the broad review and the focused soil carbon analysis, studies were evaluated based on a clear set of criteria:

General Criteria (Broad Review): The study must evaluate integrated production systems (ICL, ILF, ICF, or ICLF) under tropical and subtropical environments, with a primary focus on tropical environments. The publication must address at least one of the five core themes: system arrangements, tree growth/wood quality, soil health, animal welfare/microclimate, or greenhouse gas mitigation/offsetting. The publication must be written in English, Spanish or Portuguese.

Because direct evidence from full ICLF systems remains limited for some of the topics addressed in this review, evidence from related tree-based systems, including silvopastoral, agrosilvicultural, and broader agroforestry systems, was also considered when relevant. Throughout the review, evidence derived specifically from ICLF systems is distinguished, whenever possible, from complementary evidence obtained from these broader agroforestry contexts. Such evidence is used to support the interpretation of ecological and silvicultural processes relevant to ICLF systems rather than being assumed to represent direct ICLF-specific responses.

2.4. Data Extraction and Synthesis of Evidence

For the publications included in the focused soil carbon analysis, a standardized data extraction protocol was applied to compile a structured database containing research, site, system design, soil, and carbon-related variables.

For each publication included in the focused soil carbon analysis, the following variables were extracted, when available:

Study Metadata: Authors, publication year, geographic location, biome (e.g., Cerrado, Amazonia), and climate type.

Experimental and Soil Attributes: Soil classification, soil texture (sand, silt, and clay content), sampling depth intervals, and the duration of the system's implementation (stand age).

System Design and Silvicultural Variables: Tree species and origin (native or exotic, including *Eucalyptus* spp.), planting density, spatial arrangements (single vs. multiple rows, corridor width), pruning/thinning history, and pasture management (forage species, stocking rate).

Target Soil Carbon Data: Total soil organic carbon concentrations and/or stocks, particulate organic matter, particulate organic carbon, and carbon concentrations and/or stocks associated with mineral-associated organic matter.

In this review, ICLF systems are defined as production systems that integrate crop, livestock, and tree components within the same area, either simultaneously or sequentially. Integrated livestock–forest (ILF) systems comprise the integration of livestock and tree components and are closely related to systems commonly described in the international literature as silvopastoral systems. Agroforestry, in turn, is used as a broader term encompassing land-use systems in which woody perennials are deliberately combined with crops and/or livestock. Therefore, although ICLF and ILF/silvopastoral systems can be considered forms of agroforestry in a broad conceptual sense, evidence from these systems is distinguished throughout this review according to the specific components and configurations evaluated. Because direct evidence from full ICLF systems remains limited for some of the topics addressed in this review, evidence from related tree-based systems, particularly ILF/silvopastoral, agrosilvicultural, and other agroforestry systems, was also considered when relevant. Throughout the review, evidence derived specifically from ICLF systems is distinguished, whenever possible, from complementary evidence obtained from these broader or related agroforestry contexts. Such evidence is used to support the interpretation of ecological and silvicultural processes relevant to ICLF systems rather than being assumed to represent direct ICLF-specific responses. Additionally, it must be noted that the majority of the empirical evidence reviewed remains concentrated in Brazilian geography, reflecting the country's extensive, long-term experimental research network on tropical integrated systems, which should be taken into account when generalizing these findings to other tropical or subtropical regions.

3. Concepts, Typologies and Arrangements of Tree-Based ICLF Systems

The integrated analysis of typologies, structural arrangements, and temporal dynamics evidences that ICLF systems constitute a robust strategy for sustainable intensification in tropical environments [4]. The observed gains result from the synergy between biological diversity, structural complexity, and ecological processes, resulting in an increase in soil organic carbon, intensification of nutrient cycling, improvement of edaphic attributes, and greater functional stability of the systems. The tree component plays a central role in this process, acting as a structuring element responsible for the input of organic matter, microclimate modulation, and carbon sequestration [21]. On a global scale, these systems contribute significantly to the carbon balance and climate change mitigation [22], consol-

identifying themselves as strategic solutions for the sustainability of agricultural systems in tropical regions.

3.1. Definitions, Typologies, and Conceptual Bases

ICLF systems constitute one of the primary strategies for sustainable intensification in tropical and subtropical regions, with wide adoption in the Cerrado, Amazon, and Southern Brazil, as well as growing relevance in semi-arid environments. The adoption of these systems plays a strategic role in the face of the intensification of extreme climatic events. The recurrence of severe droughts, such as those observed between 2011 and 2016 in Brazil, highlights the vulnerability of simplified production systems and reinforces the need for strategies based on functional diversification [23]. In this context, systems that integrate intercropping, crop rotation, no-till, and livestock demonstrate greater production stability and lower sensitivity to climate variability [24].

From a conceptual point of view, integrated systems can be organized along a gradient of structural and functional complexity. Crop–Livestock Integration (ICL) corresponds to the most basic level, characterized by the alternation or intercropping of agricultural crops and pastures. The inclusion of the tree component gives rise to Crop–Forest Integration (ICF) and Livestock–Forest Integration (ILF), while Crop–Livestock–Forest Integration (ICLF) represents the most complex level, in which all three components are integrated simultaneously [5,25].

These systems reflect different levels of functional integration of ecological processes, with ICLF being characterized by more intense interactions between soil, plants, animals, and the atmosphere, configuring highly integrated agrosilvopastoral systems. In this condition, the tree component acts as a structuring element, regulating flows of energy, water, and nutrients, in addition to directly influencing the dynamics of organic matter and soil microbiota [26–28].

Although the ICL system presents high efficiency in nutrient cycling and contributes significantly to the improvement of soil structure, its ecological functionality is limited by the absence of the tree component, restricting processes such as the vertical stratification of the system and the diversification of ecological niches [29–32]. On the other hand, systems that incorporate trees, such as ICF, ILF, and ICLF, promote greater structural and functional complexity, with direct effects on microclimate modulation, the input of organic residues, and nutrient dynamics, especially phosphorus [33,34].

Scientific evidence indicates that ICLF systems promote consistent and integrated improvements in the chemical, physical, and biological attributes of the soil, including an increase in organic carbon, greater microbial activity, and an expansion of edaphic diversity [26,29,30,34,35]. The stabilization of carbon in these systems is associated with the interaction between plant residues and soil microbiota [36,37], reinforcing the role of integrated systems as carbon sinks in tropical environments.

However, to accurately evaluate the role of the soil microbiome in these tropical carbon sinks, it is critical to untangle the distinct ecological and physiological mechanisms that govern carbon processing, avoiding the assumption that enhanced microbial activity or connectivity necessarily equates to carbon persistence [26,38]. Biogeochemically, these dynamics must be evaluated through six distinct lenses:

- Microbial biomass represents the living pool of microbial carbon (e.g., microbial biomass carbon, MBC, C_{mic}), acting as a transient, highly active nutrient reservoir and the precursor to stabilized soil organic matter (SOM) [39].
- Microbial activity denotes the transient rate of metabolic processing and transformation of organic substrates, commonly measured via basal respiration (CO₂ release) or extracellular enzymatic assays [39].

- Decomposition is the physical and biochemical fragmentation of plant and animal residues, a process that mineralizes nutrients but simultaneously risks net carbon loss via heterotrophic respiration if catabolic pathways dominate [40,41].
- Microbial carbon use efficiency (CUE) is the physiological partition of assimilated carbon between biosynthetic growth (anabolism) and respiratory maintenance (catabolism). High CUE under stoichiometrically balanced, high-diversity inputs maximizes the conversion of litter into microbial biomass and eventual necromass [36].
- Soil organic carbon (SOC) accumulation is a dynamic process resulting from the balance between carbon inputs and carbon losses within the soil system. In tropical soils, such accumulation often registers predominantly in labile pools, such as particulate organic matter (POM), which remain highly sensitive to seasonal and management perturbations [42].
- Long-term carbon stabilization represents the persistence of carbon over decadal to centennial timescales. Rather than residing in active pools, long-term stabilization occurs when microbial necromass—the byproduct of high-CUE turnover—is physically protected within macro- and microaggregates or chemically sorbed onto silt and clay mineral surfaces to form Mineral-Associated Organic Matter (MAOM) [36,40].

Therefore, while the high functional connectivity and plant residue diversity of ICLF systems stimulate microbial biomass and activity [39], net long-term carbon stabilization is ultimately governed by the efficiency of the microbial filter (CUE) and the availability of soil mineral surfaces to physically protect and sorb these processed organic compounds.

Additionally, systems adapted to specific edaphoclimatic conditions, such as the Caatinga-Buffel-Leucaena (CBL) model, highlight the plasticity of these approaches in semi-arid environments, in which the integration of native vegetation, adapted pastures, and forage tree species contributes to greater production stability under water restriction [43].

Synthetically, integrated systems can be classified, from a functional point of view, into three categories: (i) systems with an environmental focus, in which the tree component acts predominantly in the provision of ecosystem services; (ii) systems with a productive focus, oriented toward the production of wood, biomass, or grains; and (iii) mixed systems, which reconcile both functions and predominate in regions such as the Brazilian Cerrado [26,27]. This functional diversity is directly associated with the different typologies presented in Table 1, evidencing the range of possible arrangements and their suitability for different productive contexts.

Table 1. Typologies of ICLF systems and associated systems reported in the literature.

System	Components	Structure	Main Function	Evidence and Relevance
ICL	Crop + Livestock	Rotation/Intercropping	Nutrient cycling, structural improvement	High productive efficiency, base for transition [24,29]
ICF	Crop + Forest	Trees + Crops	Microclimate modulation, SOM, phosphorus	Increased fertility and productivity [33,44]
ILF	Livestock + Forest	Wooded pasture	Thermal comfort, cycling, CEC	Spatial heterogeneity and chemical improvement [35]
ICLF	Crop + Livestock + Forest	Full integration	Ecological and productive synergy	Higher soil quality and resilience [26–28]
ILF	Trees + Pasture + Animals	Pasture afforestation	Animal welfare and carbon	Microclimate regulation and productivity

Additionally, agroforestry is commonly classified according to its components, spatial and temporal arrangements, and functions, allowing a comprehensive understanding of the complexity and diversity of these production systems [20,45] (Table 2).

Table 2. Classification of ICLF systems according to different organizational and management criteria.

Classification Criterion	Category	Description	Examples	References
System components	Agrosilvicultural systems (ICF)	Integrate trees with agricultural crops.	Shaded coffee, cacao, staple crops grown under tree cover.	[46]
	Silvopastoral systems (ILF)	Combine trees, pastures, and livestock, improving livestock productivity and ecosystem services.	Wooded pastures, fodder banks, live fences for cattle.	[47]
	Agrosilvopastoral systems (ICLF)	Simultaneously integrate trees, agricultural crops, and animals, constituting highly complex systems.	Integrated Crop–Livestock–Forestry	[46,48]
Spatial arrangement	Dispersed trees	Trees distributed within crops or pastures.	Scattered trees in pastures or annual crop fields.	[49,50]
	Alley cropping	Trees planted in alternating rows with agricultural crops.	Tree legumes intercropped with annual crops.	[49]
	Live fences and windbreaks	Trees established along property boundaries or for wind protection.	Live fences, shelterbelts/windbreaks.	[50]
	Multistrata systems	Integration of species across different vertical strata.	Tropical homegardens.	[49]
	Strip or block systems	Components distributed in defined strips or blocks.	Alternating forest and agricultural strips.	[50]
Temporal arrangement	Simultaneous	All components coexist throughout the entire production cycle.	Coffee under shade trees.	[46]
	Sequential	Crops are established during the initial phases of the tree component.	Taungya system.	[46]
	Rotational	Alternation of components over time.	Alternation between agriculture and forestry production.	[46]
System function	Productive	Prioritize the production of goods and commodities.	Food, timber, forage.	[50]
	Protective	Focused on the conservation of natural resources.	Soil, water, and biodiversity conservation.	[50]
	Multifunctional	Combine productive and environmental objectives.	Sustainable multi-use agroforestry systems.	[50]

Table 2. *Cont.*

Classification Criterion	Category	Description	Examples	References
Intensification level	Traditional	Based on local knowledge and low levels of external inputs.	Indigenous and traditional land-use systems.	[46]
	Improved or intensive	High-tech systems with higher management levels and input application.	Integrated Crop–Livestock–Forestry (ICLF), high-productivity commercial systems.	[46,48]

3.2. Spatial and Temporal Arrangements and Regulation of Soil Processes

The functionality of ICLF systems is intrinsically related to their spatial and temporal configuration, which determines the intensity and nature of the interactions between the system components.

From a spatial point of view, arrangements with trees distributed in single or multiple rows predominate, interspersed with corridors intended for crops or pasture, configuring different productive arrangements that directly influence system dynamics [4,35,44]. This organization, common in the Brazilian Cerrado, favors mechanization and establishes environmental gradients that directly influence the availability of light, water, and nutrients. As a consequence, the formation of soil fertility gradients is observed, with a greater accumulation of organic matter, nutrients, and microbial activity in the vicinity of the trees, characterizing biogeochemical hotspots.

The tree component plays a central role in the regulation of these processes, especially in phosphorus dynamics, promoting an increase in labile fractions through the interaction between root exudates, microbial activity, and organic matter cycling [33,51]. This mechanism is particularly relevant in highly weathered soils, such as those of the Cerrado, in which phosphorus represents one of the main limiting factors to productivity.

Under a temporal perspective, ICLF systems present a well-defined successional dynamic, starting with the agricultural phase, followed by the establishment of the pasture and the progressive development of the tree component, until the consolidation of full integration. Throughout this cycle, generally between 10 and 15 years, a continuous increase in soil organic carbon stocks, intensification of nutrient cycling, and improvement of physical, chemical, and biological attributes are observed [30,34]. Furthermore, integrated systems present greater stability of microbial biomass and enzymatic activity over time, indicating greater functional resilience compared to conventional systems.

Figure 2 synthesizes the main spatial arrangements and the typical temporal dynamics of ICLF systems, highlighting the structural organization of the tree component and the evolution of the system over time.

3.3. Applied Evidence in the Brazilian Cerrado and MATOPIBA and Connection with Soil Attributes

In the Brazilian Cerrado and the MATOPIBA region (an acronym for the states of Maranhão, Tocantins, Piauí, and Bahia), the functional expression of integrated systems is strongly associated with management history and the structural configuration of the systems.

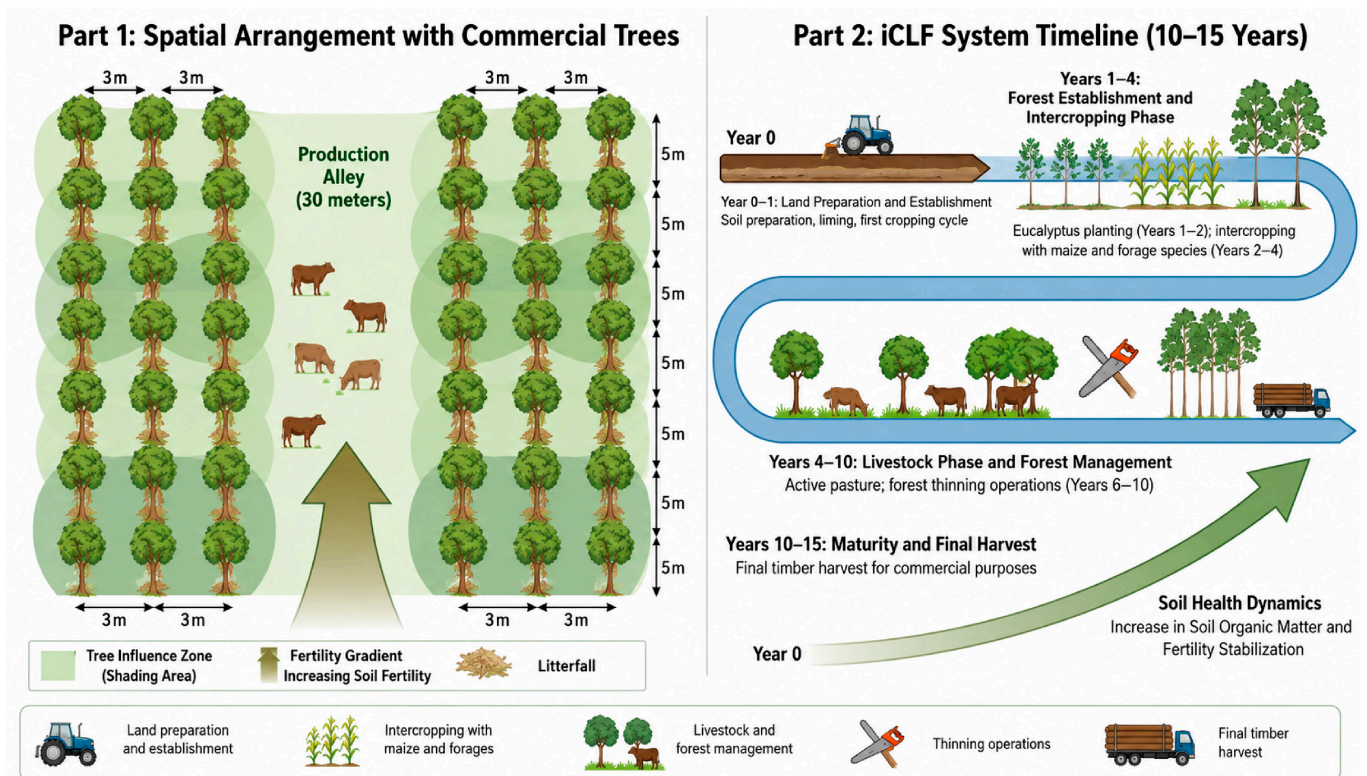


Figure 2. Representative scheme of integrated crop–livestock–forest (ICLF) systems, including (1) main spatial arrangements with commercial trees (tree density, corridor width, and canopy influence zone) and (2) typical production cycle timeline (10–15 years), covering crop implementation, pasture establishment, tree development, thinning, and final harvest. Note: Figure generated using Artificial Intelligence (ChatGPT, GPT-5.6 Sol, OpenAI, 2026), based on the authors’ conceptual design.

In the IPF system, high spatial heterogeneity of soil chemical attributes is observed, with higher levels of organic matter, Ca^{2+} , Mg^{2+} , and cation exchange capacity in the vicinity of the trees, reflecting the combined effect of litter deposition and root activity [35]. In ICF the continuous input of plant residues promotes improved fertility and agricultural productivity, especially in crops such as soybeans [34,44].

The ICL system, in turn, stands out for its efficiency in nutrient cycling and its function as an intermediate stage in the transition to more complex systems [4,29]. However, systems under no-till, although presenting high structural stability and organic matter accumulation, tend to present lower functional diversity, with greater dependence on management for the maintenance of biological processes [34].

In an integrated manner, evidence indicates that ICLF systems promote significant improvements in soil water retention and water availability, increasing productive resilience under conditions of climate variability [28]. Alterations in the structure of the soil microbiota, including bacterial and rhizospheric communities, reinforce the functional superiority of these systems relative to conventional systems [26,29,30]. These patterns are consistent with multivariate approaches, in which integrated systems tend to group in regions associated with higher soil quality, reflecting greater biogeochemical efficiency and structural stability [52].

3.4. Adoption of ICLF Systems in the Amazon Region

ICLF systems have consolidated themselves as one of the primary strategies for the sustainable intensification of agricultural and livestock production in the Brazilian Amazon, where the historical expansion of extensive livestock farming has been associated

with pastureland degradation and forest conversion. In this context, the adoption of integrated systems seeks to reconcile productivity with environmental conservation, promoting improvements in soil quality, carbon sequestration, and production diversification [53,54].

In the Amazon region, integrated agricultural systems are organized into three main typologies: (i) ICL, (ii) ILF, also referred to as silvopastoral systems, and (iii) full ICLF. These categories differ in structural complexity and level of intensification (Table 1), but share the common objective of increasing land-use efficiency and the provision of ecosystem services [18,53].

Silvopastoral systems (ILF), followed by ICLF, are the most widespread and studied in the Amazon region, particularly in areas previously occupied by degraded pastures (Table 3). As an example, a study conducted in the Eastern Amazon demonstrated that the presence of trees significantly reduces pasture surface temperature, favoring animal welfare compared to full-sun systems [55]. Furthermore, silvopastoral systems present higher soil carbon and nitrogen accumulation compared to conventional pastures, especially under moderate shading levels [56].

Table 3. Recent studies on ICLF and ILF systems in the Brazilian Amazon, including system type, main components, and reported environmental or productive benefits.

System Type	Main Components	Location	Key Findings	Reference
ICLF	Annual crops, pasture, eucalyptus	Mato Grosso, Brazil	Increased productivity, nutrient cycling, and carbon sequestration	[18]
Silvopastoral (ILF)	Native trees, pasture	Tocantins, Brazil	Higher soil carbon and nitrogen stocks	[56]
Silvopastoral (ILF)	Native and exotic tree, pasture, cattle	Pará, Brazil	Reduced temperature and improved animal thermal comfort	[55]
Silvopastoral (ILF)	<i>Dipteryx odorata</i> , pasture	Pará, Brazil	Improved soil physical and biological properties	[57]
ICLF	Eucalyptus, forages, cattle	Mato Grosso, Brazil	Sustainable livestock intensification	[58]
ICLF	Crops + pasture + <i>Khaya ivorensis</i> + <i>Dipteryx odorata</i>	Pará, Brazil	Increased soil carbon, nitrogen, and aggregate stability	[59]

Full ICLF systems, in turn, represent the most complex and multifunctional form of land use. Although less widespread in the Amazon region compared to silvopastoral systems, these arrangements have demonstrated high potential to enhance the productivity and sustainability of agroecosystems. Comparative studies indicate that ICLF systems promote greater animal protein production, improved nutrient cycling, and higher carbon sequestration relative to conventional livestock systems, primarily due to the inclusion of the tree component [18,58]. Additionally, these systems contribute to the improvement of soil structure and aggregate stability, fostering long-term sustainability [59].

A distinctive feature of ICLF systems in the Amazon region is the use of native tree species, which exhibit high adaptation to Amazonian edaphoclimatic conditions and relevant economic potential. Species such as *Dipteryx odorata* (cumaru), *Schizolobium amazonicum* (paricá), and *Bagassa guianensis* (tatajuba) have been widely utilized in silvopastoral and agrosilvopastoral systems. The establishment of *Dipteryx odorata* in degraded pastures, for instance, has shown significant improvements in soil physical and biological attributes,

bringing them closer to conditions observed in forest regeneration areas [57]. These results highlight the potential of ICLF as a productive restoration strategy in the Amazon.

Despite the widely documented benefits, the adoption of ICLF systems in the Amazon region remains uneven across states, with a higher concentration of studies and practical experiences in Pará and Mato Grosso states, whereas evidence remains limited in Acre, Roraima, and Amapá states [53]. Among the main bottlenecks to the expansion of these systems are sociopolitical limitations that compromise the formulation and implementation of effective public policies, high establishment costs, the need for enhanced technical capacity, poorly structured markets for forest products, insufficient infrastructure, logistical deficiencies, and cultural resistance to adoption [53,60,61]. Nevertheless, the growing body of scientific evidence indicates that ICLF systems constitute a promising alternative for promoting sustainable intensification in the Amazon, reconciling agricultural and livestock production with environmental conservation.

4. Biotic and Abiotic Factors Affecting the Tree Component

The growth and performance of the tree component in ICLF systems result from the simultaneous interaction of various physical, climatic, and ecological processes. The literature reports the primary biotic and abiotic determinants that influence tree development, as well as their potential impacts on wood production and timber quality (Table 4).

Table 4. Main biotic and abiotic factors affecting tree growth, wood production, and timber quality in tropical ICLF systems.

Factor	Expected Effect	Impacts on Wood	References
Canopy-intercepted radiation	Modifies light availability in the system and dictates understory shading intensity.	Proper adjustment of tree arrangement and density allows for reconciling tree development and wood formation with the maintenance of forage productivity.	[7,8,62–64]
Temperature and heat load	Attenuates microclimatic extremes, reducing radiant load and air temperature in shaded areas.	Provides a lower heat-stress environment for the tree component and other organisms, favoring resilience and development in hot tropical climates.	[8,65,66]
Water availability	Increased water infiltration coupled with reduced evaporation and surface runoff decreases water deficit and soil erosion.	A more stable and deeper soil moisture supply benefits the increment in trunk diameter and height, mitigating the effects of dry seasons or prolonged droughts.	[67–69]
Nutrient cycling	Continuous litterfall deposition (leaves, branches, dead roots) increases the return and redistribution of nutrients (N, P, K) within the soil profile.	Actively favors the maintenance of soil fertility, providing the nutritional support necessary to ensure volumetric growth and long-term wood quality.	[70,71]
Root dynamics	Promotes niche partitioning, generating complementarity in the exploitation of resources within the soil profile among intercropped species.	The distribution of tree roots at different depths optimizes water and nutrient-use efficiency, reducing competitive stress and dictating the pace of tree growth.	[67,72–74]

Table 4. *Cont.*

Factor	Expected Effect	Impacts on Wood	References
Soil microbiota	Increases the taxonomic diversity of bacteria and fungi, altering biological co-occurrence networks and mineralization dynamics.	Microbiological synergism, symbiosis with fungi, and the enrichment of nitrogen-fixing bacteria directly influence nutrient absorption, tree vigor, and stem quality.	[75–78]
Competition with grasses and legumes	Dynamic ecological interactions that can strongly intensify the competition for light, water, and nutrients, particularly in highly dense arrangements.	High interference reduces initial tree growth; however, judicious adjustments (such as correct spacing and thinning management) mitigate competition and optimize log production.	[64,67,73,79,80]
Pests and diseases	The structural diversification of vegetation and habitats attracts natural enemies, serving as a refuge and breaking the temporal continuity of the host.	This biotic regulation and efficient natural control reduce phytosanitary susceptibility to pathogens, resulting in improved tree health and superior final wood quality.	[81–85]

4.1. Abiotic Factors

The inclusion of the tree component in ICLF systems consistently and substantially alters the physical environment and the system's microclimate, especially by modifying the incidence of solar radiation, air temperature, relative humidity, water availability, and radiant heat load (RTL) when compared to forest monocultures or full-sun pastures [7,8,63,66,68]. In silvopastoral and agrosilvopastoral systems located in tropical and semi-arid environments, the attenuation of photosynthetically active radiation by the canopy reaches the understory forage species [64,80,86] and promotes a significant reduction in temperature and environmental stress [79,87].

The microclimate effects created by trees extend far beyond light attenuation, directly impacting the pasture ecosystem and animal physiology [7]. The reduction in radiation transmission yields improved thermal comfort indices, such as the Temperature-Humidity Index (THI) and the Black Globe Temperature-Humidity Index (BGTHI) [88]. This microclimatic amelioration provided by shading facilitates thermoregulation in cattle and considerably mitigates the severity of heat stress, translating into improvements in ingestive behavior, increased rumination time, and higher levels of herd welfare, health, and productive performance [79].

Additionally, abiotic factors impact the development of the trees themselves. The spatial arrangement, population density, and intrinsic interactions and competitions for light and water affect the height and diameter growth of the tree component [89–91]. The adequate adjustment of these elements determines wood production and the formation and quality of logs [92,93], and, fundamentally, dictates the system's potential to sequester carbon and mitigate greenhouse gas (GHG) emissions [11,12,94].

4.2. Biotic Factors

The biotic factors affecting the tree component in ICLF systems are governed by a complex web of ecological interactions among trees, grasses, legumes, soil microbiota, and pathogenic organisms [10,39,71,95]. The most recent literature indicates that above- and belowground interactions in these systems operate along a dynamic gradient between

competitive and facilitative processes [67,96], whose magnitude and direction depend on the canopy architecture, density, and root system of the selected species [72,97].

Regarding root dynamics, nutrient cycling, and soil microbiota, the tree component plays a key role in structuring and elevating soil fertility [9,77,78,98–100]. Diversity in tree litter deposition and root exudation actively enrich soil biology [10,101]. Detailed investigations recently conducted in the Amazon have demonstrated that tree integration promotes a significant restoration of taxonomic diversity and functional connectivity of soil microbial networks compared to extensive, degraded pastures [38].

The selection of tree species proves to be a primary factor; the use of native legumes, such as *Samanea tubulosa*, has proven highly effective in promoting consortia with nitrogen-fixing bacteria and increasing the complexity of carbon degradation processes [38,78]. In contrast, fast-growing exotic trees, such as those of the *Eucalyptus* genus, tend to select more restrictive ectomycorrhizal fungal niches, geared primarily toward nutrient extraction in poor soils [78]. This microbiological synergism among trees, pastures, and soil optimizes nutrient cycling rates and leverages the safe, long-term storage of organic matter and soil carbon, maximizing the climate-mitigation credentials attributed to ICLF systems [10,12].

Finally, regarding the biological regulation of pests and diseases, the adoption of integrated systems presents markedly superior resilience compared to traditional monoculture practices [83]. The increase in plant biodiversity within ICLF and the consequent spatial diversification of hosts break the continuous cycle of pests and diseases [85]. The heterogeneous habitat architecture attracts and serves as a refuge for natural enemies and vital pollinating insects for the ecosystem [102]. This ecological balance provides efficient natural biological control services, reducing susceptibility to phytopathogens and promoting the continuous vegetative health of trees, which is an imperative criterion to guarantee the ongoing production of high-quality timber in tropical environments [95].

In summary, the consolidated literature demonstrates that optimized management of the tree component in ICLF requires a holistic approach, given that wood production and quality are shaped by a web of biotic and abiotic determinants. The success of the system fundamentally depends on the spatial arrangement, density, and species selection, which will modulate these interactions toward maximum productive and climatic efficiency.

5. Management of the Tree Component in ICLF Systems

5.1. Criteria for Selecting Tree Species

Establishing criteria for tree species selection in ICLF systems is a fundamental step to ensure the productive, ecological, and economic performance of these agroecosystems (Figure 3). Recent studies indicate that species selection should be guided by an integrated set of silvicultural, ecological, and economic attributes, considering not only individual tree performance but also their interactions with crop and livestock components [2,16]. In this context, the main selection criteria include growth rate, stem form and architecture, edaphoclimatic adaptation, end-use of wood, biological nitrogen fixation capacity, and economic viability.

Growth rate constitutes one of the most relevant criteria in tree species selection because it is directly related to system productivity and economic return. Species exhibiting high mean annual increments in diameter, height, and volume tend to shorten rotation cycles and enhance land-use efficiency. However, in ICLF systems, it is essential that this growth performance is maintained under conditions of resource competition for light, water, and nutrients. Studies evaluating *Eucalyptus* clones demonstrate significant variations in performance among genetic materials in integrated systems, underscoring the importance of selecting genotypes adapted to specific edaphoclimatic conditions [103].

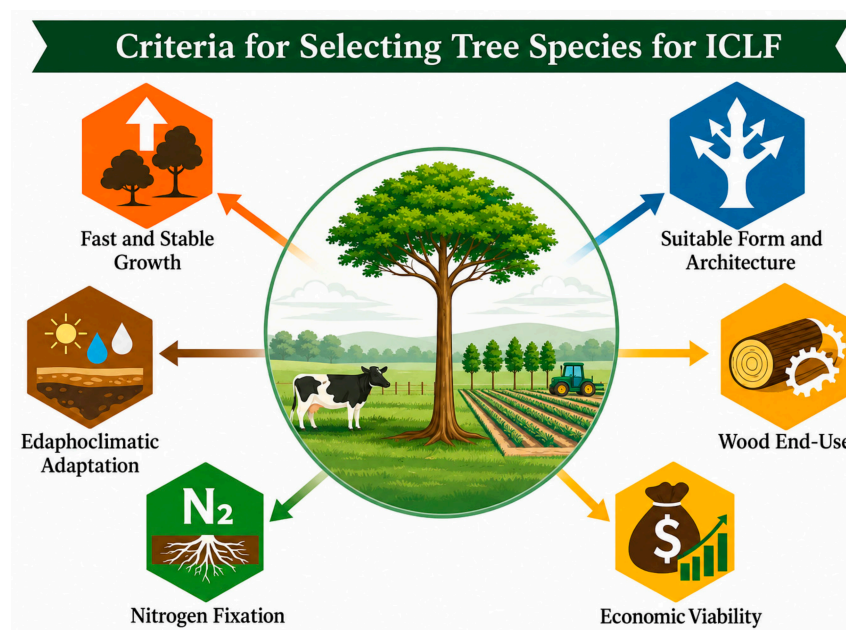


Figure 3. Criteria for selecting tree species for integrated crop–livestock–forest (ICLF) systems. Note: Figure generated using Artificial Intelligence (ChatGPT, GPT-5.6 Sol, OpenAI, 2026), based on the authors’ conceptual design.

Tree form is decisive in selecting tree species, particularly regarding crown architecture, stem straightness, and branching pattern. Trees with dense or excessively spreading crowns can reduce the productivity of crop and forage components due to excessive shading [104,105]. In contrast, individuals with straight stems and higher crowns facilitate farm mechanization and the production of higher commercial value timber. Additionally, efficient self-pruning capacity contributes to improved wood quality and reduced management costs [106].

Edaphoclimatic adaptation is an essential criterion because ICLF systems frequently exhibit greater environmental heterogeneity than homogeneous forest plantations. Species well-adapted to local soil, climate, and water regimes display higher survival rates, productive stability, and resistance to biotic and abiotic stresses [107]. Therefore, the use of species or clones previously tested under environmental conditions similar to those of the implementation site is recommended, taking into account soil fertility, texture, drainage, and climate variability.

The intended end-use of wood must be defined during the planning phase, as it directly influences species choice and silvicultural management. Species intended for bioenergy production may prioritize rapid growth, whereas those aimed at solid wood production require characteristics such as higher wood basic density, stem straightness, and a low incidence of defects [108]. Recent evidence indicates that ICLF systems can produce timber with appropriate technological quality for diverse applications, provided spatial arrangements and management are adequately planned [16,109].

The inclusion of nitrogen-fixing tree species can enhance the sustainability and nutrient-use efficiency of ICLF systems. Leguminous trees can increase biological nitrogen inputs and nutrient cycling, potentially benefiting the productivity of associated pastures and crops [110,111]. However, increased biological N fixation does not necessarily translate into higher crop or pasture productivity, as the net effect depends on N fixation rates, litter quality and decomposition, the timing and magnitude of nutrient release, water availability, and competition for resources between trees and understory plants. Furthermore, litterfall deposition from these species can contribute to improvements in soil physical, chemical, and biological properties and may reduce reliance on synthetic nitrogen fertilizers [111,112].

Nevertheless, adopting N-fixing species requires evaluating their operational compatibility with the production system and their economic potential.

The economic value of candidate species must be evaluated comprehensively, encompassing not only timber prices but also establishment, management, and harvesting costs, as well as opportunities for product diversification and ecosystem services [113]. In this regard, evaluating non-conventional tree species with high commercial value presents a strategic opportunity, particularly those targeting niche markets such as fine hardwoods, non-timber forest products, and multifunctional agroforestry. In Brazil, species such as *Dipteryx odorata*, *Hymenaea courbaril*, *Handroanthus* spp., *Swietenia macrophylla*, and *Schizolobium amazonicum* stand out for their high-quality timber and potential for noble uses [114,115]. Additionally, species such as *Inga edulis*, *Gliricidia sepium*, and *Acacia* spp. contribute to biological nitrogen fixation and nutrient cycling, enhancing overall system performance [116,117]. Together, these species display good edaphoclimatic adaptation, elevated resilience, and strong potential to improve the sustainability and profitability of ICLF systems, provided their growth, silviculture, and economic viability are supported by scientific evaluation across different integrated arrangements [114].

In summary, selecting tree species for ICLF systems must be based on a multidimensional framework that integrates productive, ecological, and economic criteria. Proper species selection maximizes system productivity and profitability while promoting environmental benefits such as improved soil quality, increased biodiversity, and climate change mitigation [118].

5.2. Tree Density, Thinning, and Pruning in ICLF Systems

ICLF systems have been widely promoted as a key strategy to increase agricultural sustainability by improving land-use efficiency and system resilience [2]. Introducing the tree component establishes complex ecological interactions involving competition and facilitation among trees, crops, and pastures. In this context, tree density represents one of the primary structural drivers regulating these interactions, directly influencing light availability, resource-use efficiency, and overall system yield [119]. Thus, defining optimal tree density ranges is fundamental to balancing forestry production and agricultural performance. However, in this review, the terms “low,” “moderate,” and “high” tree density are used as relative and system-specific categories rather than standardized quantitative classes. Because tree density effects vary considerably according to tree species, stand age, spatial arrangement, site conditions, and management objectives, the available literature does not support universal thresholds in terms of trees ha⁻¹ or basal area that can be consistently applied across ICLF systems.

Tree density strongly influences solar radiation interception and spatial distribution within the system. Increasing tree density reduces photosynthetically active radiation reaching understory crops and pastures, leading to yield declines [120]. Meta-analyses indicate that shading is the primary limiting factor in agroforestry systems, particularly for annual crops [102]. High tree densities also intensify belowground competition for water and nutrients, especially in soils with low fertility [2]. Conversely, trees contribute to nutrient cycling and soil structural improvement, promoting long-term system stability. These dynamic interactions form a balance between competition and facilitation, with tree density acting as the principal regulatory lever [119].

The quantitative ranges presented below for understory radiation availability, crop and forage yield responses, and forest productivity represent approximate values synthesized from the literature rather than universal management thresholds. These ranges should therefore be interpreted as indicative patterns, as actual responses may vary according to site conditions, tree species, stand age, spatial arrangement, crop or forage species, and

management practices. Low-density tree systems maintain high solar radiation levels in the understory—frequently exceeding 80% of incident radiation—allowing crop yields to approach those of monocultures, with reductions typically under 10% [104]. Although this configuration favors crop performance (Figure 4), lower tree numbers restrict total volumetric timber yield per unit area, limiting financial returns from the forest component and reducing revenue diversification [119].

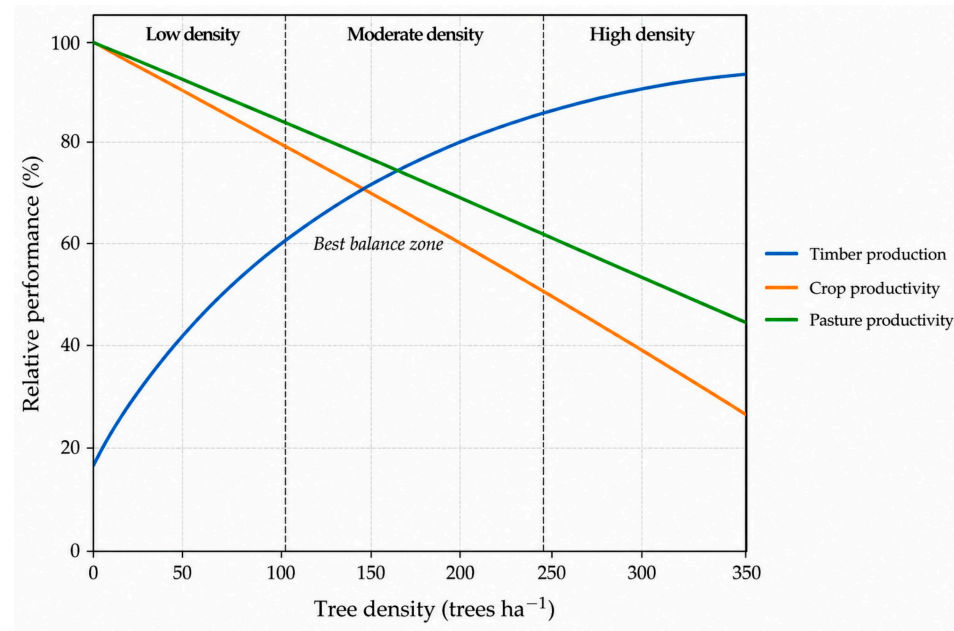


Figure 4. Continuous trade-offs between tree density, timber production, and crop/pasture performance in integrated crop–livestock–forest (ICLF) systems.

Moderate tree densities may provide a favorable balance among productive components in ICLF systems by harmonizing agricultural and forestry outputs. Under these conditions, understory light availability generally ranges between 60% and 80%, maintaining crop yields between 70% and 90% of monoculture levels while producing substantial, economically viable timber volumes [104]. This balance can optimize overall system efficiency and resource utilization. However, as trees grow, density management becomes imperative, making thinning an essential practice to preserve the balance between competition and complementarity over time [121].

High tree densities maximize wood volume production and carbon sequestration capacity, increasing forest volume by up to 30%–40% compared to wider spacings [119]. Nevertheless, this increased forestry yield occurs at the expense of understory light availability, which can drop to 30%–60% of incident radiation, aggravating competitive impacts on companion crops and pastures. Consequently, substantial yield reductions may occur, ranging from 30% to 50% in annual crops and 25%–40% in forage production, depending on site conditions and management regimes [104,121]. Therefore, high-density tree arrangements are better suited for scenarios where forest production is the primary objective rather than simultaneous crop/pasture maximization.

Determining the appropriate silvicultural regime must also be guided by the desired timber end-use, as different forest products require distinct growth rates, stem form traits, and log dimensions (Figure 5). Initial planting density, thinning schedule and intensity, as well as target diameter at breast height (DBH) and tree height represent key variables for directing forest production goals [119,121].

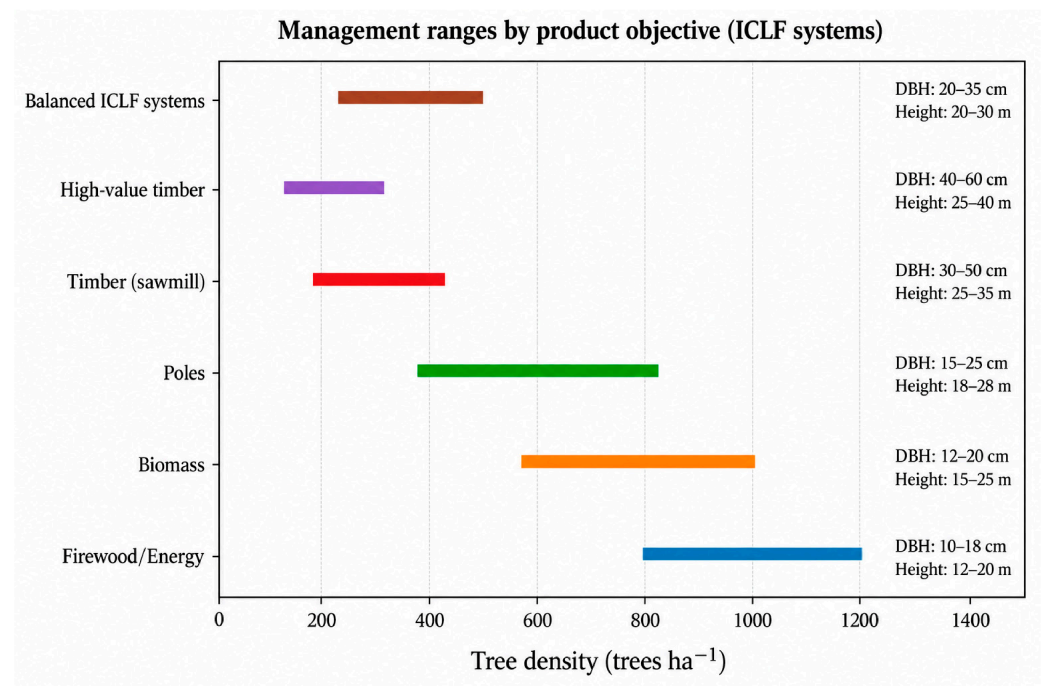


Figure 5. Tree density ranges according to end-use objectives in integrated crop–livestock–forest (ICLF) systems.

Systems dedicated to bioenergy or firewood production typically utilize higher initial densities, maximizing total volumetric yield per unit area despite smaller individual stem dimensions. Conversely, systems oriented toward high-value sawlog or structural timber production require lower final densities achieved through progressive thinnings, which promote individual diameter growth and stem quality [122].

Adaptive density management is vital to maintaining system balance throughout the rotation cycle. Silvicultural interventions such as thinning have proven effective by increasing light transmission to the understory, alleviating interspecific competition, and restoring crop and forage yields [121]. Furthermore, dynamically managed systems featuring periodic adjustments to stand density demonstrate higher resource-use efficiency and greater yield stability over time compared to fixed-density systems [2,119].

Silvicultural practices like thinning and pruning play a central role in modulating stem form, timber quality, and understory microclimate. Thinning reduces intraspecific competition, allocating more growing space and resources to residual trees, thereby enhancing diameter growth and stem uniformity (though excessive opening without complementary management may increase stem taper) [119]. Pruning directly contributes to knot-free, straight log formation, increasing the technological value of timber for premium applications [122]. Beyond their effects on the tree component, these silvicultural operations significantly alter understory microclimates by enhancing solar radiation penetration and air circulation, reducing relative humidity and shading stress, which in turn benefits crop and pasture growth [121].

In conclusion, adaptive tree density management is crucial for balancing agricultural and forestry components in ICLF systems. When aligned with specific wood product goals, silvicultural management directs tree growth and timber quality. Practices such as thinning and pruning are fundamental to mitigating competition and improving understory environmental conditions, ensuring long-term system sustainability, land-use efficiency, and economic stability.

6. Wood Production and Quality in ICLF Systems

6.1. Growth and Yield in ICLF Systems and Multiple Uses of Wood

In the current scenario of global climate mitigation, integrated agricultural systems act as essential nature-based solutions for transitioning toward low-carbon agriculture, reconciling environmental sustainability with economic viability [123]. The growth and yield balance of the forest component in these integrated arrangements are conditioned by complex ecophysiological interactions [124]. The adaptive plasticity of forest species and their resilience are directly related to competition for solar radiation [125], water, and nutrients [126], regulating volumetric increment and the multi-use of commercial timber [127].

The structural transition from dense, homogeneous monocultures to integrated agricultural systems—such as ICLF—reconfigures dendrometric variables and forest yield. While monocultures maximize gross volumetric yield per hectare at young ages under severe intraspecific competition, ICLF systems substantially alter tree morphometry through wide-row alley cropping [128].

In these integrated agricultural systems, light availability and photosynthetic efficiency are enhanced by wider usable spacing and the planned arrangement of tree rows, which optimize the interception of photosynthetically active radiation by the canopy. This solar radiation availability delays the natural recession of lower branches, expanding active leaf area and maximizing net photosynthesis. Consequently, there is a marked increase in diameter and individual tree volume, which enhances the commercial value of each individual stem and offsets the lower initial volume production per hectare during early years [129].

Furthermore, nutrient inputs and the residual effects of intensive management applied to intercropped agricultural species directly benefit the tree component in ICLF systems. Residual effects from chemical and/or biological fertilization, liming, and gypsum application enrich the rhizospheric environment during critical post-transplanting stages [117]. This expanded nutritional availability elevates the effective site index, promoting accelerated early establishment and optimizing growth curves for total height, commercial height, and merchantable wood volume for multiple uses [129].

However, introducing forest species into integrated agricultural models requires harmonizing genetic knowledge with studies on species plasticity across various spatial arrangements. Evaluating inter- and intra-specific variability and photoassimilate partitioning becomes crucial, as biological responses to wide spacings are governed by phenotypic plasticity and the resilience of genetic material under field conditions [130].

Genotypic selection can mitigate risks at the root interface between grasses, annual crops, and trees caused by limited water availability and seasonal homeostasis in regions subject to water deficits, rainfall irregularity, and high evapotranspiration. Long-term monitoring demonstrates that specific *Eucalyptus* genotypes exhibit high homeostatic capacity [131]. These genotypes optimize stomatal conductance and deep rooting, efficiently converting available resources into high mean annual increments (MAI) in volume, diameter, and height [132].

These higher volumetric increments associated with growth dynamics and forest yield are closely linked to ecophysiology and commercial stem form in integrated agricultural systems. Microclimatic and nutritional modifications in ICLF directly influence stem morphometry, modulating taper, straightness, and the intrinsic properties of commercial wood. Spacing and stem taper directly affect trunk form factor and log geometry [128].

Low competition and high lateral light incidence in wide alleys lead trees to concentrate diameter growth at the stem base to ensure static structural support against wind loads in open landscapes. This phenomenon produces stems with greater taper and lower

form factors compared to the cylindrical trunks typical of monocultures. Mathematically mapping this variation along commercial height requires applying multi-segment taper functions to accurately model multiple forest product yields [133]. While some forest species successfully reconcile fast volumetric growth with stem straightness, accelerated growth under low stand density can intensify internal growth stresses. This may induce pith eccentricity in advanced diameter classes, negatively affecting timber quality and restricting solid wood utilization [134].

To address these limitations, continuous silvicultural management through planned thinnings is imperative [135]. As trees age and canopy closure occurs within the row, intraspecific competition is re-established at restrictive levels, limiting late diameter expansion across diameter classes [132]. Timely application of scheduled thinnings redistributes light and water resources, concentrating growth increments on the most vigorous residual stems. This management optimizes essential technological wood attributes—ensuring heartwood proportions above 50% and dimensional stability—thereby maximizing the recovery of large-dimension logs and cants for high-value sawmills [127].

The economic sustainability and revenue diversification of ICLF systems depend on directing timber toward high-value solid wood markets (sawmills, veneering, construction, and rural infrastructure), while routing top residue biomass toward energy or pulpwood value chains [117]. Utilizing dendrometric tools combined with continuous forest inventories and rigorous stem profiling enables the calibration of growth and yield models and high-resolution taper functions, optimizing final commercial wood allocation in these systems [133].

This integrated framework permits stem bucking optimization across commercial profiles and multi-scenario stratification, precisely quantifying the physical recovery of noble timber assortments versus low-value industrial grades [45]. Statistical analyses demonstrate that variations in mathematical stem profiles correlate closely with physical and structural wood properties [136], which fluctuate significantly according to genotype under continuous silvicultural management [136]. Thus, combining genetic selection, silvicultural planning, and precise mathematical modeling represents the cornerstone for maximizing the conversion of gross wood volume into high-value-added assortments, mitigating financial risks, and locking in stable carbon storage within long-lifespan wood products.

6.2. Physical, Mechanical, and Anatomical Wood Properties in ICLF System

Accelerated diameter growth and altered stem morphometry resulting from wider spatial configurations in integrated agricultural systems exert a direct impact on intrinsic wood properties. Reduced intraspecific competition and modified ecophysiological dynamics alter vascular cambium activity and cell wall deposition rates, producing anatomical, physical, and mechanical wood profiles distinct from those found in dense monocultures [128,134].

The feasibility of channeling timber to noble solid wood markets is determined by technological indices evaluating dimensional stability and structural strength [45]. In integrated systems, management focused on longer rotation cycles reconciles fast growth with biological wood maturation, producing a higher-value-added product [117].

Considered the primary indexing property of wood quality, basic density correlates directly with mechanical strength and industrial yield [137,138]. Although conventional forestry paradigms often associate rapid growth with lower basic density, results in integrated agricultural systems demonstrate that under appropriate rotations, high basic density values exceeding 0.60 g/cm^3 are achievable [127]. This density threshold ensures

the necessary stiffness for mechanical conversion and structural utilization, matching or exceeding the wood quality of short-rotation energy monocultures [139].

Furthermore, heartwood biological development is accelerated by the enhanced vigor of trees grown at wide spacings [140]. Even at intermediate ages (120 months), the tree component under ICLF exhibits a heartwood/sapwood ratio greater than 1.0, with heartwood proportion exceeding 50% of commercial stem volume [127]. This characteristic is highly desirable for timber industries, as heartwood confers greater natural durability against biodeterioration agents and superior dimensional stability, minimizing warping and checking during kiln drying, whereas early-harvested dense monocultures yield high proportions of permeable, unstable sapwood [137].

However, the isolated exposure of trees in wide alleys subjects stems to mechanical action from wind loads, which can induce reaction wood formation and anatomical deviations [128]. Nevertheless, planned silvicultural management and genotypic selection keep pith eccentricity within acceptable limits below 5% in ICLF systems. This anatomical control mitigates internal growth stresses, reducing board springing and warping while optimizing clean lumber recovery in sawmills.

Mechanical strength (modulus of rupture, MOR) and stiffness (modulus of elasticity, MOE) follow the consolidation curves of wood basic density and cell wall microfibril angle [128]. Greater residual nutrient and water availability in agrosilvopastoral intercropping stabilizes the transition from juvenile to mature wood, resulting in stable MOE and MOR values that meet structural engineering and rural construction specifications [141].

Understanding the spatial heterogeneity of wood within individual trees is fundamental to optimizing multi-product stem bucking. Destructive sampling conducted across multiple commercial heights reveals distinct radial and longitudinal variation patterns in trees grown under integrated systems [142].

Regarding radial variability, wood produced under low competition in ICLF displays a progressive increase in basic density and fiber length from pith to vascular cambium [41]. In highly dense monocultures, severe competition restricts the width of outer growth rings. In contrast, integrated agricultural systems maintain an active crown leaf area that extends the secondary cell wall deposition phase throughout the hydrological year, generating a thicker, mechanically resistant peripheral zone of mature wood crucial for stable beam and plank production [45].

The longitudinal variability, heartwood proportion and basic density decrease toward the upper stem [127]. The basal portion of the log, being physiologically older, concentrates the highest extractives deposition and structured heartwood formation. Ascending along the stem, wood becomes anatomically younger, increasing sapwood proportion and bark content. This gradient dictates channeling basal logs toward noble sawlog markets while allocating upper stem tops to energy or pulpwood by-products [117].

6.3. Value Addition and Timber Utilization Supply Chains in ICLF Systems

The consolidation of superior physical, mechanical, and anatomical wood properties, combined with planned and continuous silvicultural management in integrated agricultural systems, provides the technological foundation for multi-use forestry. Transitioning from bioenergy or paper pulp markets to high-value supply chains aligns directly with global climate mitigation frameworks and national sustainable transition policies, such as the Brazilian ABC+ Plan [3].

The technical feasibility of mechanically processing *Eucalyptus* spp. timber grown under medium-to-long rotations in ICLF systems enables its penetration into noble solid wood markets, specifically for sawnwood and structural roundwood [131,143]. This end-use functions as a dual sustainability mechanism: it elevates net farm income for farmers

and serves as an ecological engineering strategy to extend the residence time of carbon fixed through tree photosynthesis [130].

Industrial yield and suitability for solid wood products are paramount for forest enterprises. Biometric and technological indicators recorded at harvest age—including low bark thickness (<3.5%), controlled pith eccentricity (<5%), and heartwood proportions exceeding 50%—grant stems high aptitude for sawmill conversion, civil construction, and rural structures [127]. While short-rotation homogeneous plantations supply direct combustion industries or short-lived panel products, wide ICLF spacings produce large-diameter logs that minimize growth stresses and maximize clean, defect-free, structurally stable lumber recovery.

Biological carbon fixation efficiency varies markedly among genetic materials in intercropped systems, reflecting their respective ecophysiological plasticities. Destructive stem assessments using Smalian's method reveal that the hybrid *Eucalyptus urograndis* (clone 3335) achieves a stem carbon fixation capacity of 50 Mg ha^{−1}, double the potential quantified for *Eucalyptus cloeziana* (25 Mg ha^{−1}) under identical agrosilvopastoral management [127]. This disparity demonstrates that selecting adapted genotypes and maintaining continuous silvicultural management are key drivers for optimizing carbon sequestration per unit area [144]. Table 5 summarizes findings from various studies across Brazil evaluating carbon stock potential in the tree component of ICLF systems.

Carbon storage in forest biomass does not end at harvest, emphasizing the importance of prolonging carbon immobilization along the industrial supply chain [117,145]. By directing high basic density stems (>0.60 g cm^{−3}) into long-lifespan wood products—such as structural beams, cants, engineered panels, and posts—fixed carbon remains securely sequestered for decades in built structures. This transfer of carbon from living biomass into the technosphere stock significantly delays CO₂ release back into the atmosphere [146]. Therefore, integrating genetic potential, continuous silvicultural management, and multi-use timber utilization establishes a long-cycle carbon sink, consolidating agrosilvopastoral systems as a core pillar for low-carbon, ecologically sound forestry companies.

Table 5. Carbon stocks in different tree genotypes across production systems, biomes, mean annual temperatures, annual precipitation, soil types, technology levels, silvicultural management regimes, spacings, and stand ages in Brazil.

Genotype	Production System	Biome	Mean Temp. (°C)	Mean Precip. (mm)	Soil Type	Silvicultural Management	Spacing	Trees ha ^{−1}	Age (months)	Biomass (Mg ha ^{−1})	Carbon Stock (Mg ha ^{−1})	References
<i>E. cloeziana</i>	ICLF	Cerrado	23.3	842.5	Inceptisol	Medium	2 × 3 m + 14 m	588	120	54.9	24.7	[127]
<i>E. urograndis</i> (Clone 3335)	ICLF	Cerrado	23.3	842.5	Inceptisol	Medium	2 × 3 m + 14 m	588	120	110.3	50.6	[127]
<i>Eucalyptus</i> spp.	ICLF	Cerrado	24.0	1438.0	Oxisol	High	10 × 4 m	250	120	108.0	52.9	[147]
<i>E. urograndis</i> (Super-clone)	ICLF	Cerrado	26.3	1800.0	Oxisol	High	1.75 × 3 m + 11 m	523	100	83.28	40.81	[146]
<i>E. urograndis</i> (Clone 1224)	ILF	Cerrado	25.0	1373.0	Oxisol	Medium	6 × 4 m	416	96	106.5	50.10	[148]
<i>E. urograndis</i>	Monoculture	Pantanal	22.0	1850.0	Oxisol	High	6.1 × 3 m	546	84	131.6	64.5	[149]
<i>E. urograndis</i>	ICLF	Amazon	25.6	1974.0	Oxisol	High	3.5 × 3 m + 30 m	270	96	75.0	35.0	[145]

7. Benefits of the Tree Component: Soil, Animal Performance, Production, and Economic Outcomes

The integration of trees into agricultural landscapes has gained significant prominence due to the capacity of these systems to provide multifunctional ecosystem services. This structural approach is vital in contemporary agriculture, which is tasked with delivering food security while simultaneously maintaining soil health, conserving biodiversity, sequestering carbon, and mitigating greenhouse gas emissions under increasing climatic uncertainty [49,150]. In this context, trees are not merely peripheral additions to silvopastoral systems; they function as fundamental ecological infrastructure that dictates the system's thermodynamics and nutrient stoichiometry [150,151].

The relevance of the woody component is particularly critical in tropical and subtropical regions, where intense solar radiation and erratic rainfall patterns impose severe environmental constraints on production [49,150]. Simplified monocultures in these regions exhibit high vulnerability to drought, thermal stress, and pedological degradation [152]. Conversely, the presence of trees enhances spatial and functional diversity, creating moderated microclimates and improving the system's resilience to environmental shocks [49,150]. In biomes such as the Brazilian Cerrado, characterized by rapid land-use conversion and fragile soil structures, the perennial tree component is a strategic necessity for long-term ecosystem stability [152,153].

Furthermore, trees influence the system through complex interactions involving nutrient cycling, carbon dynamics, and microclimate regulation [151]. Their extensive root systems and litterfall generate ecological effects that permeate the entire soil–plant–atmosphere continuum, reducing carbon losses and maintaining the ecosystem services that underpin productive stability [150,151]. Beyond ecological benefits, trees provide high-value outputs such as timber, biomass, and fruits, which diversify the property's economic base and reduce financial dependence on single commodities [150].

It is widely recognized that the performance of these systems is highly dependent on precise silvicultural management, including species selection, spacing, pruning, and thinning [150]. These factors determine whether trees act as facilitators or competitors within the system [150]. Therefore, the tree component should be viewed as a strategic element in the transition toward low-carbon, climate-resilient, and functionally diverse agricultural models [150,151].

7.1. Soil and Ecosystem Services

Soils pose serious challenges for the accumulation of soil organic carbon (SOC) in agricultural areas, especially in sandy soils of the Cerrado. In addition to the sandy texture, the high temperatures prevalent in this region and intense moisture during the rainy season intensify the decomposition of plant residues, increasing the challenges for maintaining soil cover. Soils with sandy textures are more prone to alterations in their biological communities and activity [152], with potential implications for SOC management and its productive sustainability.

The states that form the Brazilian region known as MATOPIBA (Maranhão, Tocantins, Piauí, and Bahia) have sandy soils in 60% of their areas [153]. The conversion of native vegetation to agriculture in these soils results in the loss of SOC, especially when the management practices adopted reduce biomass input or intensify its decomposition rate [150]. Typically, residue inputs of around 4 Mg ha^{-1} , associated with high temperatures and humidity, hinder the building of SOM stocks in these regions [42].

In turn, management practices that enable sustainable productive intensification (crop rotation, use of cover crops, and no-till) are capable of mitigating SOC losses [154,155]. Experiments performed in the state of Maranhão, in northeastern Brazil [42], showed

that after 10 years of conversion, no-till systems, well-managed pastures, and eucalyptus areas were able to maintain SOC stocks in the topsoil similar to those of native Cerrado vegetation areas. In the same region, the adoption of intensive and complex integrated management systems, such as crop–livestock–forestry, crop–livestock, and well-managed pastures, enabled the maintenance or even increase of SOC stocks compared to native Cerrado areas after 16 years of conversion [35].

The continuous input of residues in intensive perennial systems with the presence of animal and tree components is a key aspect for sustainability in sandy tropical soils. This condition intensifies microbial and metabolic processes, leading to a greater incorporation of carbon from plant biomass into SOC stocks. Under low-latitude conditions in eastern Maranhão (03°42'44"S), greater increases in organic carbon stocks down to a depth of 1 m were observed in a crop–forestry integration system (145 Mg ha^{−1}) after six years than in a no-till soybean system established for 17 years (135 Mg ha^{−1}) [12]. Both systems had significantly higher organic carbon stocks than the native Cerrado vegetation (70 Mg ha^{−1}). Similarly, the inclusion of babassu palm (*Attalea speciosa*) as a tree component in integrated crop–livestock–forestry systems in the pre-Amazon region of Maranhão resulted in higher levels of soil organic matter (SOM) and pH values compared to other systems [27].

Silvopastoral systems exhibit a high capacity to increase organic carbon stocks even under conditions of tropical sandy, dystrophic soils subjected to high temperatures. Under these conditions, the functional diversity of vegetation in complex management systems, the root complexity of different perennial components, and the type and quantity of organic input can outweigh the adoption time, leading to substantial accumulations of SOC. Therefore, managing SOC under conditions where its mineralization tends to be accelerated due to the predominance of sandy soils and high temperatures requires more efficient mechanisms for its stabilization.

Organic carbon accumulation rates depend on the amount of plant residues provided and their decomposition dynamics [156]. This, in turn, has shown a strong influence from the presence of animal and tree components in integrated production systems. Reference [34] demonstrated that the mixture of *Eucalyptus* sp. and *Megathyrsus maximus* cv. Tamani leaf residues in a livestock–forestry system resulted in a residue decomposition rate 40% higher than the decomposition of soybean residues cultivated under no-till. This process was facilitated by stoichiometric complementarity (cellulosic vs. non-cellulosic C/N ratio) and the coordinated activity of groups of decomposing microorganisms selected over time.

Although the quality of plant residues and their mixtures is a predominant factor in maximizing CO₂ sequestration [157], the community of decomposing organisms, the characteristics of the soil environment, and the quality of the residue are interrelated factors that influence the decomposition rate [158,159]. In this respect, the perennial nature of the pasture and the tree component in the integrated crop–livestock–forestry system, in contrast to the seasonal nature of soybeans in the no-till system, proves to be a determining factor for decomposition rates (and CO₂ sequestration), since it favors the selection of specialized microorganisms [160].

The stability of microbial communities in systems with perennial components promotes more efficient decomposition of diverse types of plant residues [41]. In contrast, in no-till soybean systems, the composition of the microbial community is strongly influenced by seasonal dynamics, which modulate the structure and functioning of soil microbial communities [26]. Integrated production systems have demonstrated a high capacity to modulate bacterial communities in Cerrado soils following fertility improvements, leading to a greater abundance of taxa [26]. These authors verified a clear association between systems with the inclusion of the tree component (crop–forestry and livestock–forestry)

and the presence in the soil of groups from the Nitrosomonadaceae family—relevant to nitrification processes in the nitrogen cycle [161]—and Sphingomonadaceae, involved in the degradation of humic substances [162].

Furthermore, the ICL system showed a strong association with the Bacillaceae family, which has multiple ecological roles in nutrient cycling and interactions with plants [163]. However, climatic seasonality has a strong influence on microbial biomass and enzymatic activity in soils with different levels of management complexity. Reference [29] demonstrated greater microbial biomass and enzymatic activity during the rainy season. Even in the dry season, integrated production systems maintain greater microbial biomass. The data from the study by [29] suggest that the differential effect of management systems on microbiological aspects reflects the state of soil health, potentially resulting in greater resilience to climatic adversities, which is a key aspect in the adoption of integrated production systems. This occurs because systems that promote microbial activity are frequently associated with better soil cover and greater accumulation of soil organic compounds (SOCs), favoring water retention [21].

7.2. Animal Welfare

The current scenario of climate change has imposed significant challenges on agricultural production. Climate modeling projections suggest that between 2030 and 2050 the duration of rainy seasons may shorten, reducing the viability of some crops in the Brazilian MATOPIBA region [164]. Other projections indicate that, by 2050, the production of important crops may need to shift toward subtropical regions, with MATOPIBA expected to be among the most affected areas [165].

Within this context, the animal component is one of the main dimensions through which the tree component expresses its value in integrated production systems. Beyond providing shade, trees modify the thermal environment, influence forage quality and distribution, and affect animal behavior, thereby impacting weight gain, feeding patterns, reproductive performance and welfare [7,146,150]. In tropical regions, where heat load is frequently a limiting factor for livestock productivity, these effects become particularly important because thermal stress can reduce performance even when forage availability is adequate. Consequently, silvopastoral and integrated crop–livestock–forestry systems are increasingly recognized as climate-adaptive strategies rather than merely alternative production arrangements [7,150].

Heat stress represents one of the main constraints affecting livestock systems under tropical and subtropical conditions. When animals are exposed to elevated temperatures, intense solar radiation, and high humidity, they activate physiological mechanisms to maintain thermal balance, including increases in respiratory rate, heart rate, and body temperature regulation effort [166,167]. These responses require energy that would otherwise be allocated to growth, reproduction, and production, resulting in lower feed efficiency and compromised productive performance, particularly in grazing animals exposed to full sunlight during the hottest periods of the day [167]. In addition to affecting productivity, heat stress can alter feed conversion efficiency and increase methane emissions per animal due to reduced metabolic efficiency [168]. Conversely, animals maintained under less stressful thermal conditions tend to be more metabolically efficient, potentially reducing heat production and enteric methane emissions associated with rumination processes [169]. Therefore, thermal comfort should be regarded as a central determinant of productivity and environmental performance in pasture-based livestock systems.

Tree cover contributes directly to animal comfort by reducing incident solar radiation and lowering thermal load at the pasture level. The microclimate beneath tree canopies generally presents lower black globe temperatures, reduced radiant heat load, and more

favorable temperature–humidity indices than open-pasture environments [7,170]. These conditions allow animals to remain active for longer periods, graze more comfortably, and spend less time seeking shade or reducing feed intake during hot hours. Consequently, the tree component helps maintain normal intake patterns and minimizes the behavioral responses typically associated with thermal stress. Such benefits are particularly relevant in beef production systems, where prolonged heat stress can delay finishing and increase the time required to reach slaughter weight [150,167].

The magnitude of these thermal benefits depends strongly on tree arrangement and canopy density. Different spacing configurations generate distinct microclimatic conditions because light interception, air circulation, and shade availability vary according to system design [7,171]. In general, moderate shading improves thermal comfort without substantially compromising forage growth, whereas excessively dense tree cover may limit light availability to the herbaceous layer. Therefore, the effectiveness of the tree component depends on achieving a balance between animal comfort and pasture productivity. The most efficient systems are those that provide sufficient shade to alleviate heat stress while maintaining adequate forage production.

Another important contribution of trees is their influence on forage quality [150]. In silvopastoral systems, shading can alter forage morphology, leaf-to-stem ratio, fiber concentration, crude protein content, and overall digestibility. Although these effects vary according to species, tree density, season, and grazing management, shaded pastures frequently exhibit improved nutritive value during dry or environmentally stressful periods [150,172]. Improved forage quality may compensate, at least partially, for reductions in biomass production under shade and help sustain animal intake and performance. This effect is particularly important during the dry season, when forage quantity and quality often decline in open pastures, increasing the risk of nutritional stress. In this way, trees contribute indirectly to animal productivity by stabilizing feed availability and improving the nutritional environment available to grazing animals.

The reduction in heat stress also has important implications for reproductive efficiency and animal welfare. Animals exposed to chronic thermal discomfort frequently exhibit altered hormonal responses, reduced estrus expression, lower conception rates, and impaired fertility. By creating a more favorable microclimate, trees help mitigate these effects and support more stable reproductive performance [7,150]. From a welfare perspective, access to shade and improved thermal regulation is increasingly recognized as a fundamental requirement for sustainable livestock production. Beyond ethical considerations, welfare directly affects productivity, as stress-related physiological disturbances can lead to slower growth, lower reproductive efficiency, and poorer overall health status.

The relationship between tree-based systems and methane emissions is another important aspect of livestock sustainability. Methane production is influenced by multiple factors, including diet quality, feed intake, digestibility, and animal physiology. By improving forage quality and reducing thermal stress, shaded systems can contribute to lower methane emissions per unit of product [146,172]. Studies conducted in silvopastoral environments have shown that the superior nutritive value of shaded pastures may reduce emissions intensity, particularly during dry periods when forage quality in open pastures is more limited [172]. Furthermore, animals experiencing lower levels of thermal stress tend to utilize dietary energy more efficiently, reducing methane losses associated with inefficient feed conversion [167]. Thus, the tree component should be viewed not only as a mechanism for improving animal comfort but also as a strategy for enhancing environmental efficiency in livestock production systems.

Empirical evidence supports these benefits. Reference [172] highlighted that the inclusion of trees in silvopastoral systems is an effective strategy for reducing animal stress, improving

productive performance, and simultaneously delivering environmental services. Under Cerrado conditions, Ref. [32] demonstrated that grazing systems incorporating *Eucalyptus* spp. in alley configurations significantly improved pasture productivity and nutritional quality while creating more favorable thermal conditions for livestock. These improvements translated into enhanced animal performance relative to conventional systems. The study also reported reductions in enteric methane emissions and increased carbon sequestration in the tree component, reinforcing the mitigation potential of integrated systems.

Similar responses have been observed under more challenging climatic conditions. In the semi-arid region of northeastern Brazil, the adoption of silvopastoral systems created more favorable thermal environments than monoculture pasture systems, resulting in lower average air temperatures and reduced animal respiratory rates, even during periods of intense thermal stress [173]. Likewise, Ref. [166] demonstrated that the inclusion of trees in grazing systems within the Amazon region improves environmental microclimatic conditions through reductions in thermal stress indices. According to the authors, these improvements contribute to long-term productivity and sustainability, highlighting the role of integrated systems as climate-smart strategies within national efforts to mitigate greenhouse gas emissions.

Evidence from both the Amazon and the Cerrado further reinforces this interpretation. Studies conducted in agroforestry and silvopastoral systems consistently report more favorable thermal indices, lower exposure to radiant heat, and improved animal behavior during the hottest hours of the day compared with conventional open-pasture systems [7,170,171]. More recent research also indicates that climate-smart silvopastoral systems can simultaneously promote animal comfort and reduce methane emission intensity, strengthening their role as multifunctional land-use strategies [28]. These findings are particularly relevant in Brazil, where a substantial portion of livestock production occurs under conditions of intense solar radiation and increasing climatic variability.

In summary, the tree component enhances livestock performance through multiple complementary mechanisms. By reducing thermal stress, improving forage quality, supporting more stable grazing behavior, and promoting animal welfare, trees contribute directly to greater productive efficiency. At the same time, they can improve emission efficiency and strengthen the resilience of livestock systems to climate-related stressors. Although the magnitude of these benefits depends on factors such as tree density, shade distribution, and forage management, the available evidence consistently demonstrates that trees are a key component of sustainable and climate-resilient livestock production systems [7,150,167].

7.3. Economic Benefits and Value Addition

ICLF systems can provide greater economic resilience and income diversification compared to conventional monoculture or extensive grazing systems. Although the integration of trees increases initial establishment costs, long-term economic assessments have frequently reported positive net present value (NPV) and attractive internal rates of return (IRR), particularly under tropical conditions [60,174]. In this context, the tree component contributes to risk reduction by diversifying production and buffering the impacts of climatic variability and market fluctuations. Such economic diversification is mainly driven by the inclusion of forest products, which provide additional long-term revenue streams within integrated systems.

Timber production represents one of the main additional revenue sources in ICLF systems. Fast-growing species, especially *Eucalyptus* spp. and *Tectona grandis*, can generate additional economic returns through the commercialization of timber for sawmills, pulp, bioenergy and biomass [175]. In tropical regions of Brazil, silvopastoral and agrosilvopas-

toral systems have shown higher profitability than conventional pasture-based systems due to the synergistic revenues from livestock and forest products [176]. In addition, timber produced in integrated systems may achieve higher market value when directed toward value-added products, including veneer, furniture, laminated wood, and certified timber. However, the profitability of these markets largely depends on wood quality, which is strongly influenced by silvicultural management.

From a structural market perspective, the economic viability of the tree component is fundamentally shaped by value-chain segmentation, cash-flow timelines, and risk-mitigation dynamics [60,176]. Rather than serving as a passive resource, on-farm timber acts as a dynamic ‘green savings account’ that reconfigures the farm’s financial resilience [4]. Unlike annual crops or livestock, which are bound to rigid seasonal harvest schedules, trees possess high biological stability and can be selectively harvested over multi-year windows [131]. This flexibility allows farmers to strategically time timber sales to take advantage of favorable market conditions, thereby providing a buffer against the price volatility of agricultural commodities [60,117]. Furthermore, the financial performance of this forestry asset is highly dependent on targeting premium solid wood markets (such as large-diameter sawlogs and structural roundwood) rather than low-value industrial biomass [117,127]. While high initial capital requirements represent a significant barrier to adoption, bioeconomic analyses demonstrate that agrosilvopastoral systems effectively resolve this cash-flow bottleneck [177]. The high-yield crop phase during the first three to four years can amortize up to 80%–85% of the total forestry establishment costs within the first 15 months, dramatically reducing the payback period and investment risk compared to pure forest plantations [177,178]. However, the conversion of high-quality wood volume into actual net profit remains strongly constrained by regional logistics and local market integration, with proximity to processing facilities, such as sawmills or pulp mills, playing a decisive role in determining the farmer’s final economic margin [175,176].

Tree spacing, thinning, and pruning practices affect stem form, diameter growth, and wood properties, directly influencing timber quality and market value [179]. Several economic analyses have demonstrated that intermediate tree densities often provide the best balance between understory productivity and timber yield, resulting in more favorable economic indicators than simplified production systems [2]. Therefore, silvicultural management plays a central role in maximizing both productive efficiency and economic returns in ICLF systems.

Beyond direct revenues from timber, ICLF systems may also generate income through Payments for Ecosystem Services (PES). The substantial accumulation of aboveground biomass and soil carbon increases the carbon sequestration potential of these systems, creating opportunities for participation in carbon markets and greenhouse gas mitigation programs [151,180]. In tropical environments, where biomass accumulation rates are typically high, carbon-related revenues may further improve the economic attractiveness of integrated systems while supporting land restoration and sustainable intensification strategies.

Additional indirect economic benefits include improved thermal comfort for livestock, enhanced nutrient cycling, greater land-use efficiency, and reduced pasture degradation, all of which contribute to greater production stability and long-term sustainability [49]. Collectively, these benefits reinforce the important role of the tree component not only as a source of timber revenue, but also as a driver of economic resilience and environmental performance in tropical integrated production systems.

8. Trees, Carbon, and Offsetting of CH₄ and N₂O Emissions

To ensure conceptual and scientific precision, a clear distinction must be established among carbon stocks, annual carbon sequestration rates, and carbon permanence. Carbon Stocks (Mg C ha⁻¹) represent the absolute pool of carbon stored in a given compartment at a single point in time; these pools are reported separately for the soil (e.g., organic carbon stocks of up to 120 Mg C ha⁻¹ in deep profiles) [10,11,38] and for standing tree biomass (e.g., eucalyptus stemwood carbon stocks of approximately 50 Mg C ha⁻¹ at 120 months) [127]. Carbon sequestration rates (Mg CO₂-eq ha⁻¹ year⁻¹) reflect the dynamic annual flux of carbon capture from the atmosphere; in this review, individual tree biomass accumulation rates of 7.63 Mg CO₂-eq ha⁻¹ year⁻¹ [22] and net system-level annual sequestration of approximately 19 Mg CO₂-eq ha⁻¹ year⁻¹ [150] are reported. Permanence refers to the length of time that sequestered carbon remains stored and prevented from returning to the atmosphere; here we contrast the dynamic, comparatively reversible nature of soil and short-lived biomass carbon with the more secure, long-term physical immobilization achieved when high-density merchantable wood is routed into long-lifespan harvested wood products [106,108,131]. The permanence and stability of Harvested Wood Products (HWPs) will be characterized by assessing their carbon storage duration, resistance to decomposition, and end-of-life (EOL) pathways, according to the definitions provided below:

- Duration of storage: We specify that when high-density timber (e.g., from medium-to-long ICLF rotations) is channeled into solid wood products (structural beams, columns, high-end furniture), the carbon remains physically locked in the technosphere for decades or even centuries (typically 30 to over 100 years) [145].
- Decomposition dynamics: We clarify that solid wood products from dense hardwoods (such as mature Eucalyptus or native species) possess high structural stability and resistance to biotic/abiotic decay due to their high lignin and extractive contents, substantially slowing down decomposition compared to particulate organic matter (POM) or short-lived biomass [137].
- End-of-life (EOL) treatments: We have expanded the text to discuss how different EOL pathways dictate final carbon release. While landfilling can physically occlude carbon under anaerobic conditions for centuries with minimal decay, and recycling into reconstituted panels (such as MDF/MDP) further extends storage duration, direct incineration without capture releases the carbon back into the atmospheric cycle. We also highlight that pairing wood-derived bioenergy with carbon capture and storage (BECCS) represents a highly stable, permanent carbon sink [145,146].

Carbon sequestration is strictly defined as the biological process of capturing atmospheric CO₂ via photosynthesis and storing it in stable, long-term physical pools, specifically aboveground tree biomass, roots, and soil organic carbon fractions [9–11]. GHG mitigation is a broader operational term encompassing any human intervention or management practice that reduces greenhouse gas emissions or enhances biological sinks; this includes carbon sequestration itself, as well as practices that actively suppress emission intensity (e.g., improving forage quality and microclimatic shading to enhance cattle metabolic efficiency and lower enteric CH₄ emissions [146], or using deep-rooting species to optimize nitrogen-use efficiency and reduce N₂O losses [181,182]). Net GHG Balance/Carbon Neutrality is the final accounting between total carbon sequestration and total GHG emissions over a defined temporal boundary (i.e., carbon sequestration—GHG emissions). Total GHG emissions include operational and biological sources, such as CH₄ from enteric fermentation, N₂O from soils and fertilizers, and CO₂ associated with external inputs. Under this convention, a positive net balance indicates that carbon sequestration exceeds GHG emissions, and zero indicates carbon neutrality.

8.1. GHG Sources and Sinks in ICLF Systems

The main sources of greenhouse gases (GHG) in ICLF systems comprise enteric fermentation in ruminant herbivores—a primary source of methane (CH_4)—as well as synthetic fertilizer application and the deposition of animal excreta and plant residues, which emit nitrous oxide (N_2O). Additionally, input applications (such as urea) and liming processes to correct soil acidity and Ca and Mg levels emit carbon dioxide (CO_2). However, ICLF systems significantly contribute to mitigating GHG emissions [183]. Greater functional biodiversity and appropriate management of the integrated components optimize resource-use efficiency and enhance the performance of carbon sinks [12,150].

Proper pasture management in integrated systems elevates livestock productivity. A characteristic feature of these systems is the production of higher-quality forage (higher crude protein content and improved digestibility), which increases feed conversion efficiency [184]. Furthermore, the microclimatic shading provided by the tree component enhances animal welfare, thereby fostering higher productive performance [59]. Reconciling these factors shortens the time required for ruminants to reach slaughter weight, resulting in reduced CH_4 emissions per kilogram of meat or milk produced.

The conversion of degraded or low-productivity pastures into intensified or integrated systems has been reported to mitigate CH_4 emissions by up to 4.5 g CH_4 per kilogram of dry matter intake and 122 g CH_4 per kilogram of average daily weight gain [40]. Moreover, transitioning from conventional pastures to biodiverse integrated systems has yielded soil CH_4 fluxes ranging from neutral to $-0.81 \text{ kg ha}^{-1} \text{ year}^{-1}$. Negative CH_4 fluxes (methane sink activity) have also been documented in integrated systems with and without trees [183]. Methane influx into the soil is primarily driven by increases in soil functional biodiversity [185].

Combining distinct plant species within the same production area (ICLF) establishes heterogeneous root structures across the soil profile, penetrating to varying depths. Enhanced root distribution throughout the soil profile favors nutrient uptake and reduces losses via leaching or denitrification of applied nitrogen fertilizers, thereby enhancing synthetic nitrogen-use efficiency and decreasing N_2O emissions. Improvements in soil physical structure (increased aeration) alongside intercropping with leguminous species (biological nitrogen fixation) represent key mechanisms inherent to ICLF systems that lower N_2O release. Converting degraded pastures into tree-integrated production systems has been found to reduce N_2O emissions by up to $1.63 \text{ kg ha}^{-1} \text{ year}^{-1}$, avoiding the release of $700 \text{ kg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ [40]. In fact, N_2O fluxes in degraded pastures can be up to 1.6 times higher than those observed in ICLF systems [183].

ICLF systems possess major carbon sinks, most notably arboreal biomass (stemwood, branches, and roots) and the soil profile, which store substantial carbon stocks. Together, these sinks confer a superior carbon sequestration capacity upon integrated systems compared to conventional farming models (Figure 6). Considering both soil and tree compartments, annual net carbon sequestrations of 19.89 and $18.97 \text{ t CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ were recorded in agrosilvopastoral and silvopastoral systems, respectively [150]. Over a four-year period, integrated systems maintained a negative net carbon balance, with maximum carbon capture achieved in systems incorporating a forestry component, ranging from 15.9 to $20.4 \text{ Mg CO}_2\text{-eq ha}^{-1} \text{ year}^{-1}$ [18].

The superior carbon sequestration potential of integrated systems stems from their dual capacity to store carbon simultaneously in woody biomass and in the soil matrix. High plant biomass production, driven by the structural integration of multiple species, optimizes long-term carbon accumulation in the soil–plant system. Ref. [127] reported a stem carbon stock of 50.6 Mg ha^{-1} in *Eucalyptus* trees (120 months post-planting) within an ICLF system established at $588 \text{ trees ha}^{-1}$. Soil organic carbon stocks of approximately

120 Mg ha⁻¹ (0–100 cm layer) were measured in a 7-year-old agrosilvopastoral system planted at 278 trees ha⁻¹ [13]. Similarly, at 5 years of age, an agrosilvopastoral system accumulated 39.06 Mg ha⁻¹ of carbon in aboveground tree biomass (333 trees ha⁻¹) and 113.96 Mg ha⁻¹ in the soil down to a 100 cm depth [150]. These empirical findings confirm the potential of integrated production systems as a key strategy for GHG mitigation.

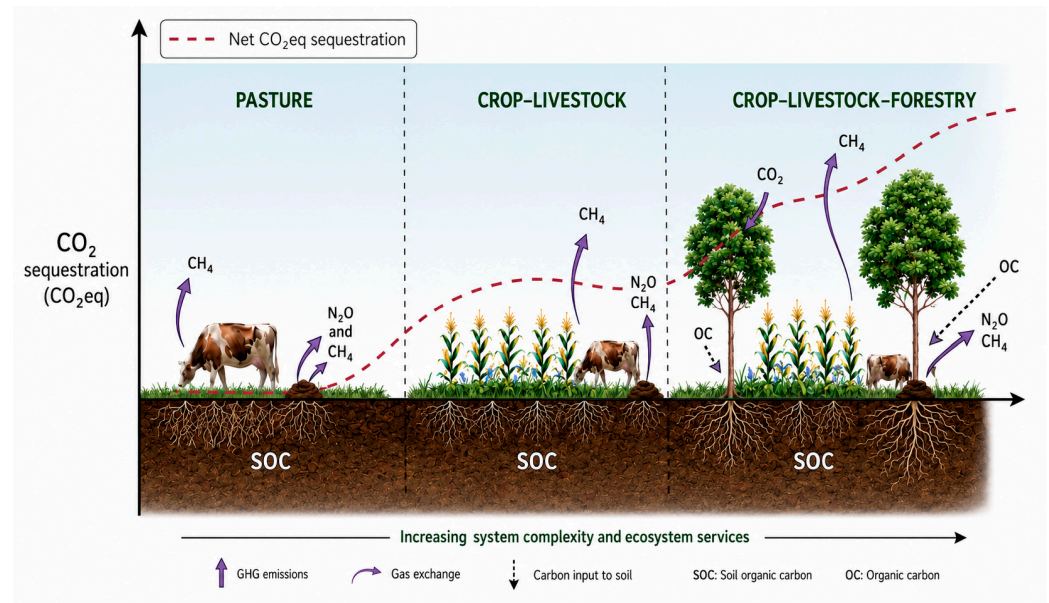


Figure 6. CO₂ sequestration potential in pasture and integrated production systems. Note: Figure generated using Artificial Intelligence (Chat GPT-5.6 Sol, OpenAI), based on the authors' conceptual design.

Although ICLF systems have the potential to mitigate GHG emissions, claims regarding GHG offsetting, carbon neutrality, or carbon credit generation should be based on whole-system GHG accounting [150]. In this approach, emission sources and carbon pools are considered together. For example, this includes CH₄ emissions from enteric fermentation in animals [18,184], N₂O emissions from soil and manure [186], CO₂ emissions associated with the use of fertilizers, liming, fuels, and other inputs, as well as changes in carbon stocks in soil and plant biomass [10,12]. The permanence of stored carbon, that is, how long carbon remains sequestered and the possibility of its release back into the atmosphere, should also be considered [145,146]. For carbon credit generation, additional relative to a baseline must also be demonstrated [150]. It is important to demonstrate that the GHG reduction or removal results from the adoption of the implemented practice, such as ICLF. Furthermore, GHG reductions and removals must be appropriately measured, reported, and verified through monitoring, reporting, and verification (MRV) protocols [150].

8.2. Offsetting Potential via the Tree Component

Integrating trees into agricultural production systems (ICLF) serves as the main structural driver transforming these land uses into net carbon sinks. Woody biomass, particularly the tree trunk, represents the most critical long-term carbon storage pool, concentrating approximately 90% of total aboveground biomass carbon [187]. However, the magnitude of this potential depends strongly on management variables, including tree density, stand age, species traits, and the precision of allometric models used to estimate carbon stocks [148,188].

Carbon sequestration achieved through tree growth is considered the primary climate mitigation mechanism in these systems, as woody biomass accumulates carbon at rates far exceeding those of monoculture pastures [150]. Additionally, the presence of trees enhances soil organic carbon stocks, particularly in deep soil horizons, compared to open pastures or simpler crop rotations [10]. As a result, numerous studies demonstrate that well-designed integrated systems can fully offset livestock-related GHG emissions, achieving net-zero or carbon-negative balances under specific management regimes [148,189].

Although trees can indirectly influence soil CH₄ uptake and N₂O exchange, the main climate mitigation benefit of tree integration remains tied to carbon storage rather than direct emission suppression of non-CO₂ gases [12,190]. Field evidence and synthesized literature indicate that well-managed integrated systems lower net greenhouse gas footprints relative to treeless baselines. The exact offset magnitude depends on tree density, grazing intensity, nitrogen fertilization rates, precipitation regimes, and whether carbon accounting includes both soil and woody biomass compartments [150,186].

Accurate quantification of trunk carbon stocks requires robust species-specific allometric equations that integrate variables such as diameter at breast height (DBH), total height, and wood basic density [191]. Wood basic density is particularly critical for converting merchantable stem volume into dry biomass and subsequent carbon equivalents. In tropical environments, basic density varies widely among species (0.27 to 0.76 g cm⁻³), directly influencing carbon stock calculations. Consequently, while fast-growing tree species rapidly accumulate wood volume, they may yield lower wood density, a trade-off that must be accounted for in carbon accounting frameworks [182]. Likewise, using a generic conversion factor of 50% carbon content in biomass has been challenged, as actual wood carbon concentrations in tropical trees range from 45.8% to 49.8%, leading to potential over- or underestimations when generic coefficients are applied [181,182]. Thus, reliable carbon inventories necessitate locally calibrated allometric equations and species-specific tissue carbon fractions [192].

In the Brazilian Cerrado, managing trees for high-value timber production enhances long-term carbon sequestration while increasing soil carbon stocks by up to 15% after 14 years of implementation [35]. Beyond soil enhancement, studies demonstrate that tree growth can completely offset emissions generated by livestock activities. Ref. [148] observed an annual tree carbon accumulation rate (7.63 Mg CO₂-eq ha⁻¹ year⁻¹) that surpassed total operational livestock emissions (5.81 Mg CO₂-eq ha⁻¹ year⁻¹), confirming the technical feasibility of carbon-neutral beef and dairy production (Figure 7). Similarly, ref. [193] demonstrated that allocating just 15% of a property's area to ICLF (at a density of ~417 trees ha⁻¹) provided sufficient biomass sequestration to neutralize the farm's entire CH₄ and N₂O footprint. Nevertheless, the extent to which integrated systems offset livestock emissions may vary according to tree species and density, system age, environmental conditions, and management practices. Thus, these results should be understood as reflecting the potential of appropriately designed and managed systems rather than a universal outcome. These findings reinforce that, under suitable site-specific conditions, the tree component can transform integrated systems into effective net carbon sinks, thereby combining agricultural production with climate change mitigation.

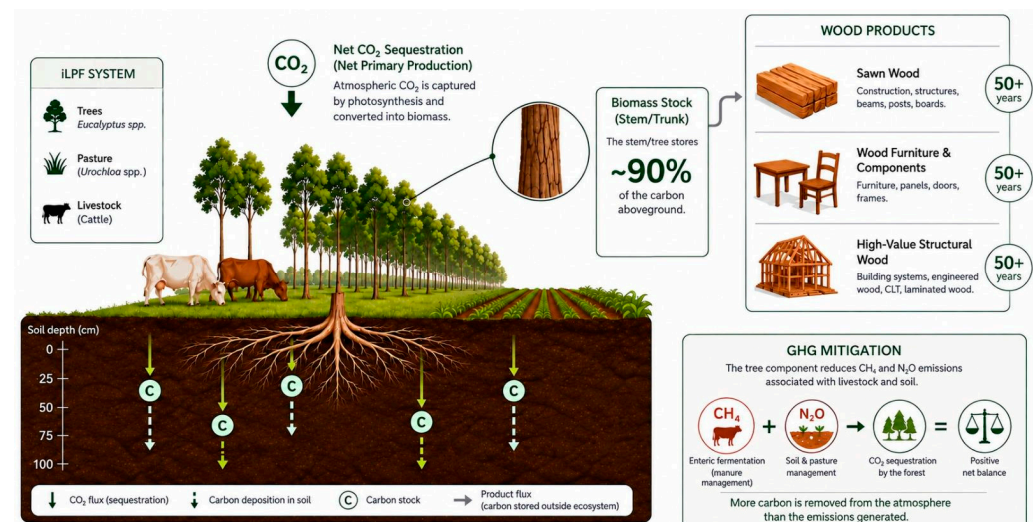


Figure 7. Conceptual scheme of CO₂ sequestration potential in tree stems within ICLF systems, harvested timber products, and GHG emission offset mechanisms. Sources: [10,150,187]. Note: Figure generated using Artificial Intelligence (Chat GPT- 5.6 Sol, OpenAI), based on the authors' conceptual design.

8.3. Carbon Credit Dynamics: Baseline, Additionality, Permanence, MRV, and Carbon Rights

While the biophysical capacity of ICLF systems to sequester carbon is well-documented, transitioning these ecological sinks into commercially tradable carbon offsets requires adherence to strict market governance and regulatory principles. Central to this transition is the concept of additionality, which dictates that the greenhouse gas (GHG) reductions or removals achieved by integrating trees must exceed those of a business-as-usual baseline. In tropical agricultural frontiers, this baseline is typically represented by extensive, low-productivity treeless pastures or continuous annual crop monocultures. Project developers must prove that the net carbon accumulation would not have occurred without the financial or technical intervention of the carbon project. Proving this additionality, however, is contingent on the implementation of robust Monitoring, Reporting, and Verification (MRV) protocols. MRV frameworks must employ whole-system GHG accounting, which subtracts all localized biogenic and operational emissions—including enteric fermentation CH₄ from cattle, N₂O fluxes from soil and animal waste, and CO₂ emissions from agricultural inputs, liming, and fossil fuels—from the total biomass and soil carbon sequestered by the system.

Furthermore, carbon credit viability is strictly governed by the principle of permanence, which addresses the risk of reversal. Unlike geological sequestration, biological carbon pools in soils and standing biomass are inherently vulnerable to natural and anthropogenic disturbances, such as forest fires, droughts, and management changes that can release stored carbon back into the atmosphere [9–11,146]. To mitigate these permanence risks, managing trees for high-value solid timber provides a strategic double-mitigation mechanism. By harvesting high-density wood and converting it into long-lifespan harvested wood products (HWPs)—such as structural roundwood, furniture, and engineered panels—the carbon fixed during the tree's growth remains locked in the technosphere for decades, extending carbon permanence long after the standing biomass is harvested [145,146].

Ultimately, the scalable adoption of ICLF-based carbon farming remains structurally bound to legal and institutional safeguards, particularly secure land and tree tenure. Across tropical regions, poorly defined property rights and ambiguous tree-use regulations create severe obstacles; tenant farmers and smallholders are often discouraged from investing in long-term tree planting due to the risk of land eviction or the legal inability to harvest timber. Because carbon credits are legal commodities, establishing clear ownership of

carbon rights requires a fully resolved ‘bundle of rights’ that legally links land ownership with the right to claim environmental service revenues. Secure land title not only unlocks credit eligibility under international voluntary carbon standards (e.g., Verified Carbon Standard) but also provides the necessary collateral for farmers to access the initial banking credit required to cover high upfront forest establishment costs.

9. Management Bottlenecks, Diversification, and Adaptation to Edaphoclimatic Conditions

The implementation of integrated agricultural systems faces major bottlenecks related to technical silvicultural management. The complexity of inter-component interactions among trees, crops, and livestock demands specialized knowledge regarding planting densities, spatial arrangements, pruning, canopy shade management, and soil nutrient dynamics. A persistent lack of technical training and specialized extension services represents a recurring barrier to widespread adoption, particularly in regions dominated by conventional monocultures. Recent studies agree that these management challenges impair both system productivity and overall sustainability, directly constraining its scalability [194].

Another critical aspect is the adaptation of ICLF models to site-specific edaphoclimatic conditions. Key drivers such as soil type, water availability, topography, and climatic regimes heavily influence agroforestry design and performance. Inadequate species selection or poor alignment with local environmental conditions can trigger severe resource competition, yield declines, and, in extreme cases, total system failure. Consequently, recent research emphasizes territorial and adaptive strategies that account for environmental variability and deliver context-specific technical solutions [195].

Furthermore, persistent gaps remain in generating and translating applied knowledge, hindering system optimization across operational scales. A shortage of integrated models and long-term multi-disciplinary studies simultaneously evaluating productive, economic, and environmental variables remains a major obstacle to consolidation. Strengthening interdisciplinary research networks and rural extension infrastructure is therefore essential to overcoming these barriers. Comprehensive policies and strategies are required to foster practices that optimize material and energy fluxes per unit of economic output, backed by a clear understanding of the prevailing social, economic, technical, environmental, and legislative frameworks [194].

9.1. Challenges of ICLF Systems

Integrated systems such as ICLF systems face structural challenges mainly associated with operational complexity, requiring the precise coordination of above- and below-ground interactions between crops, trees, and animals. This includes managing competition for light, water, and nutrients, as well as executing specific silvicultural operations like pruning, thinning, shade regulation, and livestock stocking rate adjustments [15,196].

These operational hurdles are compounded by technical and knowledge bottlenecks, such as a shortage of specialized training and limited technical assistance, which restrict broader adoption within traditional farming sectors [194]. Selecting functionally compatible and economically viable species combinations constitutes another key challenge vital for maintaining yield stability and ecosystem resilience [197]. Similarly, precise adaptation to edaphoclimatic constraints—soil physical-chemical attributes, hydrological regimes, and macroclimate—is a decisive prerequisite, as flawed designs exacerbate competitive stress and compromise yields [195]. Finally, holistic economic-environmental evaluations and scalability remain constrained by high initial capital requirements, revenue uncertainty, and a lack of multi-variable decision-support tools [198].

9.2. Diversification of Tree Species and Spatial Arrangements

Diversifying tree species and spatial configurations in ICLF systems, agroforestry systems (AFS), and silvopastoral systems (SPS) poses a significant technical challenge. Major bottlenecks exist surrounding the adoption of native species and multi-species mixtures capable of reconciling timber production, ecosystem service provision, and ecological resilience. Proper selection and combination of species demand advanced ecological and silvicultural expertise while introducing operational uncertainty due to complex multi-trophic interactions [15,46]. Market risks and supply chain uncertainties further hinder tree diversification. In emerging markets for ICLF timber, the lack of consolidated value chains, standardized grading rules, and demand stability reduces financial incentives for growers to diversify, ultimately impairing long-term economic viability and large-scale adoption [15,46].

According to [199], constraints impeding agroforestry implementation globally can be categorized into three macro-categories: (i) technical, agronomic, environmental, and climatic barriers: input availability, spatial constraints, site limitations, labor demands, and specialized technical knowledge; (ii) socioeconomic and financial constraints: market access barriers, credit constraints, capital investment risks, and social/neighbor relations; (iii) policy, legislative, and institutional factors: land tenure insecurity, subsidy access, legal definitions, and regulatory burdens (Table 6).

Table 6. Technical, socioeconomic, institutional, and biophysical constraints restricting agroforestry and ICLF adoption globally.

Category	Implementation Bottleneck	Description	Frequently Reported Regions	References
Technical and Agronomic	Lack of technical knowledge	Limited knowledge on design, establishment, and silvicultural management of AFS/ICLF.	Africa, Asia, Latin America, Europe	[178,199]
	Scarce agroforestry expertise	Insufficient training and restricted technology transfer.	Global	[199]
	Lack of technical assistance	Deficient rural extension services and training programs.	Africa, Latin America	[199,200]
	Management complexity	High knowledge required for managing multi-species interactions.	Global	[200]
	Tree-crop competition	Above- and belowground competition for water, light, and nutrients in drylands.	Tropical and semi-arid regions	[201]
	Inadequate species selection	Use of tree species poorly adapted to local climate and edaphic conditions.	Global	[20,49]
Economic	High initial establishment costs	Heavy upfront capital required for seedlings, fencing, planting, and maintenance.	Global	[177,199]
	Delayed financial returns	Long payback periods before forestry revenues are realized.	Global	[199]
	Limited credit access	Financial institution barriers in funding long-term agroforestry systems.	Africa, Latin America, Asia	[200]
	Undeveloped markets	Lack of structured commercial value chains for agroforestry products.	Global	[199]
	Price volatility and uncertainty	Market risk and unknown future value of timber products.	Global	[178]

Table 6. *Cont.*

Category	Implementation Bottleneck	Description	Frequently Reported Regions	References
Social	High labor demand	Increased operational labor requirements compared to simplified monocultures.	Global	[199]
	Low benefit perception	Perceived high risk and uncertain long-term returns by growers.	Global	[178]
	Lower educational levels	Reduced capacity to adopt complex, multi-component technologies.	Africa, Asia	[178]
Institutional	Land tenure insecurity	Uncertain legal rights over agricultural land or planted trees.	Africa, Latin America	[202]
	Inadequate public policies	Absence of comprehensive national policies promoting integrated land use.	Global	[199]
	Insufficient incentives	Lack of subsidies, tax breaks, or Payment for Ecosystem Services (PES).	Global	[200]
	Bureaucratic burdens	Regulatory restrictions on tree establishment, harvesting, and transport.	Europe, Africa, Latin America	[197]
Biophysical	Drought and climate variability	Increased tree mortality and reduced overall system productivity.	Dryland and semi-arid regions	[201]
	Degraded soils	Low natural fertility, erosion, and soil compaction limiting tree growth.	Africa, Asia, Latin America	[201]
	Extreme weather events	Floods, heatwaves, and severe storms damaging system stability.	Global	[177]

9.3. Edaphoclimatic Conditions and Regionalization of Recommendations

Addressing edaphoclimatic variability and regionalizing technical guidelines represent critical factors for ICLF success, as system performance relies heavily on site-specific climate–soil–management interactions. Soil physical attributes (texture, moisture retention), chemical fertility, and climatic drivers (rainfall distribution, thermal regimes, seasonality) dictate the selection of species, spatial configurations, and management regimes best suited for each environment [46,50]. Uncritical extrapolation of generalized models without local adaptation leads to productive inefficiencies, severe inter-component competition, and financial risks [15]. Recent studies across Latin America stress the necessity of territorial, context-sensitive frameworks to optimize system resilience and productivity [50,195].

In Brazil, scaling up ICLF effectively requires establishing regional management protocols tailored to contrasting biomes, such as the Cerrado, Amazon, South/Southeast, and Semi-arid zones. Structural parameters—including tree density, fertilization regimes, species choices, and pasture management—must be precisely calibrated to local environments. Applying generic packages risks destabilizing inter-component synergies, adversely affecting crop, livestock, and timber yields [15,46]. Conversely, regionalized management protocols optimize resource-use efficiency, climate resilience, and economic returns under sustainable intensification pathways [4,100].

10. Conclusions

Despite the well-documented benefits of ICLF systems, persistent knowledge gaps remain that hinder the full optimization of their potential in tropical environments. Future research must prioritize the evaluation of wood properties and technological behavior across a wider array of spatial arrangements and ICLF configurations, which remain underexplored in the current literature. Furthermore, there is a critical need for long-term, comprehensive studies capable of quantifying complete carbon balances. These assessments must encompass CH₄, N₂O, and CO₂ fluxes alongside biomass and soil carbon dynamics over extended temporal series to accurately determine the net climate mitigation impact of these complex agroecosystems.

To achieve a harmonious balance between productive efficiency and ecosystem resilience, the silvicultural management of the tree component must adhere to integrated design principles:

- Maximizing timber production and quality: Farmers should select high-performing, site-adapted genetic materials and adopt wider initial spacings to accelerate individual stem diameter growth. The implementation of scheduled thinnings and timely pruning operations is essential to suppress branch knots, control pith eccentricity below a 5% threshold, and ensure a high heartwood conversion rate (>50%), which is a strict prerequisite for accessing premium solid wood markets.
- Sustaining crop and pasture productivity: System designs should incorporate wide alleys—a spacing of approximately 30 m has been shown to be adequate—oriented in an east–west direction. Canopy closure must be carefully regulated through thinning interventions to ensure that 60% to 80% of photosynthetically active radiation (PAR) reaches the understory, thereby mitigating shading stress and sustaining both annual crop yields and forage nutritional quality.
- Enhancing CH₄ and N₂O offsetting capacity: The strategic provision of canopy shade is crucial for alleviating heat stress in livestock; this improves animal metabolic efficiency and subsequently lowers the intensity of enteric methane (CH₄) emissions. Additionally, incorporating deep-rooting and leguminous tree species improves soil aeration and biological nitrogen fixation, which enhances synthetic nitrogen-use efficiency and minimizes nitrous oxide (N₂O) losses through leaching and denitrification pathways.

The integration of trees within agricultural landscapes positions ICLF systems as a central pillar in national climate action agendas and international decarbonization initiatives. In Brazil, these integrated land-use models represent a primary technology within the Sectoral Plan for Adaptation and Low-Carbon Emission in Agriculture (ABC+ Plan), directly contributing to national targets for restoring degraded pastures and achieving net-zero carbon goals. Moreover, the dual carbon sink mechanism of ICLF—which combines soil organic carbon stabilization with stemwood biomass accumulation—facilitates robust participation in both voluntary and compliance carbon credit markets. Crucially, aligning these systems with emerging low-carbon certifications, such as the Carbon Neutral Brazilian Beef (CNBB) initiative, underscores the importance of using validated stem carbon stocks to scientifically offset operational and enteric greenhouse gas emissions. In this context, prioritizing the production of sawmill timber fractions is particularly strategic, as these long-lifespan products ensure the secure, long-term storage of sequestered carbon in built structures.

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