

Review

Forage Integration for Sustainable Intensification in Mixed Crop–Livestock Systems: Mechanisms, Trade-Offs and Design Principles

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Abstract

Mixed crop–livestock systems remain central to sustainable intensification because they reconnect feed, biomass, soil cover, livestock productivity, and household livelihoods. However, forage integration benefits are neither automatic nor uniformly transferable across regions. This structured critical integrative review asks when forage integration generates net system-level gains. It also asks when integration merely shifts costs among production, labor, water, nutrients, emissions, household risk, or territorial nutrient balances. The review synthesizes evidence on forage legumes, tropical and temperate grasses, dual-purpose crops, grazed cover crops, pasture rotations, silvopastoral arrangements, and beyond-farm feed–manure exchanges. Examples from the Brazilian Cerrado, western São Paulo, and Minas Gerais illustrate tropical pathways involving *Urochloa/Brachiaria* integration, crop–pasture rotations, crop–livestock–forest systems, and habitat-mediated pest regulation. These examples are interpreted alongside evidence from African, Asian, European, and temperate systems to maintain regional balance. The review contributes a diagnostic framework for assessing system design, evidence strength, and scaling feasibility. The framework links forage portfolios to integration niches, management quality, resource constraints, gendered labor implications, external-input dependency, and adaptive scaling pathways. Forage integration can improve feed quality, animal performance, soil cover, nutrient cycling, biodiversity functions, and emission intensity. These gains require careful management of establishment, grazing, manure distribution, phosphorus and potassium balances, water demand, labor allocation, markets, and governance. Future research should move beyond short-term demonstrations toward causal inference, longitudinal whole-system accounting, transparent evidence-quality grading, and documentation of failed, partial, or discontinued interventions.

Keywords: forage integration (FI); mixed crop–livestock systems; sustainable intensification; nutrient cycling; resilience; ecosystem services; livestock systems; design principles



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1. Introduction

Agriculture must increase food, feed, and income while protecting soil, water, biodiversity, and climate-regulating functions under degradation, climate volatility, and unstable input markets [1,2]. This challenge has intensified the sustainable-intensification debate, whose central test is whether higher output can be achieved without transferring environmental or social costs elsewhere. Mixed crop–livestock systems (MCLS) are central to this debate because they already contain relevant biological and managerial linkages.

These include biomass recycling, manure return, diversified enterprises, and risk buffering [3–5]. Forage integration (FI) is one of the main entry points for strengthening those linkages. Legumes, grasses, cover crops, dual-purpose crops, and multipurpose trees can connect crop and livestock components through feed, soil cover, nutrient cycling, and manure flows. Existing studies show that these practices may improve dietary quality, reduce reliance on synthetic fertilizers, enhance soil functions, and lower greenhouse-gas emission intensity [6–8]. These effects often arise through better nutrient use and improved animal-performance efficiency. However, the same intervention can create trade-offs in residue management, labor demand, water use, manure handling, stocking density, and land opportunity costs. The key question is therefore not whether FI has potential benefits, but when those benefits exceed establishment, management, nutrient-redistribution, and coordination costs.

Recent syntheses have documented mixed crop–livestock integration, sustainable intensification, agroforestry, forage–legume benefits, territorial recoupling, and tropical forage technologies [9–12]. Its narrower purpose is to bridge domains that are often evaluated separately. Agronomic studies often emphasize biomass, feed quality, or short-term soil indicators. Livestock studies commonly emphasize diet and animal performance. Socioeconomic and adoption studies often emphasize labor, tenure, liquidity, gendered income control, seed systems, and extension support. Legumes, perennial grasses, dual-purpose cereals, cover crops, and silvopastoral components differ sharply in establishment risk, water demand, nutrient dynamics, management intensity, and market fit. Treating forages as a single technology therefore obscures the design conditions under which integration succeeds or fails. Recent work on territorial recoupling further shows that integration may occur within farms or among specialized farms and value chains [13–18]. The gap addressed here is diagnostic. The review connects forage function, system scale, management quality, socioeconomic feasibility, and evidence strength when judging sustainable-intensification claims.

This review addresses this diagnostic gap by synthesizing FI as a system-design problem rather than as a catalogue of forage species or production effects. First, it evaluates mechanisms that link FI to feed supply, livestock performance, soil–water functions, nutrient cycling, greenhouse-gas dynamics, biodiversity, livelihoods, and territorial resilience. Second, it identifies forage portfolios and integration niches that align with sustainable-intensification goals under contrasting agroecological and institutional settings. Third, it examines trade-offs, failure modes, and enabling conditions that separate whole-system improvement from isolated technical success. By combining agronomic, livestock, household-economic, and territorial perspectives, the review converts dispersed evidence into practical diagnostic questions. These questions are intended for researchers, extension professionals, and policy actors. The central thesis is that the contribution of FI is best understood as conditional recoupling [19]. Forages contribute to sustainable intensification when they reorganize biomass, nutrients, water, labor, and income flows. These changes must reinforce crop–livestock feedback across time and scale. FI is less convincing when feed or soil-cover gains depend on hidden labor burdens, displaced food production, nutrient concentration, water depletion, or greater exposure to imported inputs [9]. It is also weaker when benefits rely on institutional arrangements that farmers cannot sustain. Trade-offs, management quality, context dependency, and recoupling are treated as established concepts. These ideas are well established in the work of de Faccio Carvalho, Franzluebbbers, Bonaudo, Martin, Bell, Herrero, Thornton, and others [9,10,12,16,19–21]. The added value of this review is to organize these concepts into a forage-specific diagnostic framework as highlighted in Table 1. The framework links portfolio choice, integration niche, implementation quality, evidence confidence, and scaling pathway.

Table 1. Theoretical positioning and contributions of the current review relative to the established literature.

Key Focus Area	Contributions of Prior Literature	Diagnostic Gap Addressed in This Review
Mixed crop–livestock systems [3,4,20]	Reconnects crops, livestock, nutrients, and livelihoods for sustainable intensification.	Identifies how forage portfolios and management quality determine net gains versus displaced costs.
Recoupling & forage circularity [9,10]	Links grazing livestock and crop landscapes to enhance ecosystem services.	Operationalizes recoupling via a forage-specific diagnostic framework with stop/go boundaries.
Tropical forage technologies [11,22]	Outlines productivity and environmental benefits of improved tropical varieties.	Integrates regional risks, socioeconomics, gender dynamics, and territorial scaling.
Agroecological redesign [12,13,16–18]	Explores farm-to-territory integration and principles for system redesign.	Connects macro-level recoupling to micro-level niches, manure logistics, and N-P-K balances.
Adoption & transitions [23–25]	Attributes adoption success to institutional frameworks, labor, and local assets.	Embeds adoption constraints directly into evidence weighting and strategic design.

2. Review Methodology and Analytical Framework

2.1. Review Design and Scope

This study uses a structured critical integrative-review design with an explanatory and diagnostic objective. It identifies mechanisms, boundary conditions, trade-offs, evidence quality, and enabling factors that determine whether FI generates net system-level gains. A formal meta-analysis was not appropriate because the evidence base combines field experiments, long-term system trials, farm surveys, modeling studies, territorial analyses, and conceptual frameworks. These sources use different indicators, time horizons, and units of analysis. The synthesis emphasizes comparative interpretation and decision-oriented design principles rather than pooled effect-size estimation.

2.2. Search Strategy and Information Sources

The evidence base was assembled from the Web of Science Core Collection, Scopus, CAB Abstracts, and AGRICOLA. The search was supplemented by Google Scholar, backward reference screening, and forward citation tracing of influential papers. Database searching was conducted in June 2025–March 2026. The final search update was completed on 31 May 2026. The review prioritized English-language literature published from 2000 onward. Foundational studies were included when they remained conceptually central to crop–livestock integration, forage-based intensification, territorial recoupling, or climate-resilience theory. Search strings combined forage terms, crop–livestock integration terms, and sustainable-intensification outcomes. The representative search used three Boolean blocks. The forage block included “forage integration”, forage*, fodder*, pasture*, “cover crop*”, “dual-purpose crop*”, silvopastor* and “crop–pasture rotation*”. The system block included “mixed crop livestock”, “crop–livestock system*”, “integrated crop livestock” and “crop livestock integration”. The outcome block included “sustainable intensification”, agroecology*, “nutrient cycling”, “soil fertility”, resilience, “resource-use efficiency”, “greenhouse gas*”, mitigation, adoption, and scaling. Additional searches covered forage legumes, tropical grasses, manure recycling, feed-gap analysis, silvopastoral systems, residue allocation, phosphorus and potassium cycling, stocking density, gendered labor, adoption costs and durable use.

2.3. Eligibility, Screening, and Study Selection

Studies were selected for relevance to FI within mixed or functionally integrated crop–livestock systems. Eligible papers had to show how forage components linked enterprises through feed, nutrients, land, labor, markets, or ecosystem-service pathways. Inclusion required explicit relevance to forage, pasture, cover crop, dual-purpose crop, silvopastoral, or feed–manure integration. Sources also had to provide evidence or conceptual analysis linked to at least one system-level outcome. These outcomes included feed supply, livestock performance, soil and water functions, nutrient cycling, greenhouse-gas dynamics, biodiversity, livelihoods, adoption, and scaling. Finally, sources needed enough methodological or contextual information to interpret boundary conditions. Excluded sources addressed stand-alone forage production or feeding with no system-level implication. Papers focused only on monocrop yield without crop–livestock linkage were also excluded, just like opinion pieces without an analytical framework. Studies were excluded when their claims could not be connected to the review’s outcome domains. The final cited evidence corpus contained 163 sources. Each source was assigned one primary evidence-use category in the evidence inventory. The categories were field/system agronomic or livestock studies, soil or biogeochemical process studies, and farm surveys/adoption/economic studies. Other categories were modeling/territorial or decision-support studies and prior reviews/conceptual/policy syntheses. The eligibility criteria applied to evidence selection are detailed in the Supplementary Materials (Table S1), while the operational evidence-quality categories used during interpretation are presented in Table S2. Furthermore, Table S3 outlines the diagnostic trade-off domains and indicators. To contextualize this selection process, Figure 1 presents the evidence-mapping flow and the screening logic utilized for this integrative synthesis.

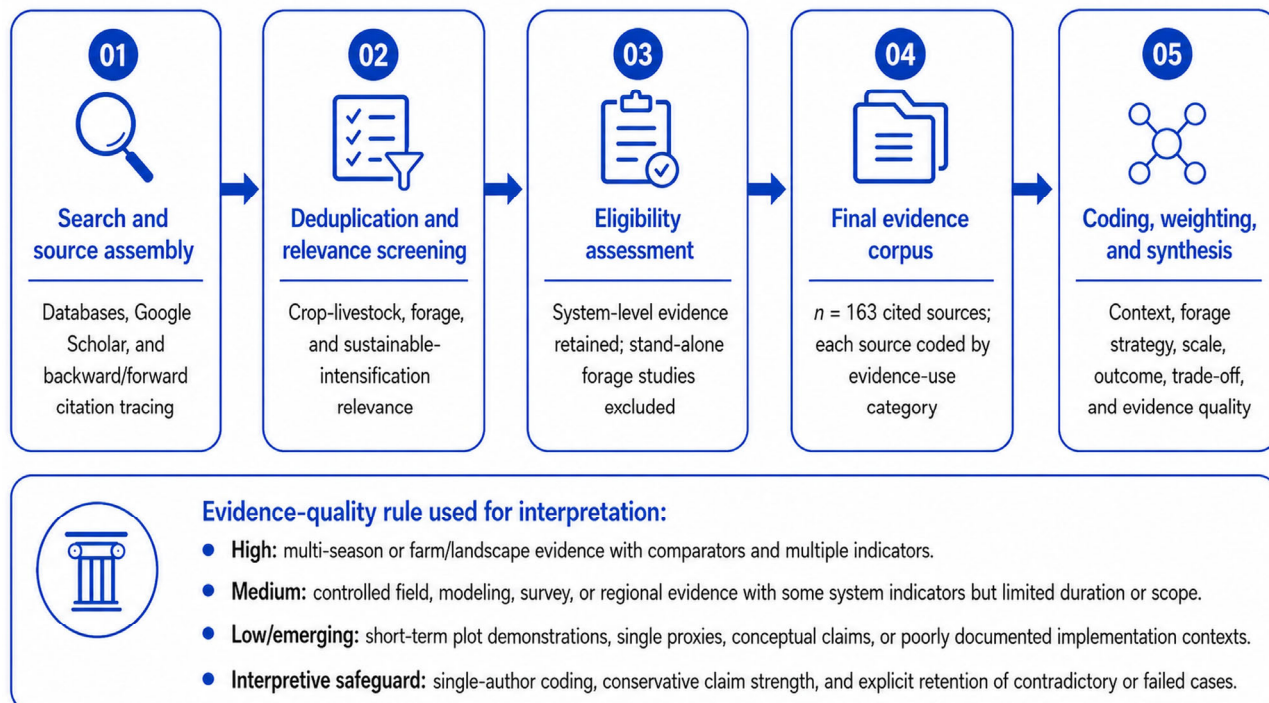


Figure 1. Structured evidence-mapping workflow used to identify, screen, code, weight and interpret evidence in this integrative critical review. The flow reports the final evidence corpus and the evidence-quality rule used for interpretation.

2.4. Coding and Synthesis

Eligible sources were coded across eight analytical dimensions: system context, forage strategy, integration niche, scale of integration, outcome domain, trade-offs or constraints, enabling condition, and evidence quality category. Evidence types were further distinguished by methodology. Categories included short-term field experiments, long-term system trials, farm surveys, adoption and economic studies, modeling studies, territorial analyses, conceptual analyses, and prior reviews. Coding focused on whether each source supported claims about mechanism, performance, adoption, failure, or scaling. The synthesis used a multi-scalar perspective spanning plot, pasture, farm, household, value-chain, and landscape levels. This perspective enabled a critical assessment of systemic interactions. It also helped to avoid interpreting displaced labor, nutrient, water, economic, or environmental burdens as sustainable intensification gains.

2.5. Evidence Weighting

Evidence weighting used a three-level confidence classification. High-confidence evidence referred to findings supported by multi-season or long-term studies, farm- or landscape-scale observations, explicit comparators or counterfactuals, and multiple outcome indicators. Medium-confidence evidence referred to controlled field experiments, modeling studies, surveys, or regional analyses that addressed relevant mechanisms but had shorter duration, narrower spatial coverage, or incomplete socioeconomic accounting. Low or emerging evidence referred to short-term plot demonstrations, single-proxy environmental claims, conceptual arguments, or studies with incomplete implementation details. Important missing details included establishment quality, labor demand, nutrient redistribution, and counterfactual resource use. To limit interpretive subjectivity in screening and coding, eligibility rules, coding dimensions, confidence categories, and inclusion rationales were documented in the supplementary evidence inventory. Broad claims were interpreted conservatively. Conflicting findings were reported where possible, and evidence strength was stated when interpreting major claims. Broad claims were limited to mechanisms supported across more than one evidence type or region. Where controlled experiments and system-level observations diverged, longitudinal and multi-indicator evidence received greater interpretive weight than short-term productivity responses.

2.6. Preparation of Conceptual Figures

Three schematic figures support the review's transparency and synthesis. Figure 1 reports the evidence-mapping flow used to assemble and interpret the corpus. Figure 2 synthesizes the mechanism and outcome domains that structure the system-performance analysis. Figure 3 connects structural drivers, enabling conditions, design choices, learning processes, and outcomes. These figures are explanatory aids rather than inferential evidence, and no causal claims rely on the figures alone.

2.7. Review Limitations

The evidence base has important limitations because methods, indicators, and time horizons vary widely, limiting direct comparison across studies. Geographic coverage is uneven. Mechanistic evidence is stronger for Brazilian and other Latin American systems than for many African, Asian, European, and territorial exchange contexts. Publication bias is likely because positive demonstrations are more visible than failed establishment, discontinued use, or marginal adoption. In addition, this review was not registered as a systematic review and does not provide pooled quantitative estimates of effect size. These directly motivate the diagnostic framing used in this review. Claims about FI are treated as strong only when supported by multi-indicator, multi-season, or system-level evidence.

Strong claims also require explicit attention to land, labor, nutrients, water, external-input dependency, gender equity, and livelihoods.

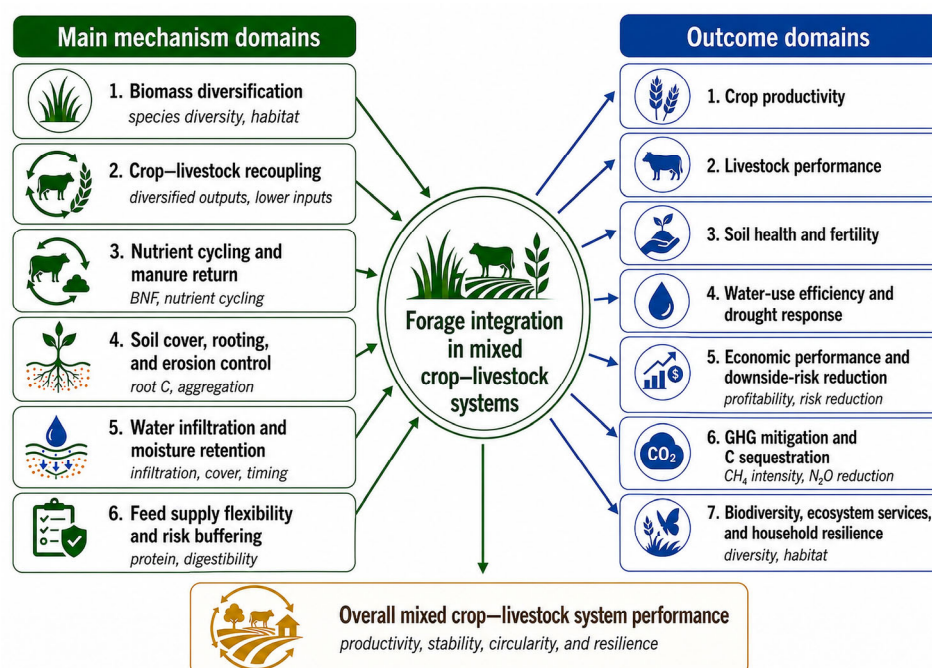


Figure 2. Main mechanism and outcome domains through which forage integration can influence mixed crop–livestock system performance.

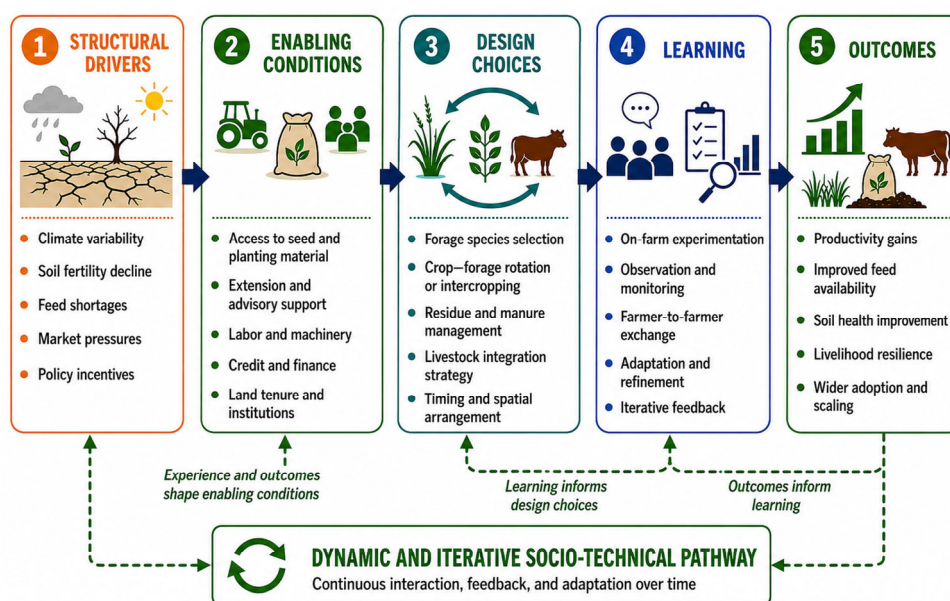


Figure 3. Conceptual sociotechnical pathway for scaling forage integration. The framework illustrates linkages among structural drivers, enabling conditions, design choices, iterative learning and adoption outcomes.

3. Forage Integration in the Sustainable Intensification Debate

Historically, MCLS emerged as integrated configurations where farm performance relied on the tight coupling of crops, animals, labor, and nutrients within relatively closed loops. In these multifunctional systems, livestock provided traction, manure, and the conversion of non-edible biomass into food, while crops supplied grain, residues, and

seasonal grazing niches [15]. Such arrangements fostered substantial adaptive capacity, particularly in regions characterized by variable rainfall and resource scarcity [3,26,27].

The novelty of the present analysis does not rest on the existence of integration itself, since MCLS have long linked crops, animals, labor, and nutrients. The analytical question is how contemporary specialization has weakened crop–livestock feedbacks and where forage-based recoupling can restore them. Specialization has redistributed nutrients, increased dependence on external inputs, and eroded ecological buffers in diversified systems [28–30]. Spatial separation often produces nutrient surpluses in livestock-dense areas and deficits in arable regions, increasing runoff, emissions, and fertilizer dependence [31–33]. FI is therefore important not simply because it adds biomass. It can also rebuild functional connections among feed supply, soil cover, manure return, and livelihood strategies weakened by specialization and policy incentives.

The literature suggests that FI operates across at least three distinct scales, each offering unique pathways for sustainable intensification. At the plot scale, strategies such as intercropping, relay systems, and the use of dual-purpose cereals maximize land-use efficiency through complementary biomass production and enhanced resource capture [21]. At the farm scale, the integration of forage strips, pasture phases, and silvopastoral arrangements optimizes the temporal distribution of feed supply, facilitates soil recovery, and streamlines manure return [34]. Where comprehensive on-farm integration is unfeasible, beyond-farm models restore circularity by establishing functional linkages between specialized agricultural units [35]. These frameworks utilize shared grazing infrastructure and reciprocal feed–manure exchanges to recapture resource loops that are otherwise lost in isolated production systems [14,36,37]. Because the value of these configurations is intrinsically scale-dependent, FI should be viewed as a flexible suite of design choices rather than a standardized technological package.

The functional role of FI is dictated by systemic constraints and environmental contexts. In low-input smallholder systems, it primarily bridges feed gaps, improves protein supply, and supports soil fertility when mineral fertilizers are unaffordable [19,38]. In intensive commercial systems, it can support nutrient recoupling, erosion control, and lower reliance on purchased inputs [10,39,40]. In drought-prone regions, its primary value may be seasonal buffering and risk mitigation [41]. In humid, high-output environments, the emphasis shifts toward nutrient leaching control and year-round ground cover. This context dependency explains why a critical review must evaluate mechanisms and boundary conditions. Average treatment effects alone are insufficient for judging system performance.

Regional evidence reinforces this context-specific interpretation. Comparisons must remain cautious because systems differ in scale, market orientation, climate, labor organization, and policy environment. Across much of Sub-Saharan Africa, farming and livestock are deeply linked within small-scale systems [15,42]. Relevant indicators include seasonal feed gaps, residue allocation, manure access, household labor peaks, gendered control over livestock income, seed availability, and staple-food protection [15,43,44]. In South America, reintegration is often discussed through no-till crop–livestock integration, maize or sorghum intercropped with *Urochloa/Brachiaria* forage grasses. It also includes crop–pasture rotations, crop–livestock–forest systems, and agroecological diversification in perennial crops [45,46]. Cerrado and western São Paulo show that forage grasses can serve as feed resources, soil-cover providers, nutrient recyclers, and biological-structure builders [47–50]. Minas Gerais coffee studies show that cover crops, agroforestry, and non-crop vegetation provide habitat, pollen, nectar, and refugia for natural enemies [51–53]. Accordingly, Brazilian cases illustrate specific tropical crop–forage and perennial-crop diversification mechanisms. They should be compared with, rather than directly applied

to, African smallholder systems, Asian integrated farming systems, or European territorial recoupling arrangements.

Across Asia, integrated farming systems combine crop production, livestock, forestry, aquaculture, and recycling of organic matter across multiple trophic levels [54–56]. Their policy relevance is often linked to livelihood diversification, household nutrition, water management, and resilience under climate variability. This differs from commercial crop–pasture rotation models. In Europe and other highly specialized regions, the emphasis is shifting away from recreating mixed farms. The focus is on rebuilding complementarity among specialized farms and value chains through beyond-farm integration [16–18,35,57]. Persuasive indicators in these settings include feed–manure transport costs, regional N-P-K balances, inter-farm contracts, land-access rules, and territorial governance. These regional differences explain why public-policy indicators must be localized. Smallholder adoption is often driven by feed security and risk reduction. Commercial or specialized adoption may depend more on input prices, nutrient regulation, carbon or biodiversity incentives, and coordination costs.

4. Forage Portfolios, Integration Niches, and Management Quality

Forage portfolios should be understood as functional combinations rather than lists of promising species. Legumes such as *Medicago sativa*, *Vicia* spp., *Lablab purpureus*, *Mucuna* spp., and *Macroptilium atropurpureum* can supply protein, biological nitrogen fixation, and soil-protective cover. Their benefits depend on rhizobia compatibility, phosphorus availability, soil moisture, establishment success, and grazing control [58]. Tropical and temperate grasses such as *Urochloa*, *Megathyrsus maximus*, and *Pennisetum purpureum* provide bulk biomass, persistence, rooting depth, and soil structure benefits. Poor nutrient replacement can still turn high biomass removal into nutrient mining [59]. Dual-purpose cereals, forage brassicas, and cover crops add temporal flexibility where dedicated forage land is scarce [60–62].

Brazilian evidence helps to clarify the functional role of tropical grasses in integrated systems. Its inference is strongest for high input, mechanized, tropical, and subtropical contexts. In maize and sorghum systems, intercropping with forage grasses such as *Urochloa ruziziensis*, *Urochloa brizantha*, and *Megathyrsus maximus* can increase off-season biomass. Grain-production functions can be maintained when management is well synchronized [47]. This supports evaluation of tropical grasses as more than pasture species. In Central and Southwestern Brazilian no-till systems, they also operate as cover crops, nutrient-cycling agents, soil-structure modifiers, and potential feed reserves [63,64]. These advantages depend on row arrangement, sowing time, light competition, fertility management, phosphorus availability, stocking density, and timing of desiccation or grazing.

The central design principle is functional complementarity rather than maximum biomass yield. A high-yield forage may create planting or harvest bottlenecks. In that case, it may be less valuable than a lower-yield but persistent and locally accessible species. Likewise, a high-protein legume may underperform when seed systems are weak, persistence is poor or water demand is high. Robust portfolios therefore combine a protein source, a bulk biomass source, and a seasonal bridging option. This distributes feed, soil-cover, and nutrient functions across the year instead of concentrating them into one fragile component [10,65,66].

Identifying optimal integration niches is foundational to enhancing agroecosystem performance. Consequently, cereal–legume intercropping and relay systems serve as vital, space-efficient strategies, providing both food and feed in resource-constrained environments [34]. Using cover crops and grazed fallows during idle periods helps to capture nutrients, protect the soil, and provide seasonal feed [67]. While rotating crops with pasture

effectively restores soil health and manages grazing, doing so often requires reorganizing land use and ensuring stable land ownership through institutional support [68].

Silvopastoral arrangements further contribute to climate resilience by providing shade, high-quality fodder, and habitat diversification. Their success depends on environmental compatibility, strategic species selection, and regional market demand [44,45]. Brazilian crop–livestock–forest studies show that tree-based integration changes soil quality and resource distribution unevenly across fields. Eucalyptus-based integrated systems in western São Paulo can diversify production and improve soil properties. They still require precise spatial management to limit competition with understory crops for light, nutrients, and water [50].

As shown in Table 2, success or failure of these integration niches depends heavily on management quality. The table presents a matrix of integrated crop–livestock systems (ICLS) against key performance metrics. This framework supports assessment of productivity, environmental health, and economic resilience trade-offs. Success relies on high-quality seed, precise planting schedules, proper soil preparation, and protection from uncontrolled grazing [23,69]. Forage integration improves soil health and nutrient distribution only when grazing pressure, stocking density, residue retention, and manure redistribution are actively managed. Otherwise, it can contribute to overgrazing, compaction, nutrient hotspots, and land degradation [70–72]. Effective FI also relies on hay, silage, grazing infrastructure, water access and storage capacity to bridge feed gaps. Underperformance is often caused by weak management and institutional support rather than by the forage concept alone [73].

Table 2. Agronomic and socioecological taxonomy of integrated crop–livestock systems (ICLS).

Integration Niche	Expected Gains	Key Drivers	Operational Risks & Trade-Offs	Geographic Evidence	Interpretation Guidelines	References
Cereal–legume intercrop	- High grain/fodder yield - Protein enrichment - LER > 1.0	- Niche complementarity - Legume N-fixation - Optimized light use	- Harvest labor peaks - Establishment failure - Moisture competition	Smallholders in Sub-Saharan Africa, South Asia	- Food–feed co-production - Grain stability outweighs fodder volume	[74,75]
Grazed/cut cover crops	- Seasonal feed & soil cover - Nutrient/erosion mitigation	- Biomass cycling - Excreta-driven soil activity	- Wet soil compaction - Water depletion - Termination timing	- Temperate rotations (EU/USA) - Highland mixed systems	- Hydrological effects vary - High fertilizer baselines mask benefits	[70,76]
Crop–pasture rotation	- SOC & structure recovery - Water infiltration	- Perenniality effect - Root soil aggregation - Broken pest/weed cycles	- Lower cash-crop area - Demands tenure security - High capital (fencing/water)	- South American Cerrado - Australasian mixed farms	Captures multi-year resilience over single-season technical gains	[77,78]
Silvopastoral arrangement	- Thermal comfort & habitat - Income (timber/fruit/C)	- Vertical partitioning - Deep-root subsoil use	- Delayed ROI - Management complexity - Canopy light competition	Humid tropical/subtropical livestock (Brazil, Colombia)	Outcomes rely strictly on canopy management and light competition	[79,80]
Beyond-farm exchange	- Regional nutrient coupling - Spatial specialization	- Circular bioeconomy - Spatial decoupling with closed loops	- High logistical costs - Coordination barriers - Uneven wealth dynamics	Specialized regional systems (e.g., France, Denmark)	- Essential for territorial sustainability - Requires policy frameworks	[16–18]

Pragmatically, FI must be conceptualized as a multidimensional innovation bundle comprising species selection, spatial–temporal arrangement, management protocols, and the broader institutional support environment [81]. Analytical frameworks that isolate forage species from their social context tend to overstate technology transferability as

successful adoption depends on combining technical and social factors [82]. Consequently, a critical evaluation must move beyond species introduction to assess shifts in crop phenology, grazing regimes, nutrient cycling, storage capacity, labor dynamics, and extension support.

This complexity is further mediated by regional agroecologies. While tropical and sub-tropical systems often prioritize drought-resilient grasses and cut-and-carry legumes [83], temperate systems emphasize rotational grazing and mechanized forage conservation integrated into broader rotations [66]. Furthermore, a single species' functional role depends on the context. For example, a dual-purpose cereal might act as a drought-resistant emergency backup in one system yet serve as a high-yield foundation in another [84]. To accurately assess FI viability, the conceptualization of “system fit” must transition from a late-stage implementation concern to a primary determinant within the evaluative hierarchy [7,85]. To maximize the synergies within ICLS, it is essential to classify forages based on their specific ecological and agricultural functions. Table 3 offers a functional classification of key forage resources, evaluating their primary agroecosystem roles alongside the management constraints associated with their implementation. This framework serves as a strategic decision-making tool for optimizing forage-based interventions within integrated landscapes.

Table 3. Functional classification of forage resources in integrated systems regarding agroecosystem roles and management constraints.

Forage Functional Group	Primary Agroecosystem Functions	Key Biochemical or Nutritional Metric	Best-Fit Integration Niches	Main Boundary Conditions & Constraints	References
Leguminous forages	Protein supply; biological N-fixation; soil organic matter enrichment.	N-Fixation: Yields 50–300 kg N ha ^{−1} yr ^{−1} ; high crude protein content.	Intercrops, relay systems, protein banks, short-term leys.	Requires specific rhizobia, P/K availability, and establishment moisture; grazing sensitive.	[86–88]
Perennial C ₄ grasses	High biomass; deep rooting for C sequestration; persistent soil cover.	Fiber Dynamics: High NDF/ADF; high water-use efficiency under thermal stress.	Long-term pasture phases; silvopastoral understories; degraded land reclamation.	Risk of nutrient mining if unfertilized; requires intensive grazing to maintain digestibility.	[21,89]
Dual-purpose cereals	Strategic flexibility (grain vs. fodder); energy-dense biomass; bridging feed-gaps.	Harvest Index: Yield trade-off between grain and vegetative biomass quality (ME).	Land-constrained mixed systems, intensive crop rotations, silage production.	Critical harvest timing; grain penalties if grazing extends beyond the “hollow stem” stage.	[62,90,91]
Cover crops & brassicas	Nutrient scavenging; weed suppression; high-digestibility “break” crops.	Nutrient Capture: Reduces nitrate leaching >70%; high non-fiber carbohydrates.	Fallow windows, no-till rotations, winter-finishing systems.	Highly dependent on rainfall windows for establishment and precise termination timing.	[92,93]
Woody perennials	Microclimate regulation (shade); drought-reserve fodder; carbon sequestration.	Secondary metabolites: Tannins or alkaloids impact rumen bypass protein or palatability.	Silvopastoral systems, living fences, plantation-integrated systems.	High initial capital/labor; prolonged return on investment; requires secure land tenure.	[3,94–96]

Effective management extends beyond establishment and includes distribution forage across livestock categories and stockpiling biomass to mitigate seasonal feed deficits. System performance is shaped by the trade-off between forage utilization and soil health [97]. Managers must balance residue extraction, grazing, or disposal with the need to retain organic matter for soil cover, erosion control, carbon inputs, and nutrient cycling [98]. Residue management should therefore be treated as allocation and recycling within the crop–livestock system, not as simple residue competition. Management decisions frequently explain outcome variability. Delayed legume harvests reduce forage quality, overgrazing

compromises soil protection, and uncollected biomass misses an opportunity to address feed deficits [85]. Outcome heterogeneity therefore reflects both management diversity and context-specific resource constraints.

5. Mechanisms Linking Forage Integration to System Performance

The primary mechanism driving system performance through forage integration is the optimization of feed quantity, quality, and temporal availability. In many rainfed MCLS, particularly within smallholder contexts, livestock productivity is often constrained by a reliance on low-quality crop residues during dormant seasons [11,99]. This nutritional bottleneck significantly impairs dry matter intake, lactation, weight gain, and reproductive efficiency, while subsequently reducing manure output [100]. The strategic integration of high-protein or high-digestibility forages directly alleviates these constraints by enhancing dietary density and diversifying feed sources across seasons [99,100]. Furthermore, bioeconomic models show that using a diverse range of forages reduces feed shortages and helps to manage the financial risks of stocking density decisions [19,101].

A secondary, critical mechanism is the recoupling of carbon and nutrient cycles. Forages facilitate the flux of biomass within the MCLS, dictating the spatial and temporal patterns of nutrient fixation, excretion, and sequestration. Leguminous species enhance nitrogen levels through biological nitrogen fixation, which reduces the need for synthetic fertilizers [102,103]. Meanwhile, deep-rooted perennial grasses minimize nutrient leaching during fallow periods by capturing nutrients from deeper soil layers [104]. When livestock are effectively integrated, manure and urine are returned directly to the land, recycling nutrients back into the cropping phase [12]. This system optimizes nutrient supply for crop demand, if storage, transport, and application are managed effectively [10,105,106].

Brazilian research provides mechanistic evidence for this nutrient-recoupling pathway. *Brachiaria/Urochloa* cover crops in no-till Oxisols can improve phosphorus cycling and availability to subsequent soybean crops [49]. This indicates that forage grasses may contribute to nutrient-use efficiency, not only biomass accumulation. Similarly, intercropping maize–*Brachiaria* intercrops can recycle nitrogen to maize and mitigate soil N₂O emissions [48]. Tropical forage grasses can therefore influence both agricultural productivity and greenhouse-gas dynamics in integrated rotations. These findings show that tropical Brazil FI operates through root activity, residue return, nutrient capture, and microbial nitrogen transformations, not simply through additional aboveground feed supply.

A third mechanism involves enhancement of soil physical and hydraulic functions. Elevated root biomass, persistent ground cover, and augmented residue return promote aggregate stability, infiltration, and soil organic matter, thereby increasing resistance to erosion [38]. Pasture or cover crop phases can restore functions within otherwise extractive cropping sequences, especially in degraded systems with chronic tillage and low biomass recycling [45,107,108]. These improvements can strengthen water capture and buffer short-term moisture deficits, but hydrological outcomes remain context dependent. Forage crops can increase transpiration or reduce the subsoil moisture available for the next crop [109]. Net water balance effects depend on rainfall, soil depth, planting time, grazing, and termination.

A fourth mechanism concerns environmental efficiency and climate mitigation. Enhanced dietary quality can significantly reduce methane emission intensity (emissions per unit of milk or meat) by improving digestibility and individual animal performance [8,110,111]. Lowering dependence on synthetic nitrogen cuts industrial emissions and reduces nitrous oxide risks, while certain forage genotypes further manage nitrogen dynamics via biological nitrification inhibition [112,113]. These gains are complemented by improved habitat structure and biological diversity. However, they remain highly

sensitive to stocking densities, nutrient concentration, and the specific metrics used for environmental accounting.

Finally, forage integration reshapes household economics and systemic risk exposure. Stabilizing feed supplies enhances strategic options for dairy intensification, livestock finishing, and herd retention during climatic extremes, allowing producers to capitalize on favorable market pricing. Diversifying outputs across grain, fodder, animal proteins, and ecosystem services reduces vulnerability to single-commodity price volatility or localized climate shocks [15,114,115]. Because market access, gender dynamics, and liquidity constraints shape these benefits [44], MCLS performance is fundamentally a sociotechnical process rather than a strictly biophysical one.

A fundamental mechanism of forage integration involves the enhancement of biodiversity, habitat heterogeneity, and animal welfare. Diversified swards, complex tree–pasture arrangements, and longer soil coverage increase structural complexity, promoting more beneficial insects and soil activity than simplified or degraded pastures [22,116,117]. Within this context, biodiversity is not merely an output but a functional driver of ecosystem stability [118]. Silvopastoral shade serves as a critical buffer against thermal stress, enabling livestock to maintain healthy metabolism and consistent grazing, even in intense heat [119]. These systems balance animal welfare with land-use efficiency, linking improved welfare to stable production [79]. Such an approach is vital for sustainable intensification, as it maintains functional capacity under environmental stress, a factor frequently ignored in traditional, production-centric assessments.

Research led by Venzon and colleagues in Brazilian coffee systems broadens this biodiversity mechanism. In Minas Gerais coffee landscapes, vegetational diversification via cover crops and agroforestry enhances conservation biological control [51]. These diversified systems provide natural enemies with vital microclimatic refugia, alternative prey, and nutritional subsidies. Cover-crop intercropping has been shown to increase biological control in coffee crops, while intercropped plants can serve as reservoirs of predatory mites [52,53]. Although these systems lack consistent livestock integration, they are directly relevant to this review. They illustrate that diversifying forage and cover crops yields ecosystem-service benefits through habitat-mediated pest regulation; an important mechanism frequently overlooked in feed-centric interpretations of FI.

These mechanisms are synergistic and inter-dependent, rather than merely additive. Higher forage digestibility can increase both manure volume and nutrient density, while improved ground cover can enhance water infiltration and forage persistence. Together, these processes stabilize soil structure and support future crops. Consistent animal performance can also stabilize household cash flow, allowing farmers to re-invest in seed, fencing, or other management improvements. Because these elements are linked, whole-system redesign can improve resistance to climate extremes more effectively than isolated technical changes [120]. Piecemeal changes often fail because they leave critical feedback loops disconnected. Figure 2 illustrates the interaction between seasonal feed constraints, forage adoption, soil health, and yield response.

Climate Risk and Forage System Design

Climate risk changes forage-integration performance because drought, flooding, and heat stress affect several processes at once. These processes include establishment, productivity, feed quality, animal welfare, and nutrient cycling. Drought can increase the value of deep-rooted C4 grasses and drought-reserve fodder. It can also suppress biological nitrogen fixation, reduce legume persistence, lower forage crude protein, and intensify water competition with the following crop [21,111,112]. Flooding and waterlogging can reduce root aeration, compromise legume nodulation, and delay planting or termination

of cover crops. Heat stress increases the importance of shade, diversified swards, and silvopastoral arrangements. Thermal comfort affects intake, grazing time, reproduction, and milk or meat output [79,119].

Designing for climate volatility requires matching forage portfolios to rainfall reliability, soil depth, waterlogging risk, heat load, and probable feed deficits. Species should not be selected only for average biomass yield. Climate-resilient portfolios often combine a drought-tolerant biomass source, a locally reliable protein source, and a flexible seasonal bridge. Seasonal bridges may include dual-purpose cereals, grazed cover crops, fodder banks, or conserved forage [19,99,111,120]. These designs should be evaluated with water-balance indicators and economic downside-risk metrics. The same forage that buffers one season may create moisture, labor, or opportunity–cost penalties in another. This climate-risk lens is incorporated into the diagnostic framework in Section 9.

6. Empirical Evidence of Systemic Performance and Productivity Gains

6.1. Productivity Synergies in Feed Supply and Animal Performance

Evidence from multiple regions shows that FI can improve feed supply and animal performance. The magnitude of response depends on baseline resource scarcity, species complementarity, establishment success, and management quality [19,121]. Improved tropical forages often outperform crop residues because higher-quality grasses and legumes increase dry-matter intake and animal productivity [11,60]. In Sub-Saharan systems, this can support grain–stover synergies when forages reduce pressure on residues and improve nutrient recycling [11]. In South America, diversified crop–pasture and silvopastoral systems often outperform simplified systems in herbage accumulation and animal weight gain. The results still depend on stocking control, pasture management and input availability [45,122]. Central and Southwestern/Southeastern Brazil provide strong empirical evidence for tropical forage–grain integration. Transferability depends on comparable climate, soil, input, and management conditions. Intercropping maize and sorghum with forage grasses can augment off-season biomass production. When grain crop competition is managed, the practice can improve feed availability, soil cover, and subsequent crop performance [47]. Maize–*Brachiaria* systems further show that one forage component can provide feed or mulch, recycle nitrogen and potentially mitigate soil N₂O emissions [48].

6.2. Environmental Performance and Mitigation Potential

Forage-based systems can improve soil fertility and resource-use efficiency, but environmental performance is highly context dependent [123]. Legume-based forages may improve subsequent crop performance and reduce synthetic-nitrogen demand, if phosphorus, moisture, and management conditions support biological nitrogen fixation [124,125]. Pasture phases and grazed cover crops may increase soil organic matter, aggregate stability, and hydraulic conductivity through biomass return, persistent cover, and rooting effects [126–128]. These benefits are strongest when FI is embedded in a redesign of nutrient flows; they weaken where manure storage, collection, transport, or redistribution is poor [129–131].

Environmental and climate-related claims warrant rigorous scrutiny. Improvements in methane intensity, fertilizer displacement, soil cover, and erosion control are promising. However, many studies rely on proxies or short observation windows rather than whole-farm, counterfactual, or life-cycle accounting [110,111,132]. Some case studies report substantial reductions in warming potential when forage configuration changes the feed base, such as silage-oriented redesigns [133]. Mitigation claims should therefore remain bounded. Robust assessment must include land-use substitution, herd dynamics, manure

concentration, nutrient redistribution, water demand, external input dependency, and associated crop yield effects.

Studies from Brazilian no-till Oxisols also show that the environmental performance depends on nutrient-specific processes. *Brachiaria* cover crops can improve phosphorus-use efficiency in soybean rotations, which is especially relevant in highly weathered tropical soils where phosphorus fixation limits crop productivity [49]. Similarly, *Urochloa*-based systems also use deep root structures to support soil coverage, residue recycling, and nutrient retention. Net performance varies with phosphate and potassium inputs, micronutrient correction, lime use, residue management, rainfall distribution, and biomass accumulation time. Some sustainable-intensification pathways also increase dependence on imported or purchased inputs, including phosphate fertilizers, micronutrients, maize- or soy-bean-based supplementation, fencing, water infrastructure, and mechanized forage conservation. Exposure to currency volatility, geopolitical supply disruptions, or weak local markets can reduce resilience. Higher stocking rates can also concentrate manure and urine in small areas, creating nutrient hotspots even when reuse within the farm system is theoretically possible [130,131,134,135].

6.3. Socioeconomic Dimensions of System Performance

Socioeconomic outcomes are the least uniform and the most revealing of context. Positive gross-margin effects are plausible when FI reduces purchased feed or fertilizer, increases livestock sales, or stabilizes production through drought [15,115]. Continued use depends on whether households can absorb establishment costs, manage added labor, and secure returns from better animal performance [23,24,136]. Comparable economic evaluation should include establishment cost, feed-cost savings, gross margin, labor opportunity cost, downside-risk exposure, input-dependency ratio, and market volatility. Net present value is also needed where perennial investments are involved [114,115]. Benefits are distributed unevenly when cut-and-carry feeding, forage conservation, or manure handling increase labor without improving control over income or assets [25,44]. In many mixed systems, women may supply extra labor for forage harvesting, feeding, watering, or manure management while men retain greater control over cattle sales or cash income [44]. Socioeconomic performance therefore depends on household organization, liquidity, gendered labor and income control, and market access. It does not depend on biophysical response alone.

6.4. Regional Synthesis and the Sociotechnical Conditions for Success

At a broader interpretive level, FI should be treated as a pathway toward potential system improvement. It is not a guaranteed bundle of benefits. Positive outcomes occur when forage options align with feed deficits, crop calendars, rainfall regimes, residue needs, livestock demand, markets, labor capacity, gender safeguards, and institutional support [11,110]. Evidence is weaker when whole-system benefits are inferred from isolated short-term agronomic responses. It is also weaker when establishment, labor, water, nutrient, input-dependency, and market costs are excluded.

Regional comparisons highlight where current research is most compelling:

- Sub-Saharan African mixed systems: Integrating food crops with forage legumes or improved grasses is most persuasive under specific constraints. These include chronic protein deficits, soil fertility depletion, manure scarcity, and intra-annual feed instability [11,128]. Interventions should avoid displacing staple crops or increasing uncompensated labor. Policy indicators should include seasonal feed-gap reduction, residue allocation, manure recovery, seed access, gender-disaggregated labor time, and household food-security protection.

- Latin American systems: Commercial crop–pasture rotations and crop–livestock–forest systems provide robust evidence for whole-farm redesign. This evidence is strongest for soil cover, stocking-rate control, phosphorus and nitrogen cycling, and recoupling of carbon and nutrient flows [45,122]. However, these systems often rely on mechanization, fertilizer correction, lime, fencing, water infrastructure, and market access. Indicators should therefore include input-dependency ratio, P and K balances, manure hotspots, soil cover, land value, and return on investment
- Humid tropical plantations: Integrating livestock, cover crops, forage banks, or habitat-diversifying vegetation under perennial tree crops can intensify land use. It can also support biological control, shade, and income diversification. However, the empirical base remains fragmented and should not be generalized to all mixed systems [51–53,79].
- Temperate and specialized systems: Inter-farm feed–manure exchange, grazed cover crops, and territorial recoupling are increasingly relevant where farms have specialized away from mixed production [16–18,137]. The strongest policy indicators extend beyond animal performance. They include transaction costs, feed transport distance, regional N-P-K balances, inter-farm contract reliability, nutrient regulation, and governance capacity.

Ultimately, forage integration is a sociotechnical transition. Its effectiveness requires fitting among technological complexity, climate risk, economic incentives, household labor organization, and community or territorial capacity.

6.5. Incremental Pathways and Methodological Caveats

System performance is often optimized through phased, targeted FI rather than immediate whole-farm conversion [138]. Incremental interventions can reduce risk while allowing producers to test labor requirements, feed value, establishment reliability, and economic returns [23,24,107]. Examples include contour forage strips, dry-season fodder banks, relay legumes, grazed cover crops, and winter forage windows. Larger redesigns should follow only after these factors are understood.

A critical synthesis also reveals important publication and implementation biases. Successful demonstrations are more visible than failed establishment, discontinuation, low persistence, or partial adoption [139]. Many reported gains come from research stations or well-supported pilot settings with stronger management than typical farms. This is especially important in smallholder contexts, where labor, liquidity, land, and seed access are binding constraints [11,24]. For this reason, the review gives greater interpretive weight to evidence that reports implementation quality, counterfactual resource use, and durability across seasons. A comprehensive assessment of ICLS requires the evaluation of production metrics together with biophysical functions, economic risk, territorial resilience, and social equity. Table 4 provides a synthesized overview of these complex dynamics. The framework distinguishes direct biophysical outcomes from socioeconomic mechanisms that govern adoption. Biophysical outcomes include feed production, nutrient cycling efficiency, soil cover, phosphorus and potassium balances, water regulation, biodiversity, and soil carbon. Socioeconomic mechanisms include labor availability, market access, gendered control over income, input dependence, and risk management capacity. By organizing outcomes across environmental, economic, territorial, and social dimensions, Table 4 highlights the synergies and trade-offs needed for policy and management.

Table 4. Multi-dimensional outcome domains of ICLS and critical evaluation of dominant biophysical and socioeconomic mechanisms.

Outcome Domain	Dominant Mechanisms	Suitable Indicators	Spatiotemporal Sensitivity	Common Failure Points in Current Evidence	References
Productivity and feed security	Forage CP/digestibility Biomass gap mitigation Climate buffering	DM yield (t ha ⁻¹) Milk/meat output LER/Feed Gap Index Drought survival %	Seasonal rainfall Intercrop competition Climate extremes	Land reallocation costs Crop water penalties Peak labor bottlenecks	[20,140]
Nutrient circularity	Rhizobia BNF Excreta turnover Residue return synchrony P/K recycling	Soil organic C N-P-K balances/NUE Manure recovery rate Soil aggregate indices	SOC lag time ≥ 5–10 yrs) Stocking density spikes	Manure–crop asynchrony Single-nutrient (N) bias	[141,142]
Hydrological and climate risk	Ground cover protection Root microporosity Surface runoff reduction Canopy shading	Infiltration rate Soil moisture/WUE Water balance deficit Flood survival %	Threshold weather events Extreme droughts Flash floods	Transpiration penalties Intercrop water conflict Drought legume failures	[143,144]
Footprint and biodiversity	Fertilizer substitution CH ₄ intensity reduction Habitat heterogeneity Biological pest control	GWP per product unit N ₂ O/NH ₃ flux Nitrate leaching/connectivity Predator abundance	Herd dynamic cycles Landscape context	Single-proxy bias (SOC-only) Short-term trial timelines	[145,146]
Economics and livelihoods	Risk diversification Input self-reliance Household liquidity Gendered labor splits	Gross margin/NPV/ROI Labor opportunity cost Gendered work hours Input dependency ratio	Short-term cash shocks Peak season constraints	Real adoption expenses Intra-household burdens Regional transaction costs	[147,148]

7. Systemic Trade-Offs and the Determinants of Integration Failure

Explaining outcome variability requires moving beyond a list of benefits. FI succeeds only when biophysical potential, management capacity, household objectives, gender-equitable labor arrangements, market conditions, and institutional support are aligned. When these conditions are missing, the practice may become too difficult to scale. It may also generate water stress, labor bottlenecks, higher food–feed competition, nutrient hotspots, purchased-input dependence, or unequal distribution of income and decisions.

7.1. Resource Competition and Food–Feed Trade-Offs

In land-constrained settings, dedicating area to forage creates direct competition with staple crops, particularly where farm sizes are small and tenure is weak. Integrated systems can improve land-use efficiency and reduce total land demand when intercropping, dual-purpose crops, or crop–pasture rotations raise whole-systems output per unit area: however, this is not automatic. Trade-offs may shift from land area to labor peaks, water demand, delayed cash returns, or land-value pressures in regions where integrated systems increase real estate or rental values [123,133]. Even agronomically superior forages may be rejected if they threaten immediate food security, increase establishment risk, or require labor that households cannot spare [74].

7.2. Socioeconomic Constraints of Labor Elasticity and Managerial Intensity

Forage integration requires precision in planting, weed control, grazing, conservation and manure handling, and these demands often peak during periods of high seasonal labor competition. Forages may therefore fit poorly in resource-poor households unless labor-saving technologies, collective arrangements, or phased adoption are available [149]. Labor effects are also gendered. Cut-and-carry forage, daily watering, stall feeding, and manure handling may increase women's time burdens, while livestock sales and high-value output markets may remain controlled by men. Technical efficacy therefore cannot predict long-term utilization when labor, liquidity, knowledge, and intra-household equity constraints are ignored [23,24,44,136].

7.3. Biogeochemical Imbalances and Hydrological Sensitivity

While crop–livestock integration is praised for circular nutrient economies, these systems are not self-closing. Higher animal densities can cause uneven nutrient distribution, especially in intensive or peri-urban dairy and feedlot-influenced systems [105]. This creates localized manure and urine hotspots. Without strict nutrient budgeting and spatial redistribution, integration may relocate environmental hazards rather than eliminate them. Hazards include nitrate leaching, phosphorus accumulation, potassium imbalance, ammonia volatilization, and nitrous oxide emissions [134,135]. Ground cover can improve infiltration, but increased biomass can also raise evapotranspirative demand. In moisture-limited areas, forages may either buffer drought or intensify crop–water competition, depending on rainfall, rooting depth, termination timing, and the following crop's water demand [45,107].

7.4. Scalability, Climate Volatility, and Institutional Lock-Ins

Scale-dependent effects create further heterogeneity. Plot-level successes may fail when evaluated against household labor pools, input access, or market returns. In contrast, manure-for-feed exchange opportunities may emerge only at landscape or territorial scale [13,16]. Climate volatility can suppress nitrogen fixation, reduce forage quality and disrupt establishment when cash flow is most vulnerable [150]. Institutional lock-ins also create structural barriers to the coordination required for integrated systems. Examples include monoculture subsidies, weak extension coordination, insecure tenure, volatile fertilizer and feed markets, and limited inter-farm governance [44,138]. Table 5 summarizes the main trade-off domains, their likely severity, and the strength of evidence supporting each claim.

Table 5. Qualitative evidence map of major forage-integration trade-offs, severity, and interpretive confidence.

Trade-Off Domain	Primary Mechanisms	Vulnerable Contexts	Risk & Confidence	Critical Indicators	References
Biomass allocation	Forage–grain land competition Grazing vs. soil-cover trade-offs Crop residue depletion	Land-scarce smallholders Conservation agriculture	High risk (high confidence)	Food-grain output Residue-retention rate Soil cover %	[140,151]
Climate exposure	Transpiration spikes Drought/flood vulnerability Establishment failure	Semi-arid zones Shallow soils Waterlogging regions	Medium–high risk (medium confidence)	Soil moisture tracking Water-use efficiency Drought	[152,153]

Table 5. Cont.

Trade-Off Domain	Primary Mechanisms	Vulnerable Contexts	Risk & Confidence	Critical Indicators	References
Input dependence	Manure concentration P/K nutrient mining Machinery costs	Commercialized ICLS Peri-urban dairy units High-output rotations	High risk (high confidence)	Farmgate N-P-K balance Manure recovery rate Nutrient-hotspot maps Input-dependency ratio	[30,154]
Managerial intensity	Cut-and-carry bottlenecks Fencing & handling labor Technical skill limits	Resource-poor households Labor-scarce farms Gendered farming split	High risk (medium confidence)	Gendered work hours Income control metrics Adoption persistence	[155]
Economic scaling	Delayed multi-year ROI High startup expenses Transaction costs	Delayed multi-year ROI High startup expenses Transaction costs	Delayed multi-year ROI High startup expenses Transaction costs	Delayed multi-year ROI High startup expenses Transaction costs	[77,142]

8. Drivers of Adoption and Institutional Pathways for Adaptive Scaling

Adoption is best understood as a managed sociotechnical transition rather than a one-time decision to use a particular forage species [156,157]. The long-term use of FI depends on seed systems, land tenure, credit, extension capacity, gendered labor organization, market outlets, and the perceived reliability of benefits. A technically sound forage option can fail if the enabling environment does not support establishment, learning, conservation, grazing control, and marketing.

8.1. Structural Barriers and the Enabling Environment

Underdeveloped seed systems frequently restrict access to site-adapted germplasm, increasing transaction costs for producers. Furthermore, extension services often operate in silos, focusing on either crops or livestock while neglecting their synergistic interactions. Credit and output markets also remain poorly aligned with the non-linear returns of pasture establishment or the value of soil-protective ecosystem services [158,159]. Mitigating these risks requires robust seed networks, participatory niche identification, and financial products synchronized with seasonal cash flows [23,24].

8.2. Knowledge Systems and Iterative Learning

Because forages are highly sensitive to local agroecology, integration requires iterative experimentation over fixed technological packages. Decision-support systems (DSSs), such as feed-balance tools and forecasting models, allow households to identify feed gaps and align species selection with available labor and land [19,36]. Peer-learning and farmer-to-farmer networks are essential for sharing practical expertise. They help farmers to manage crop establishments during unpredictable rainfall and balance fodder production with food-crop priorities [160].

8.3. Adaptive Scaling and Functional Policy Support

Scaling should be treated as adaptive scaling, meaning that design principles are transferred across landscapes rather than replicated as a uniform species package [139]. Monitoring systems should track actionable indicators such as seasonal feed gaps, milk or live-weight response, residue allocation, manure recovery, soil cover, and establishment failure. They should also track labor peaks, gender-disaggregated labor burden, input-dependency ratio, and N-P-K balances [148]. Policy support works best when it aligns private interests with public benefits. Useful measures include forage seed business sup-

port, cost-sharing for fencing and water infrastructure, stronger inter-farm manure–feed contracts, and rewards for ecosystem services. Relevant services include erosion control, nutrient recycling, biodiversity conservation, and territorial nutrient balance [16,138]. Figure 3 illustrates a pathway linking structural drivers, design choices, and learning, showing that institutional support shapes financial and organizational feasibility alongside technical performance.

Table 6 synthesizes the primary challenges, potential interventions, and broader impacts associated with scaling up integrated forage systems. The framework captures interactions between on-farm technical limits and systemic barriers, including seed availability, policy, finance, labor organization, and territorial coordination. Strategic enabling initiatives should use co-designed, participatory research that aligns agroecological principles with regional economic incentives and equity safeguards.

Table 6. Sociotechnical barriers, strategic enabling responses, and systemic implications for the regional scaling of integrated forage systems.

Barrier or Enabling Domain	Sociotechnical Constraints	Strategic Interventions	Systemic Scaling Implications	References
Seed systems	Germplasm access limits Early-generation seed deficit	Community multiplication Decentralized distribution Quality assurance	Mandates reliable value chains Precludes landscape transitions	[161,162]
Knowledge and extension	Information asymmetry Fragmented advisory services Institutional extension silos	Participatory trials Farmer-to-farmer networks Integrated advisory packages	Extension silos halt transfer Decouples crop–livestock learning	[18,163]
Finance and insurance	High capital intensity Liquidity constraints Delayed perennial ROI	Seasonal credit lines Risk-sharing instruments Bundled climate finance	Requires biological lag calibration Buffers climate investment risks	[164,165]
Land and labor	Food–feed land competition Gendered labor imbalances Insecure land tenure	Intercrop configurations Phased adoption pathways Targeted mechanization	Unaddressed bottlenecks limit scaling Freezes adoption to micro-niches	[166,167]
Coordination	Weak horizontal links Deficient territorial governance Fragmented nutrient flows	Collective storage nodes Manure–feed contract templates Landscape grazing frameworks	Requires beyond-farm governance Drives territorial nutrient loops	[17,142]

Note: Barrier categories follow a sociotechnical transition framework. “Scaling” encompasses both horizontal (geographic) and vertical (institutional/policy) expansion. ROI = return on investment.

9. Diagnostic Framework and Design Principles for Systemic Forage Integration

9.1. Diagnostic and Ecological Principles

The reviewed evidence supports a shift from technology-push models toward diagnostic system design. Practitioners should first identify the binding constraint. Possible constraints include protein deficit, seasonal biomass shortage, residue allocation, degraded soil structure, nutrient leakage, phosphorus or potassium imbalance, drought exposure, and heat stress. Other constraints include weak livestock-market linkage, uncompensated labor, gendered income control, and lack of territorial nutrient coordination. The forage portfolio should then address that constraint without creating a larger burden elsewhere. Species and niches should be matched to rainfall, soil fertility, soil depth, waterlogging risk, crop calendars, livestock categories, labor, land tenure, manure logistics, markets,

and finance. Claims of sustainable intensification should follow this diagnostic step, not precede it.

9.2. Sociotechnical and Scalar Principles

A robust design framework requires simultaneous evaluation across multiple outcome domains. Productivity gains must be weighed alongside N-P-K balances, hydrology, biodiversity, labor distribution, household food security, territorial resilience, and economic risk. This is important because soil-health benefits often accrue slowly, while labor requirements and establishment risks appear immediately [168]. Safeguards should include phased forage introduction, protection of household food security, and gender-disaggregated accounting of labor and income control. They should also include nutrient-budgeting plans for manure redistribution and sensitivity analysis for fertilizer, feed, fuel, and seed costs [24,25,44]. The scaling strategy must align with the organizational level of the constraint. Within-farm redesign fits diversified farms, whereas beyond-farm coordination is needed in specialized landscapes where nutrient circularity often requires collective, territorial action [16,137].

These principles are intended as a decision-oriented framework rather than a prescriptive package. Implementation requires attention to required functions, optimal positioning, management, cost responsibility, gender-equitable labor, nutrient redistribution, water-risk thresholds, and effective performance indicators. Diagnostic use of the framework can prevent overgeneralized claims by making functional fitness, trade-offs, implementation quality, evidence strength, and scale explicit.

These principles are not a one-size-fits-all solution. They provide a structured method for converting a diffuse literature into a decision-oriented framework. The decisive question is not whether to integrate forages in the abstract. It is how to design integration so that crops, livestock, soil, and household objectives improve without shifting costs to another group, resource, or scale [139]. Operationalizing this approach requires site-specific diagnostics. A farm with acute dry-season protein deficits and available family labor requires one type of intervention. A land-scarce farm with severe labor constraints and access to purchased concentrates requires another [23]. This framework helps to identify the appropriate integration form, risks, evidence strength, and institutional support needed before broad-scale implementation.

10. Future Directions and an Agenda for Systemic Evidence

10.1. Causal Inference and Holistic Systems Accounting

The literature is mature enough to move from documenting FI potential toward explaining the contexts, beneficiaries, and mechanisms that generate durable net gains. Stronger causal inference is needed to separate forage effects from management intensity, rainfall, soil fertility, market access, livestock genetics, household labor, and advisory support. Future studies should use longitudinal designs, matched counterfactuals, and whole-system accounting. They should evaluate productivity, N-P-K balances, greenhouse-gas emissions, water, labor, income, gender-equitable outcomes, and risk across multiple seasons.

10.2. Sociotechnical Differentiation and Implementation Quality

A critical knowledge gap concerns how household structure, labor division, gendered and control over livestock income affect biophysical outcomes [25]. Studies often fail to report crucial sociotechnical details. These include who manages adoption, who supplies additional labor, who controls income, how costs are financed, and what institutional support exists. Without this information, the success of pilot programs is difficult to

replicate [157]. Methodological progress requires integration of on-farm experimentation, bioeconomic modeling, and territorial analysis. This combination can anticipate food–feed–labor trade-offs, access economic risk and evaluate how manure-for-feed exchanges alter regional nutrient geographies [19,36,57].

The evidence agenda also requires a harmonized indicator architecture that captures productivity, nutrient circularity, climate footprint, water balance, biodiversity, labor, gender equity, livelihood outcomes, and territorial resilience across multiple seasons. Failure should be treated as analytical evidence rather than as an embarrassment to be excluded. Establishment failure, weak persistence, discontinuation, partial adoption, low returns, input-dependency exposure, and negative trade-offs reveal the boundary conditions under which FI is inappropriate or requires institutional support. Reporting these outcomes would make future recommendations more credible and more useful for policy and practice.

Brazilian tropical and subtropical evidence is best interpreted as bounded design learning, not as a regional template for global adoption. Central Brazilian Cerrado systems and western São Paulo crop–livestock–forest experiments are well suited for testing long-term soil-carbon, nutrient-cycling, stocking-rate, and greenhouse-gas outcomes under commercial-scale mechanized agriculture. Minas Gerais coffee agroecological systems are valuable for understanding how cover crops and non-crop plant diversity regulate pests and beneficial arthropods. These lessons should be compared explicitly with smallholder African feed-gap systems, Asian integrated farming systems, European beyond-farm nutrient recoupling, and temperate grazed-cover-crop systems. Such comparison can clarify which principles are transferable, which are context-bound, and which policy indicators are most persuasive in each region.

The evidence agenda requires a more rigorous, harmonized indicator architecture that captures productivity, nutrient circularity, climate footprints, economic risk, water balance, and equity across multiple seasons. Crucially, research must reframe discontinuation and partial adoption, often dismissed as attrition, as vital evidence of systemic constraints [139]. Understanding why producers reduce forage area or shift management strategies, such as moving from grazing to cut-and-carry systems, is as informative as documenting high-performing cases. By linking forage decisions to resilience, ecosystem services, household economics, and territorial coordination, future work can evaluate forage integration as a comprehensive sustainable-intensification strategy rather than a narrow feeding intervention.

11. Conclusions

Forage integration is a credible but conditional pathway for sustainable intensification in MCLS. It works best when it functions as targeted recoupling rather than simple biomass addition. The evidence synthesized here shows that FI can improve feed quality, seasonal feed supply, livestock productivity, soil cover, nutrient cycling, biodiversity functions, and emission intensity. These gains depend on functional fit, management quality, water availability, climate risk, labor capacity, gender-equitable benefits, manure redistribution, P and K balance, market, inputs, and institutions. The same intervention can create net benefits in one setting and displaced costs in another.

The main contribution of this review is therefore to reposition FI as a diagnostic system-redesign strategy. The framework links forage portfolios, integration niches, mechanisms, trade-offs, evidence strength, climate risk, economics, gendered labor, and adaptive scaling. It helps to distinguish genuine agroecological synergies from short-term or narrow gains. This contribution is best understood as a synthesis of diagnostic principles derived from mature literature. It is not a claim that recoupling, trade-offs, or context dependency are newly discovered concepts.

In conclusion, forage-based sustainable intensification requires rigorous research and pragmatic policy. Future research should prioritize longitudinal whole-system accounting, robust causal inference, and transparent reporting of implementation failures and quality metrics. Policy frameworks should support context-specific integration through reliable seed systems, risk-sharing finance, nutrient budgeting, gender-sensitive extension, climate-risk planning, and tenure-sensitive territorial coordination. Stakeholders can secure defensible, long-term benefits by resolving clear system bottlenecks and evaluating outcomes across the crop–livestock–household–territory nexus.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16151647/s1>, Table S1. Eligibility criteria applied to evidence selection; Table S2. Operational evidence-quality categories used in interpretation; Table S3. Diagnostic trade-off domains and indicators.

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Abbreviations

The following abbreviations are used in this manuscript:

FI	Forage integration
ICLS	Integrated crop–livestock systems
IFS	Integrated forage systems
MCLS	Mixed crop–livestock systems
ROI	Return on investment

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