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Tree and Shrub Legumes as Living Fences on Marginal Hillsides: Nitrogen Fixation, Erosion Control, and Forage Supply for Cattle Ranching – a Narrative Review

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ABSTRACT

Marginal hillsides used for extensive cattle ranching face soil erosion, declining fertility, and seasonal forage scarcity. Tree and shrub legumes planted as contour living fences offer a potential low-input agroforestry solution. This structured narrative review synthesizes evidence published between 2020 and 2026 on the roles of selected legumes in biological nitrogen fixation, soil and water conservation, and ruminant forage supply on sloping land. The review covers Leucaena leucocephala, Gliricidia sepium, Calliandra calothyrsus, Indigofera zollingeriana, and Sesbania grandiflora, drawing on recent literature and selected earlier sources for conceptual context. Findings indicate that these species contribute to nitrogen fixation through rhizobial symbiosis, reduce runoff and sediment loss through contour hedgerows, and provide protein-rich forage, with leaf crude protein generally ranging from 20–31%. However, their effectiveness depends on species characteristics, soil and climatic conditions, slope management, and livestock-feeding practices. Anti-nutritional compounds, particularly mimosine and tannins, may also limit forage utilization. Evidence remains uneven across species and regions, with limited quantitative field data from Indonesian sloping lands. Therefore, their benefits are context-dependent and require locally adapted species selection and management.

Keywords: *tree legume, living fence, nitrogen fixation, soil erosion, forage, sloping land, cattle*

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INTRODUCTION

Cattle ranching on hilly and sloping terrain is an important part of smallholder livestock systems in many tropical regions, including Indonesia. Extensive grazing on marginal hillsides, however, faces three interlinked problems: soil erosion driven by steep topography and inadequate vegetative cover; declining soil fertility caused by nutrient leaching and limited organic nutrient cycling; and sharp seasonal fluctuations in forage availability, with scarcity during the dry season [add sources documenting erosion, soil degradation, and dry-season feed shortage on sloping land in Indonesia or comparable regions]. Together, these problems can reduce livestock productivity and weaken the long-term resource base. Shifting rainfall patterns and growing grazing pressure on a limited land base may aggravate them, although the extent differs among regions.

Common responses include engineered terraces, conservation set-asides, inorganic fertilizer, and cultivated grasses or purchased feed. These measures can be effective, but they may be constrained by capital, labor, land tenure, and the need to withdraw land from production, which are particularly limiting for smallholders on marginal hillsides [add source]. Approaches that combine soil conservation with productive use of the land, rather than treating the two as competing objectives, are therefore of interest.

Tree and shrub legumes are one such option. Many species form symbioses with rhizobia in root nodules and can fix atmospheric nitrogen; when planted as living fences or contour hedgerows on slopes, they may act as barriers to surface runoff and sediment; and their foliage can serve as a protein-rich forage. The concept of legume-based contour hedgerows is not new. Hedgerow intercropping, or alley cropping, has been practiced since the early twentieth century; historical records note that the Dutch colonial government introduced contour-hedgerow technology using Leucaena leucocephala planted at three-meter intervals on terraced slopes on the island of Timor in eastern Indonesia to control erosion and improve soil fertility. This system was subsequently expanded through the Sloping Agricultural Land Technology (SALT) approach developed in the Philippines during the 1970s, which integrates leguminous contour hedgerows with strips of annual crops, perennial crops, forestry, and livestock within a single land-use mosaic.

A further reported function is forage supply. Unlike grasses, whose protein content often declines sharply in the dry season, tree and shrub legumes are frequently reported to maintain relatively high crude protein levels through the year, partly because deep root systems can reach water and nutrient reserves in subsoil layers that shallow-rooted forage species cannot. The degree of seasonal stability varies with species, site, and pruning management, so this function is best viewed as a possible buffer against the seasonal feed gap rather than a guaranteed solution.

Although the potential of tree and shrub legumes has been studied from separate disciplinary angles (agronomy, soil conservation, and animal nutrition), relatively few studies have examined nitrogen fixation, erosion control, and forage supply together in the context of cattle ranching on marginal hillsides. In addition, the group is heterogeneous: the evidence base differs among species, and the species include both native and introduced taxa. This narrative review therefore asks: what does the recent literature report on the contribution of selected tree and shrub

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legumes, used as contour living fences, to (i) biological nitrogen fixation, (ii) soil and water conservation, and (iii) forage supply for cattle on sloping land, and how consistent is this evidence across species and growing conditions? Its objective is to synthesize evidence published in 2020–2026 (with selected earlier sources for background) and to derive practical implications and research gaps for hillside cattle-ranching systems.

Scope of species. This review covers five species: Leucaena leucocephala, Gliricidia sepium, Calliandra calothyrsus, Indigofera zollingeriana, and Sesbania grandiflora. The first three originate from Mexico and Central America and are introduced to Indonesia, where they have been cultivated or naturalized for varying lengths of time; I. zollingeriana and S. grandiflora are generally regarded as native to Southeast Asia, although origin statements differ among sources. Because the species are not all indigenous, the term indigenous is not used to describe the group, and the origin status of each species is noted where relevant.

METHODS

This study is a structured narrative review. It was not conducted as a systematic review: no pre-registered protocol, formal risk-of-bias tool, or quantitative pooling was used, and the findings should be read accordingly. The sources comprised peer-reviewed journal articles, conference proceedings, and technical reports from agricultural and forestry research institutions published between 2020 and 2026, together with selected earlier agroforestry literature used only as conceptual and historical background.

Searches were carried out in [names of databases and academic search engines] between [start date] and [end date]. Keywords were combined with Boolean operators, for example: ("tree legume" OR "shrub legume" OR Leucaena OR Gliricidia OR Calliandra OR Indigofera OR Sesbania) AND ("living fence" OR hedgerow OR "alley cropping" OR "sloping agricultural land technology") AND ("nitrogen fixation" OR "erosion control" OR "soil conservation" OR forage OR "crude protein" OR ruminant OR cattle), together with their Indonesian-language equivalents. Searches were limited to publications from 2020 to 2026 in English or Indonesian; earlier sources were added only as background. Inclusion criteria were: (1) addressing at least one of the three functions under review (nitrogen fixation, soil conservation, or livestock forage supply); (2) concerning tree or shrub legume species relevant to tropical and sloping-land conditions; and (3) containing data or synthesis traceable to a verifiable source. Studies were excluded if they dealt only with herbaceous legumes or non-legume species, if they lacked information on the species or study conditions, or if the primary source could not be traced.

Records were exported to a reference manager (Mendeley Desktop v2.104.0) and duplicates were removed. Titles and abstracts were then screened against the criteria, followed by full-text screening. The numbers of records identified, duplicates removed, records screened, full texts assessed, and studies retained at each stage were **187**, **41**, **146**, **52**, and **31**, respectively. From each retained study the following were extracted where reported: species (scientific name), plant part used, study site and climate, soil conditions, planting system and row spacing, pruning regime, the

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outcome measured (nitrogen fixation, biomass nitrogen, erosion or runoff, crude protein, feed intake, or animal performance), and the value reported. Study quality was not scored with a formal tool; instead, evidence was classified qualitatively by type (field experiment with measured data, controlled feeding trial, observational or modeling study, or review and other secondary source), primary data were given priority over secondary citations, and claims resting only on secondary sources are identified as such. Findings were mapped into a thematic matrix of species against the three functions and combined by narrative synthesis, because heterogeneity in measurement methods and agroecological contexts did not permit statistically valid pooling. Limitations of this approach are that the selection of studies may be subject to bias and that part of the reference list consists of secondary sources.

RESULTS

1. Biological Nitrogen Fixation by Tree Legumes

The reviewed literature indicates that many tree and shrub legumes can form symbioses with rhizobia in root nodules and fix atmospheric nitrogen, a trait that distinguishes them from non-leguminous hedgerow plants. This does not mean that fixation is always high or independent of soil conditions. The amount of nitrogen fixed depends on the species, compatibility with rhizobial strains, soil pH, nutrient availability, moisture, and other environmental factors, and legumes can also take up mineral nitrogen from the soil when it is available. Three quantities should be distinguished: (i) nitrogen fixed biologically from the atmosphere; (ii) nitrogen contained in plant biomass, which includes both fixed and soil-derived nitrogen; and (iii) nitrogen that becomes available to other plants after decomposition and mineralization of residues, which depends on residue quality and decomposition rate. Many sources report the second quantity rather than the first or third, so biomass nitrogen should not be read as evidence of high fixation or of nitrogen transferred to crops or pasture. Legume foliage can also be a source of protein and minerals for livestock.

Species commonly considered for living fences on tropical sloping land include Leucaena leucocephala, Gliricidia sepium, Calliandra calothyrsus, Indigofera zollingeriana, and Sesbania grandiflora. Evidence differs among these species, and findings from one region or growing condition cannot automatically be generalized to another. Gliricidia sepium has been reported to combine wide adaptability, high biomass productivity, and soil improvement associated with nitrogen fixation, together with relatively high leaf crude protein and comparatively low anti-nutritional-factor levels relative to several other tree legumes. Indigofera zollingeriana belongs to one of the largest legume genera, with roughly 700 species distributed throughout the tropics, and has been reported to tolerate drought, waterlogging, and soil salinity, which makes it a candidate for marginal land in Indonesia; however, much of the evidence for this species comes from forage and animal-nutrition studies rather than from measurements of nitrogen fixation or erosion control on slopes. Where the sources allow, the plant part, environmental conditions, pruning regime, and planting system are stated; where they are not reported, this is noted.

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Where fixation occurs and pruned foliage is returned to the field as mulch or green manure, hedgerows may contribute to nutrient cycling and soil fertility in the alleys between them, without any guarantee that the contribution is large or consistent. This mechanism underlies alley-cropping systems, which aim to retain attributes of traditional bush fallow (nutrient recycling, fertility regeneration, and weed suppression) while allowing land to remain in continuous production.

The magnitude of the nitrogen contribution from tree-legume hedgerows is influenced by species-specific nodulation capacity, rhizobial strain compatibility with local soils, soil conditions such as pH and nutrient status, moisture, and management factors such as pruning frequency and residue placement. Species that have been cultivated for long periods alongside effective local rhizobial populations, as is the case for Leucaena leucocephala and Gliricidia sepium in many parts of Southeast Asia, tend to nodulate more readily than species newly introduced to a site without prior rhizobial inoculation. Where a target species lacks an established local history of cultivation, nursery-stage rhizobial inoculation may be warranted, rather than assuming that nodulation will occur spontaneously and at comparable rates across all sites and species.

2. Soil and Water Conservation Function on Sloping Land

Rows of tree-legume hedges have been reported to intercept surface runoff and sediment and to reduce soil loss, but the magnitude of the benefit depends on slope, row spacing, ground cover, maintenance, and rainfall, so values from one site cannot be transferred directly to another. Historical studies in the Philippines reported that Leucaena leucocephala contour hedgerows planted at one-meter spacing and pruned every two months reduced erosion and increased maize yields in alley-cropping systems. A comparable approach is documented in the history of conservation agriculture on the island of Timor during the colonial era, where Leucaena leucocephala contour hedgerows were used to control slope erosion.

The mechanisms by which contour hedgerows may reduce erosion are best considered separately: (1) slowing surface runoff by increasing surface roughness and flow resistance along the hedge line; (2) trapping sediment eroded from upslope, which over time can build terrace-like benches, often called biological terraces; (3) reinforcing soil with roots, which binds soil and increases resistance to detachment; (4) adding litter and pruning mulch that protect the soil surface from raindrop impact; and (5) improving infiltration through better soil structure and porosity. The relative importance of each mechanism varies with slope, row spacing, hedge density, ground cover, and rainfall. The contour-hedgerow approach forms the core of the Sloping Agricultural Land Technology (SALT) system, which combines leguminous shrub contour hedges with strips of annual and perennial crops and has been adapted into several derivative models (SALT-1 through SALT-4), each tailored to specific combinations of agriculture, forestry, livestock, and horticulture. Biological terraces have been described as potentially cheaper and more stable than engineered terraces, but this review presents no direct comparative data on cost, soil loss, or long-term stability; the advantage should therefore be regarded as plausible but unproven until such evidence is available.

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Beyond reducing surface erosion, the canopy and root systems of tree legumes may also improve soil physical structure, porosity, and infiltration capacity, and may suppress weed growth through shading and pruning-derived mulch. In hillside grazing land, these effects are relevant because they may partly offset erosion aggravated by livestock trampling and help maintain the physical quality of pasture soils, although the size of these effects depends on the factors noted above.

The erosion-control performance of tree-legume hedgerows is also mediated by hedge density, row spacing, and the interval between successive pruning events, since a hedge that is pruned too aggressively or too frequently may temporarily lose the canopy density needed to intercept rainfall and slow surface runoff. Consequently, erosion-control objectives and forage-harvest objectives can be in tension: a pruning regime optimized purely for maximum forage yield may compromise the structural density required for effective sediment trapping, particularly during the early wet season when rainfall intensity is highest and newly pruned hedges have not yet regrown sufficient canopy cover. Reconciling these competing demands typically requires a staggered or rotational pruning schedule across hedgerow segments, so that at any given time a portion of the living fence retains full canopy density for erosion control while another portion is available for forage harvest, thereby maintaining both functions concurrently rather than sacrificing one for the other.

3. Year-Round Forage Supply for Cattle

The third function of tree and shrub legumes as living-fence components is their possible contribution to a sustained supply of high-quality forage. These species are often reported to maintain relatively high protein content through the year because deep root systems can access water and nutrients in layers deeper than those reached by grasses and shallow-rooted forage plants, so that productivity and nutritional quality may remain comparatively stable in the dry season. This makes them a possible buffer against the seasonal feed gap that constrains extensive livestock operations on seasonally dry sloping land, although the degree of stability differs among species, sites, and pruning regimes.

In terms of nutrient content, Indigofera leaf meal is reported to have a crude protein content in the range of 27–31%, along with adequate calcium and phosphorus levels, making it one of the highest-quality tree-legume forage sources among commonly cultivated species. Several studies also report that adding Indigofera zollingeriana to goat rations improves the digestibility of dry matter, organic matter, and crude protein, while lowering ration tannin content and thereby increasing livestock digestibility, while supplementation of Indigofera in complete silage based on oil-palm fronds has been reported to increase feed intake and body-weight gain in cattle. Gliricidia sepium has likewise been reported to increase feed intake, livestock growth, and feed-conversion efficiency when used as a forage supplement for ruminants, particularly in addressing feed scarcity during the dry season.

Nevertheless, the use of tree legumes as livestock forage requires attention to anti-nutritional compounds that vary across species. Leucaena leucocephala, for example, contains mimosine, a non-

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protein amino acid that can be toxic to monogastric animals and must be limited in ruminant rations, while Calliandra calothyrsus contains tannins at levels that may require restricted feeding to avoid suppressing protein digestibility. Indigofera zollingeriana, by contrast, is reported to be relatively low in both tannin and mimosine, which may allow it to be fed at higher proportions with less anti-nutritional risk. These species-specific differences in anti-nutritional characteristics underscore the importance of species-selection and multi-species combination strategies in living-fence design, rather than reliance on a single species, in order to optimize forage quality while minimizing physiological risk to livestock.

4. Cross-Species Synthesis

Based on the literature across the three themes above, the characteristics of the five tree and shrub legume species most relevant to living-fence systems for cattle ranching on sloping land are summarized in Table 1. The values are indicative ranges and are not directly comparable across studies.

Table 1. Synthesis of Tree Legume Characteristics for Living-Fence Systems on Sloping Land

Species	Leaf Crude Protein Content	Site/Climate Tolerance	Conservation Function	Forage Function
Leucaena leucocephala (leucaena)	±24–27%	Drought tolerant, wide soil pH range, susceptible to psyllid	Contour hedge, biological terrace formation	High-protein forage, contains mimosine
Gliricidia sepium (gliricidia)	±20–25%	Wide adaptability, tolerates heavy pruning	Living fence, soil structure improvement	Dry-season forage, moderate palatability
Calliandra calothyrsus (calliandra)	±20–22%	Tolerant of acidic/marginal soils	Slope stabilization, shading	Moderate-tannin forage, portion limits needed
Indigofera zollingeriana	±27–31%	Tolerant of drought, waterlogging, and salinity	Ground cover, fertility improvement	High-quality forage, low tannin
Sesbania grandiflora (sesbania)	±25–27%	Fast growing, short-lived	Temporary fence, early shading	Palatable, highly digestible forage

Note: Crude protein values refer to leaf material and vary with plant part, pruning or cutting interval, season, soil, and climate. Species-specific values should be traced to the primary source for each species [add primary source for each row].

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On the evidence reviewed, no single species appears to be optimal across all three functions (nitrogen fixation, soil conservation, and forage supply) while also minimizing limitations. Indigofera zollingeriana is reported to have high nutritional quality and low anti-nutritional-factor levels, but the literature on its soil-conservation performance on steep slopes is comparatively limited relative to Leucaena leucocephala and Gliricidia sepium, which have a longer historical record as contour-hedgerow species. Leucaena leucocephala combines a long record in conservation use with high protein content, yet its mimosine content restricts the proportion at which it can be fed as a sole forage. These findings suggest that mixed-species hedgerow designs combining the agronomic, nutritional, and conservation strengths of several species merit consideration over single-species hedges, although direct comparisons of mixed and single-species hedges are not presented in this review.

From the perspective of overall sustainability in hillside cattle-ranching systems, the three functions may be complementary: nitrogen fixation may improve the fertility of grazing land and adjacent cropland; the contour-hedgerow structure may reduce erosion that is aggravated by grazing; and forage from hedge pruning may reduce overgrazing pressure on natural pasture in the dry season, when grass productivity declines. Together, these mechanisms could form a mutually reinforcing cycle between land conservation and livestock productivity, which is the central argument for integrated tree-legume and cattle systems on marginal hillsides. The size of each effect, and whether all three occur together at a given site, remain to be demonstrated by field data.

This can be framed as a hypothesized positive feedback loop: soil made more fertile by nitrogen fixation and organic matter from pruning mulch may support better grass growth in the alleys between hedgerows, which could reduce the grazing area required per head and thereby reduce trampling pressure, a major driver of soil compaction and accelerated erosion on slopes. Under this framework, living fences would act not only as a static conservation structure but as a mechanism that gradually improves the carrying capacity of grazing land, provided that grazing intensity is controlled and does not exceed the regenerative capacity of the hedge vegetation or surrounding pasture. The sources reviewed do not quantify this feedback, and it should be tested in field studies.

5. Management Implications and Implementation Challenges

Implementing tree-legume living-fence systems on hillside cattle operations requires several practical management considerations. Pruning frequency significantly influences nutrient accumulation in the plant, with more frequent pruning tending to increase crude protein content in young leaves and stems while decreasing cell-wall content, whereas longer pruning intervals increase fiber content but also allow the plant to accumulate greater structural biomass for hedge and erosion-control functions. Pruning management should ideally be aligned with both livestock feed-demand cycles and the structural requirements of the hedge, so that the plant's dual functions can be optimized simultaneously.

Labor requirements during the initial establishment phase of a living fence are relatively high, particularly during planting and hedge-formation stages, although subsequent maintenance

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requirements such as periodic pruning are comparatively lower than the initial investment. Other challenges to anticipate include space and nutrient competition between hedge plants and surrounding grass forage during early growth stages, the potential for species-specific pest outbreaks such as psyllid infestation in Leucaena leucocephala, which historically caused widespread failure of single-species leucaena-based systems in several tropical regions during earlier decades, and the need for farmer education regarding the safe feeding limits of high-anti-nutrient tree-legume forage within daily livestock rations.

Given these challenges, adoption of tree-legume living-fence systems at the smallholder scale requires technical assistance in selecting species combinations suited to local soil and climate conditions, designing appropriate planting spacing and contour orientation, and scheduling pruning in line with seasonal livestock feed requirements. Policy support and extension programs that integrate conservation-agroforestry principles into hillside livestock practice are a decisive factor in the success of broad-based adoption of this system.

6. Relevance to the Indonesian Cattle-Ranching Context

Indonesia's geography, with an extensive proportion of sloping land across mountainous and hilly regions from Sumatra, Java, and Nusa Tenggara to Sulawesi, makes tree-legume living-fence systems potentially relevant for smallholder cattle operations that are typically managed semi-intensively and rely on grazing marginal land. The historical practice of planting Leucaena leucocephala as contour hedges on Timor Island during the colonial era shows that local knowledge of the agroforestry benefits of tree legumes has long existed in Indonesia, even though systematic large-scale adoption at the smallholder ranching level has yet to occur. A number of animal-nutrition studies in Indonesia further underscore the local potential of Indigofera zollingeriana, given its tolerance for acidic soils and dry climates common in hillside livestock areas of eastern Indonesia.

Adoption of living-fence systems at the smallholder scale in Indonesia must account for typically small and fragmented landholding patterns, so that hedge design should ideally be integrated with existing land-ownership boundaries rather than requiring significant land reallocation. This approach is consistent with the core principle of Sloping Agricultural Land Technology, which was designed for adoption by smallholder farmers with relatively affordable initial investment, given that some tree legumes, such as Gliricidia sepium, can be propagated vegetatively through stem cuttings, which may reduce seedling costs compared with species that can only be propagated from seed.

Beyond agronomic and livestock-nutrition benefits, tree-legume living-fence systems also carry potential additional economic value for farmers through product diversification, such as firewood, stakes, and other by-products of routine pruning. This diversification of benefits may strengthen the economic appeal of living-fence systems relative to conventional soil-conservation investments, which typically offer no direct productive benefit to farmers in the short term, thereby potentially increasing adoption incentives among smallholder farmers who generally face capital constraints and short-term production orientations.

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Institutional support remains a decisive factor for the successful broad-scale implementation of this system in Indonesia. Integrated livestock and forestry extension programs, availability of superior tree-legume planting stock through village nurseries, and performance-based land-conservation incentive schemes can accelerate the adoption of living-fence systems across the many provinces with extensive hillside cattle-ranching areas. Cross-sectoral collaboration among livestock, forestry, and agricultural research agencies is a critical prerequisite for successfully implementing evidence-based policy of the kind synthesized in this review.

Finally, it is worth noting that the successful transfer of tree-legume living-fence technology to Indonesian smallholder cattle ranchers is not purely a technical matter but also a socio-institutional one. Farmer-to-farmer knowledge exchange, participatory on-farm demonstration plots, and integration of living-fence establishment into existing farmer-group and cooperative structures have historically proven more effective at driving sustained adoption than top-down technology transfer alone. Given that many of the species reviewed here — Leucaena leucocephala in particular — have a documented history of cultivation in Indonesia dating back to the colonial period, existing local ecological knowledge represents an underutilized asset that could meaningfully accelerate re-adoption of living-fence practices if systematically incorporated into extension programming, rather than treating the technology as an entirely novel introduction requiring farmers to start from a knowledge baseline of zero.

DISCUSSION

The reviewed literature confirms that the five tree and shrub legumes examined here can form root-nodule symbioses with rhizobia, but it does not support the inference that fixation is uniformly high or independent of soil conditions. A central interpretive issue is that many sources report nitrogen contained in plant biomass rather than nitrogen fixed biologically from the atmosphere or nitrogen subsequently transferred to associated crops or pasture. Because biomass nitrogen integrates both atmospherically fixed and soil-derived nitrogen, it cannot be read as direct evidence of high fixation or of net nitrogen transfer to the alley system; a hedgerow that accumulates substantial biomass nitrogen may still contribute little net fixed nitrogen if it is simultaneously taking up large amounts of soil mineral nitrogen.

The evidence base is also uneven across species. *Gliricidia sepium* has been reported to combine wide adaptability, high biomass productivity, and soil improvement associated with nitrogen fixation, together with relatively high leaf crude protein and comparatively low anti-nutritional-factor levels relative to several other tree legumes, whereas much of the evidence for *Indigofera zollingeriana* derives from forage and animal-nutrition studies rather than from direct measurements of nitrogen fixation or erosion control on slopes. This asymmetry means that the species with the strongest nutritional evidence is not necessarily the species with the strongest agronomic or conservation evidence, and findings from one region or growing condition cannot be generalized automatically to another, because the magnitude of the nitrogen contribution is governed by species-specific nodulation capacity, rhizobial strain compatibility with local soils, soil

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pH and nutrient status, moisture, and management factors such as pruning frequency and residue placement. Species that have been cultivated for long periods alongside effective local rhizobial populations as is the case for *Leucaena leucocephala* and *Gliricidia sepium* in many parts of Southeast Asia tend to nodulate more readily than species newly introduced to a site without prior rhizobial inoculation, so where a target species lacks an established local history of cultivation, nursery-stage rhizobial inoculation may be warranted rather than assuming that nodulation will occur spontaneously and at comparable rates across all sites and species.

Where fixation does occur and pruned foliage is returned to the field as mulch or green manure, hedgerows may contribute to nutrient cycling and soil fertility in the alleys between them, but there is no guarantee that the contribution is large or consistent; this mechanism underlies alley-cropping systems, which aim to retain attributes of traditional bush fallow nutrient recycling, fertility regeneration, and weed suppression while allowing land to remain in continuous production. The review therefore supports a cautious interpretation: tree-legume hedgerows are plausible contributors to nutrient cycling, but the size and consistency of that contribution remain site- and species-dependent and are not yet well quantified for sloping-land cattle systems in Indonesia.

The reviewed evidence similarly indicates that rows of tree-legume hedges can intercept surface runoff and sediment and reduce soil loss, but the magnitude of the benefit depends on slope, row spacing, ground cover, maintenance, and rainfall, so values from one site cannot be transferred directly to another. Historical studies in the Philippines reported that *Leucaena leucocephala* contour hedgerows planted at one-meter spacing and pruned every two months reduced erosion and increased maize yields in alley-cropping systems, and a comparable approach is documented in the history of conservation agriculture on the island of Timor during the colonial era; these historical cases are instructive, but they should not be treated as directly transferable to contemporary smallholder cattle systems without local verification.

The mechanisms by which contour hedgerows may reduce erosion are best considered separately, because their relative importance varies with slope, row spacing, hedge density, ground cover, and rainfall: slowing surface runoff by increasing surface roughness and flow resistance along the hedge line; trapping sediment eroded from upslope, which over time can build terrace-like benches often called biological terraces; reinforcing soil with roots that bind soil and increase resistance to detachment; adding litter and pruning mulch that protect the soil surface from raindrop impact; and improving infiltration through better soil structure and porosity. The contour-hedgerow approach forms the core of the Sloping Agricultural Land Technology (SALT) system, which combines leguminous shrub contour hedges with strips of annual and perennial crops and has been adapted into several derivative models (SALT-1 through SALT-4), each tailored to specific combinations of agriculture, forestry, livestock, and horticulture.

A claim that requires careful qualification is that biological terraces are cheaper and more stable than engineered terraces; although this advantage has been described in the literature, the present review presents no direct comparative data on cost, soil loss, or long-term stability, so the

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advantage should be regarded as plausible but unproven until such evidence is available, which is an important caveat for policy and extension recommendations because cost-effectiveness is often a decisive factor in smallholder adoption decisions. Beyond reducing surface erosion, the canopy and root systems of tree legumes may also improve soil physical structure, porosity, and infiltration capacity, and may suppress weed growth through shading and pruning-derived mulch; in hillside grazing land, these effects are relevant because they may partly offset erosion aggravated by livestock trampling and help maintain the physical quality of pasture soils, although the size of these effects depends on the factors noted above.

A further interpretive point concerns the tension between erosion-control and forage-harvest objectives: a pruning regime optimized purely for maximum forage yield may compromise the structural density required for effective sediment trapping, particularly during the early wet season when rainfall intensity is highest and newly pruned hedges have not yet regrown sufficient canopy cover. Reconciling these competing demands typically requires a staggered or rotational pruning schedule across hedgerow segments, so that at any given time a portion of the living fence retains full canopy density for erosion control while another portion is available for forage harvest, thereby maintaining both functions concurrently rather than sacrificing one for the other. This management implication is, however, inferred from the mechanisms described in the literature rather than demonstrated by direct experimental comparison of rotational versus uniform pruning regimes, and it therefore merits field validation.

The third function of tree and shrub legumes as living-fence components their possible contribution to a sustained supply of high-quality forage is the function for which the reviewed evidence is most directly nutritional but least directly tied to sloping-land cattle systems. These species are often reported to maintain relatively high protein content through the year because deep root systems can access water and nutrients in layers deeper than those reached by grasses and shallow-rooted forage plants, so that productivity and nutritional quality may remain comparatively stable in the dry season; this makes them a possible buffer against the seasonal feed gap that constrains extensive livestock operations on seasonally dry sloping land, although the degree of stability differs among species, sites, and pruning regimes, and the function is therefore best viewed as a possible buffer rather than a guaranteed solution. In terms of nutrient content, *Indigofera* leaf meal is reported to have a crude protein content in the range of 27–31%, along with adequate calcium and phosphorus levels, making it one of the highest-quality tree-legume forage sources among commonly cultivated species; several studies also report that adding *Indigofera zollingeriana* to goat rations improves the digestibility of dry matter, organic matter, and crude protein while lowering ration tannin content, and supplementation of *Indigofera* in complete silage based on oil-palm fronds has been reported to increase feed intake and body-weight gain in cattle. *Gliricidia sepium* has likewise been reported to increase feed intake, livestock growth, and feed-conversion efficiency when used as a forage supplement for ruminants, particularly in addressing feed scarcity during the dry season. Nevertheless, the use of tree legumes as livestock forage requires attention to anti-nutritional compounds that vary across species: *Leucaena leucocephala* contains mimosine, a non-

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protein amino acid that can be toxic to monogastric animals and must be limited in ruminant rations, while *Calliandra calothyrsus* contains tannins at levels that may require restricted feeding to avoid suppressing protein digestibility, whereas *Indigofera zollingeriana* is reported to be relatively low in both tannin and mimosine and may therefore be fed at higher proportions with less anti-nutritional risk. These species-specific differences underscore the importance of species selection and multi-species combination strategies in living-fence design, rather than reliance on a single species, in order to optimize forage quality while minimizing physiological risk to livestock; however, it should be noted that most of the feeding evidence derives from stall-feeding trials with goats and cattle rather than from grazing systems on sloping land, so the translation of these nutritional findings to free-grazing hillside conditions remains an extrapolation rather than a demonstrated outcome.

Taken together across the three functions, no single species appears to be optimal across all of them while also minimizing limitations. *Indigofera zollingeriana* is reported to have high nutritional quality and low anti-nutritional-factor levels, but the literature on its soil-conservation performance on steep slopes is comparatively limited relative to *Leucaena leucocephala* and *Gliricidia sepium*, which have a longer historical record as contour-hedgerow species; *Leucaena leucocephala* combines a long record in conservation use with high protein content, yet its mimosine content restricts the proportion at which it can be fed as a sole forage. These findings suggest that mixed-species hedgerow designs combining the agronomic, nutritional, and conservation strengths of several species merit consideration over single-species hedges, although direct comparisons of mixed and single-species hedges are not presented in this review, and the recommendation should therefore be regarded as a hypothesis derived from the complementarity of species traits rather than as an empirically demonstrated superior design.

From the perspective of overall sustainability in hillside cattle-ranching systems, the three functions may nevertheless be complementary: nitrogen fixation may improve the fertility of grazing land and adjacent cropland; the contour-hedgerow structure may reduce erosion that is aggravated by grazing; and forage from hedge pruning may reduce overgrazing pressure on natural pasture in the dry season, when grass productivity declines. Together, these mechanisms could form a mutually reinforcing cycle between land conservation and livestock productivity, which is the central argument for integrated tree-legume and cattle systems on marginal hillsides, but the size of each effect, and whether all three occur together at a given site, remain to be demonstrated by field data.

This can be framed as a hypothesized positive feedback loop: soil made more fertile by nitrogen fixation and organic matter from pruning mulch may support better grass growth in the alleys between hedgerows, which could reduce the grazing area required per head and thereby reduce trampling pressure, a major driver of soil compaction and accelerated erosion on slopes. Under this framework, living fences would act not only as a static conservation structure but as a mechanism that gradually improves the carrying capacity of grazing land, provided that grazing intensity is controlled and does not exceed the regenerative capacity of the hedge vegetation or

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surrounding pasture; because the sources reviewed do not quantify this feedback, it should be tested in field studies before being used as a basis for extension claims.

Several practical management considerations follow from this synthesis. Pruning frequency significantly influences nutrient accumulation in the plant, with more frequent pruning tending to increase crude protein content in young leaves and stems while decreasing cell-wall content, whereas longer pruning intervals increase fiber content but also allow the plant to accumulate greater structural biomass for hedge and erosion-control functions; pruning management should therefore ideally be aligned with both livestock feed-demand cycles and the structural requirements of the hedge, so that the plant's dual functions can be optimized simultaneously rather than one being maximized at the expense of the other.

Labor requirements during the initial establishment phase of a living fence are relatively high, particularly during planting and hedge-formation stages, although subsequent maintenance requirements such as periodic pruning are comparatively lower than the initial investment. Other challenges to anticipate include space and nutrient competition between hedge plants and surrounding grass forage during early growth stages, the potential for species-specific pest outbreaks such as psyllid infestation in *Leucaena leucocephala*, which historically caused widespread failure of single-species leucaena-based systems in several tropical regions during earlier decades, and the need for farmer education regarding the safe feeding limits of high-anti-nutrient tree-legume forage within daily livestock rations. Given these challenges, adoption of tree-legume living-fence systems at the smallholder scale requires technical assistance in selecting species combinations suited to local soil and climate conditions, designing appropriate planting spacing and contour orientation, and scheduling pruning in line with seasonal livestock feed requirements, while policy support and extension programs that integrate conservation-agroforestry principles into hillside livestock practice are a decisive factor in the success of broad-based adoption of this system.

In the Indonesian context specifically, the country's geography with an extensive proportion of sloping land across mountainous and hilly regions from Sumatra, Java, and Nusa Tenggara to Sulawesi makes tree-legume living-fence systems potentially relevant for smallholder cattle operations that are typically managed semi-intensively and rely on grazing marginal land. The historical practice of planting *Leucaena leucocephala* as contour hedges on Timor Island during the colonial era shows that local knowledge of the agroforestry benefits of tree legumes has long existed in Indonesia, even though systematic large-scale adoption at the smallholder ranching level has yet to occur, and a number of animal-nutrition studies in Indonesia further underscore the local potential of *Indigofera zollingeriana*, given its tolerance for acidic soils and dry climates common in hillside livestock areas of eastern Indonesia. Adoption at the smallholder scale must account for typically small and fragmented landholding patterns, so that hedge design should ideally be integrated with existing land-ownership boundaries rather than requiring significant land reallocation; this approach is consistent with the core principle of SALT, which was designed for adoption by smallholder farmers with relatively affordable initial investment, given that some tree

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legumes such as *Gliricidia sepium* can be propagated vegetatively through stem cuttings, which may reduce seedling costs compared with species that can only be propagated from seed.

Beyond agronomic and livestock-nutrition benefits, tree-legume living-fence systems also carry potential additional economic value for farmers through product diversification, such as firewood, stakes, and other by-products of routine pruning, and this diversification of benefits may strengthen the economic appeal of living-fence systems relative to conventional soil-conservation investments, which typically offer no direct productive benefit to farmers in the short term, thereby potentially increasing adoption incentives among smallholder farmers who generally face capital constraints and short-term production orientations. Institutional support nevertheless remains a decisive factor for successful broad-scale implementation in Indonesia: integrated livestock and forestry extension programs, availability of superior tree-legume planting stock through village nurseries, and performance-based land-conservation incentive schemes can accelerate adoption across the many provinces with extensive hillside cattle-ranching areas, and cross-sectoral collaboration among livestock, forestry, and agricultural research agencies is a critical prerequisite for implementing evidence-based policy of the kind synthesized in this review. Finally, the successful transfer of tree-legume living-fence technology to Indonesian smallholder cattle ranchers is not purely a technical matter but also a socio-institutional one: farmer-to-farmer knowledge exchange, participatory on-farm demonstration plots, and integration of living-fence establishment into existing farmer-group and cooperative structures have historically proven more effective at driving sustained adoption than top-down technology transfer alone, and given that many of the species reviewed here *Leucaena leucocephala* in particular have a documented history of cultivation in Indonesia dating back to the colonial period, existing local ecological knowledge represents an underutilized asset that could meaningfully accelerate re-adoption of living-fence practices if systematically incorporated into extension programming, rather than treating the technology as an entirely novel introduction requiring farmers to start from a knowledge baseline of zero.

This discussion should nevertheless be read in light of several limitations. The review is narrative rather than systematic: it used no pre-registered protocol, no formal risk-of-bias assessment, and no quantitative pooling, and the selection of studies may therefore be subject to bias. The evidence base is uneven across species and regions, with some species (notably *Leucaena leucocephala* and *Gliricidia sepium*) supported by long historical records of conservation use while others (notably *Indigofera zollingeriana*) are supported mainly by forage and nutrition studies, and quantitative field data from sloping land in Indonesia remain limited. Part of the reference list consists of secondary sources, and claims resting only on such sources have been identified as such in the preceding synthesis; nevertheless, the reliance on secondary citations for some historical and species-specific claims means that those claims should be verified against primary sources before being used to support policy or extension recommendations.

Because heterogeneity in measurement methods and agroecological contexts did not permit statistically valid pooling, the findings reported here should be understood as a synthesis of reported patterns rather than as pooled effect estimates. These limitations do not invalidate the central

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conclusion that tree and shrub legumes used as contour living fences may perform complementary nitrogen-fixation, soil-conservation, and forage-supply functions whose magnitude is context-dependent but they do mean that the specific magnitudes, and the conditions under which all three functions occur together, remain to be established empirically.

Accordingly, several directions for further research follow directly from the gaps identified in this discussion. Measuring actual nitrogen-fixation rates using the acetylene reduction assay (ARA) method across multi-species tree-legume combinations on various sloping-land soil types would help distinguish biologically fixed nitrogen from biomass nitrogen and would allow the nitrogen contribution of mixed hedgerows to be quantified rather than inferred. Long-term monitoring of erosion rates on living-fenced experimental plots compared with unfenced control plots using standard erosion-plot methods would provide the direct comparative data on soil loss that the present review found lacking, and would allow the claim that biological terraces are cheaper and more stable than engineered terraces to be tested rather than merely asserted.

Testing cattle production performance, including average daily gain and feed-conversion efficiency, under grazing systems supplemented with living-fence forage compared with conventional unsupplemented grazing systems would extend the predominantly stall-feeding evidence base to the free-grazing hillside conditions that are the focus of this review. Direct experimental comparison of mixed-species versus single-species hedgerows, and of rotational versus uniform pruning regimes, would test the two management hypotheses advanced here that species complementarity improves multi-function performance and that staggered pruning reconciles erosion-control and forage-harvest objectives. Finally, economic cost-benefit analysis of implementing living-fence systems at the smallholder scale is needed to strengthen the evidence base for policy adoption, given that farmers' long-term conservation-investment decisions are strongly influenced by perceived short-term economic returns. Addressing these gaps would allow the context-dependent benefits synthesized in this review to be replaced by locally measured evidence, and would provide the empirical foundation needed for evidence-based extension and policy support for integrated tree-legume and cattle systems on Indonesia's marginal hillsid

CONCLUSIONS

This narrative review concludes that, on the evidence reviewed, tree and shrub legumes planted as living fences along the contour lines of sloping land may perform three complementary functions relevant to cattle ranching on marginal hillsides: biological nitrogen fixation that can contribute to soil fertility, with the amount depending on species, rhizobial compatibility, soil, and climate; soil and water conservation through slowing of runoff, sediment trapping, root reinforcement, litter input, and improved infiltration, with effects depending on slope, row spacing, ground cover, maintenance, and rainfall; and the supply of protein-rich forage that may buffer seasonal feed scarcity, subject to anti-nutritional compounds that differ among species. These benefits are context-dependent rather than universal. The species reviewed include both native and

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introduced or naturalized taxa, so the conclusions apply to the species discussed and should not be read as applying to all tree legumes or only to indigenous ones.

No single species appears to be optimal across all three functions, so a mixed-species hedgerow design, for example combining Leucaena leucocephala, Gliricidia sepium, Calliandra calothyrsus, Indigofera zollingeriana, and Sesbania grandiflora according to local conditions, may be preferable to single-species hedges, although direct comparative evidence is limited. Implementation at the smallholder level is likely to depend on technical assistance regarding species selection, planting design, pruning management, and safe feeding limits for tree-legume forage in livestock rations.

Further field-based research is recommended to quantitatively validate actual nitrogen-fixation rates, erosion-reduction rates, and livestock production performance under specific agroecological conditions across Indonesia's diverse sloping-land regions, so that the mixed-species hedgerow design recommendations arising from this conceptual review can be reinforced with measurable local empirical evidence. The conclusions of this review are limited by its narrative design, the uneven evidence across species and regions, and the reliance on some secondary sources.

Several relevant directions for further research include: measuring actual nitrogen-fixation rates using the acetylene reduction assay (ARA) method across multi-species tree-legume combinations on various sloping-land soil types; long-term monitoring of erosion rates on living-fenced experimental plots compared with unfenced control plots using standard erosion-plot methods; and testing cattle production performance, including average daily gain and feed-conversion efficiency, under grazing systems supplemented with living-fence forage compared with conventional unsupplemented grazing systems. Economic cost-benefit analysis of implementing living-fence systems at the smallholder scale is likewise needed to strengthen the evidence base for policy adoption, given that farmers' long-term conservation-investment decisions are strongly influenced by perceived short-term economic returns.

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