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Review Article

Forty years' trajectory of forage legume species introduction, adaptation, cultivation, and their usage strategies in livestock feeding and farming systems in the semi-arid region of eastern Indonesia: A review

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Abstract

The semi-arid regions of eastern Indonesia are major contributors to the national beef supply but face persistent feed shortages during prolonged dry seasons. Over the past four decades, the introduction and adaptation of various forage legume species—ranging from tree, shrub, to herbaceous types—have played a vital role in improving feed quality and livestock productivity. The introduction of *Leucaena leucocephala* in the 1920s and its subsequent expansion in the 1970s significantly transformed the Amarasi cattle fattening system in West Timor. However, the psyllid (*Heteropsylla cubana*) outbreak in the mid-1980s triggered extensive evaluation of resistant and alternative species such as *Leucaena leucocephala* cv. Tarramba, *Gliricidia sepium*, and *Acacia angustissima*. Parallel trials identified highly adaptable herbaceous and shrub legumes, including *Clitoria ternatea*, *Centrosema pascuorum*, *Pueraria phaseoloides*, *Vigna luteola*, *Desmanthus virgatus*, *Stylosanthes seabrana*, and *Desmodium rensonii*. This review synthesizes more than forty years of research and field experience through a systematic literature search using Scopus, Google Scholar, and ScienceDirect, complemented by expert field observations and AI-assisted synthesis for enhanced organization and verification. Despite high adaptability and nutritional potential, the adoption of forage legumes by smallholders remains limited due to seed scarcity and technical constraints. Successful models such as the *Leucaena*-based Amarasi system and legume supplementation strategies have proven effective in improving cattle performance and reducing calf mortality. Future opportunities include the development of community-based seed systems, drone-assisted oversowing, and wider integration of legumes into climate-resilient farming systems.

Keywords: Eastern Indonesia, Forage legumes, *Leucaena leucocephala*, Adaptation, Cultivation, Livestock feeding, Farming systems

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Introduction

The eastern Indonesia region covers Sulawesi, Nusa Tenggara (East and West), Maluku, and Indonesian Papua (Parkinson, 1993). Bali, as the gateway to the region, is also mentioned for forage species cultivation and feeding strategy. Sulawesi, West Nusa Tenggara, and East Nusa Tenggara are the most important provinces that supply beef cattle to the other parts of Indonesia, especially Java.

The climate is defined by its distinct dry and wet seasons, ranging from short wet to a prolonged dry season (7 to 9 months) as presented in Figure 1. Animal production depends on the native grasslands, where productivity fluctuates with the changing seasons (Bamualim, 2011; Wirdahayati and Bamualim, 1994). Forage is abundant during the wet season and very limited during the dry season, causing low cattle productivity. Wet season rainfall is highly variable, which impacts forage production.

The native grasslands of eastern Indonesia are dominated by hardy perennial species such as *Heteropogon* spp., *Bothriochloa* spp., *Ischaemum timorense*, *Themeda triandra*, and *Sorghum nitidum,* as well as annual grasses like *Sorghum timorense* and *Cenchrus polystachion*. These species are well adapted to the region's semi-arid conditions but generally exhibit low productivity and nutritional value, particularly during the long dry season when crude protein levels often decline below 4%. The native pastures also contain very low proportions of leguminous species (typically less than 5%), limiting biological nitrogen fixation, contributing to low production of high-quality fodder, and reducing soil fertility over time. As a result, livestock grazing these rangelands experience feed scarcity, low growth rates, and poor reproductive performance, especially during the dry months. These limitations have long underscored the need for introducing high-yielding, drought-tolerant, and nitrogen-fixing non-native forage species that can improve feed availability, pasture quality, and the sustainability of smallholder livestock production systems.

Livestock production in eastern Indonesia is dependent on the availability of crude protein in their diet, which could come from native grasses in the native grasslands, local and introduced tree and herbaceous legumes, as well as leaves from non-legume trees. Legume fodder, whether it comes from tree legumes, shrub legumes, or herbaceous legumes, usually has a higher nutritional quality, such as in crude protein content (i.e., *Leucaena leucocephala* has > 24% (Nulik, 2021) crude protein, and *Clitoria ternatea* forage has a crude protein of up to 23% (Mayberry et al., 2021) compared to that of the grasses, where the best could reach only about 12% crude protein (Nulik et al., 2024). The crude protein may even be doubled in legumes compared to the grasses in wet and dry seasons (Nulik, 1987). However, biomass production may be less during the dry season. Legumes, through their symbiosis with the bacteria, *Rhizobium* spp., form nodules on the legume's roots can fix atmospheric Nitrogen. The fixed Nitrogen can then be used for self-needs or benefit to the companion crops planted with them (Hosang et al., 2016) or pastures.

Tree legumes have been a component of livestock production systems in Timor and other parts of eastern Indonesia, especially since the introduction of the small weedy *Leucaena leucocephala* by the colonial Dutch in the 1920s and have been increased in use since the 1970s in the Amarasi region of West Timor following the introduction of the giant cultivars. The Amarasi cattle fattening system enabled farmers to significantly increase household income through feeding *Leucaena leucocephala* leaves (Metzner, 1983). The use of leucaena in animal production systems was downgraded since 1986, when the leaf-sucking psyllid *Heteropsylla cubana* arrived in Indonesia, resulting in a significant reduction in leaf production (Nampompeth, 1989), with the western part of the island of Timor losing over fifty percent of the 4,300 km^2 of leucaena that had been planted. Farmers have also fed cattle native tree legumes such as *Acacia leucophloea*, which are a major component of the Timor rangelands, also the other species (*A. nilotica*), which seemed to invade the heavily grazed native pastures in West Timor.

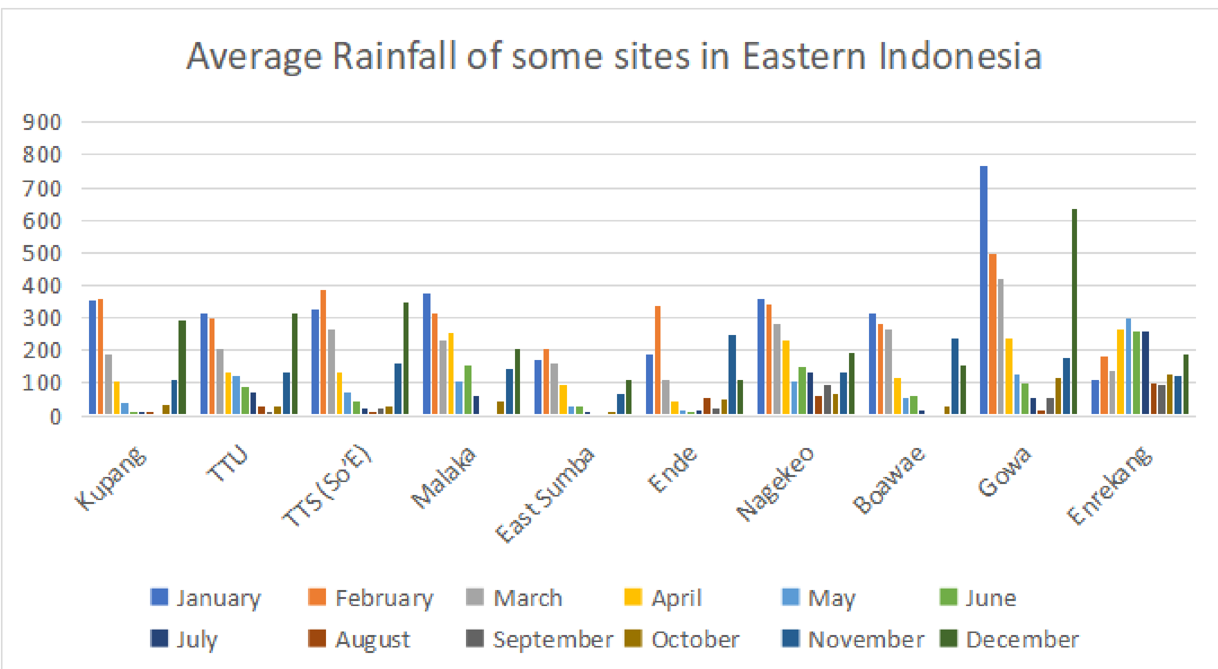
Though legumes are high in protein content, legumes are well known for being low in sugar (Water Soluble Carbohydrate/ WSC) and high in buffering capacity (Tjandraatmadja et al., 1994; Pahlow et al., 2002; Dewhurst et al., 2009). Legumes are therefore not suitable as silage if used as the sole source of feed, but need to be mixed with grass species, which are usually higher in sugar and lower in buffering capacity.

Forage legumes have been tested for their adaptation to the soil, climate, altitude, and integration into farming systems (Piggin et al., 1987; Nulik, 1994a), in monoculture and mixture (Nulik, 1994b, 1994c), and their feeding strategy to improve livestock and crop production in the semi-arid region of Indonesia, specifically East Nusa Tenggara.

Despite numerous studies and development projects on forage legumes in eastern Indonesia, knowledge has remained fragmented across different time periods, locations, and institutional initiatives. Each decade has contributed partial insights into species adaptation, management practices, and farmer adoption, yet no integrated synthesis has traced the evolutionary pathway—or trajectory—of these innovations within the region's semi-arid farming systems. Understanding this trajectory is critical because it reveals how ecological, social, and policy factors have shaped the success or failure of legume introductions over time. By reconstructing this forty-year development process, the review identifies patterns of adaptation, institutional learning, and technology diffusion that explain the current status of forage use in smallholder systems. This approach not only documents past progress but also provides a framework for guiding future innovation—linking species suitability, farmer practices, and climate-resilient farming strategies into a coherent development pathway.

The following paper discusses the various species introduction, testing for adaptation, evaluation for management strategies to obtain maximum biomass production, uses in the farming systems, and feeding strategy, as well as their usage as animal fodder either on their own or in mixed with grass species in the semi-arid region farming systems (Mayberry et al., 2021; Bell et al., 2022) in eastern Indonesia, and is compared with information and experiences in other semi-arid regions in the world.

Figure-1. Long-term average annual rainfall (mm) in some sites of Eastern Indonesia (Data derived from the statistical agency of each district, published in the regency in numbers).



Methodology

This review synthesizes over four decades of experience and research related to forage legume species (including tree, shrub, and herbaceous legume species) in the semi-arid region of Eastern Indonesia. It draws upon both expert insights and a structured review of global literature to provide a comprehensive account of the introduction, adaptation, cultivation, and utilization strategies of tropical forage legumes in livestock and farming systems.

Relevant literature was sourced through targeted searches in Google Scholar, Scopus, and ScienceDirect using keywords such as "forage legumes," "drought adaptation," "tropical pasture systems," "semi-arid agriculture," and "legume-

livestock integration." Priority was given to peer-reviewed publications, regional research reports, and case studies from similar agroecological zones.
To support the identification and synthesis of key adaptive traits and management strategies, the AI language model ChatGPT (OpenAI, GPT-4.5, 2025 version) was used as an auxiliary tool. The model facilitated the extraction of relevant insights from selected sources and helped organize information in alignment with the author's field-based understanding and findings. All information derived with AI assistance was cross-verified with the original references. The AI was not used to generate primary content but served as a support tool to enhance efficiency and clarity in the review process (Table 1).

Forage legume introduction and adaptation

Herbaceous and shrub legumes

East Nusa Tenggara: Several research projects have been conducted since the 1980s (1984 to 1987) and from 2006 to 2019 in East Nusa Tenggara to study species' adaptation to the climate and soil in the region for exotic species of forage legume (Nulik, 1987; Dalgliesh et al., 2014; Bell et al., 2022). About 66 accessions from 15 genera and 44 species of herbaceous and shrub legumes (mostly from Australia, from the Commonwealth Plant Introduction collection, with CPI number) were tested in East Sumba District (Nulik, 1987). The genera evaluated included: *Aeschynomene*, *Alysicarpus*, *Arachis*, *Cassia*, *Centrosema*, *Clitoria*, *Desmodium*, *Lablab*, *Macroptilium*, *Macrotyloma*, *Neonotonia*, *Rhynchosia*, *Stylosanthes*, *Teramnus*, and *Vigna*. Attributes studied included: drought tolerance, forage production, insect and disease tolerances, seed production capacity, and seed germination potential (hardseededness), as well as potential use in the integration with crop and livestock systems (suitable for direct grazing or cut and carry) and in feeding experiments (Mayberry et al., 2021). The genera with high and stable forage and seed yields included: *Cassia* (*Cassia rotundifolia*, Syn *Chaemacrista rotundifolia*), *Clitoria* (*Clitoria ternatea*), *Macroptilium* (*Macroptilium lathyroides*), *Stylosanthes* (*Stylosanthes guianensis* cv Graham), and *Vigna* (*Vigna unguiculata*). At the same time, grass species were also evaluated (from 32 accessions, 11 genera, 21 species: *Andropogon*, *Brachiaria*, *Cenchrus*, *Chloris*, *Bothriochloa, Digitaria*, *Panicum, Paspalum*, *Setaria*, *Sorghum,* and *Urochloa*) for their adaptation, and further evaluated in grass-legume mixture experiments (Nulik, 1987).
In West Timor, in the concurrent time (1982 to 1986), some herbaceous and shrub legumes were also evaluated and tested under the NTTLDP (Nusa Tenggara Timur Livestock Development Project) and further evaluated within the sub-districts of Timor Tengah Selatan (South Central Timor) and Timor Tengah Utara (North Central Timor) during late 1980s and 1990s in the form of village nurseries or village forage gardens for seed provision (Piggin et al., 1987) under NTTIADP (Nusa Tenggara Timur Integrated Area Development Project).
Later evaluation during the years 2006 to 2019 (a collaboration between Indonesia and Australia, led by ACIAR) was conducted in West Timor, Flores, and East Sumba, confirming also adding additional adapted species identified with high and stable forage and seed yields, including *Clitoria ternatea*, *Centrosema pascuorum*, *Stylosanthes seabrana* (syn. *S. scabra*), *Vigna* (*Vigna luteola*), and other promising genera of shrub legume *Desmanthus virgatus* (Nulik et al., 2013) which was also found to perform well on the red soil of East Sumba compared with *Centrosema pascuorum* cv Cavalcade and cv Bundey. In 2017, the herbaceous legume *Pueraria phaseoloides* (syn. *P. javanica*) was introduced from Java and planted in the experimental plot at Naibonat Village in Kupang District. It was found to be very well adapted, persistent, and palatable to the livestock (cattle and goats) and thus promising for further widespread use in the region. The latter species was found to be flowering in late May and early June, up to November. The start of flowering in *P. phaseoloides* was noted to be triggered by short sun radiation (11.30 hours) and low night temperatures (as low as 18^0C), and completely stopped flowering when radiation time was longer (12.30 hours) and night temperature was at 24^0C. The same flowering time was also noted in *Centrosema pubescens*. In contrast, *Clitoria ternatea* can flower at any time of the year, provided that water is not the limiting factor.
Following the introduction of exotic herbaceous and shrub legumes from Australia in the 1980s onward, several native and naturalized legume species have continued to coexist and, in some areas, recover within the grazing landscape. Palatable native legumes such as *Alysicarpus spp.*, *Desmodium intortum*, *Aeschynomene americana*, *Vigna trilobata*, *Uraria spp.*, and *Mucuna pruriens* (during the vegetative stage) are commonly observed along roadsides, in

fallow croplands, forest boundaries, and within native pastures, particularly during the wet season. Although their composition in natural grasslands remains low (<5%), these species contribute to seasonal forage diversity and soil enrichment. In some sites, natural reseeding of *Centrosema pubescens* and *Macroptilium atropurpureum* has occurred, suggesting partial naturalization of earlier introductions. Overall, the coexistence of native and introduced legumes has increased the botanical diversity and resilience of pasture systems, although further research is needed to assess long-term ecological interactions and palatability dynamics under grazing pressure or cut-and-carry systems.

West Nusa Tenggara: Less information is available on herbaceous legume introduction and testing in West Nusa Tenggara province, except for information on seed production of *Stylosanthes guianensis* that has been produced at the Serading BPTHMT station (Balai Pembibitan Ternak dan Hijauan Makanan Ternak, Livestock Breeding and Forage Multiplication Station) to meet demands from within and outside provinces. One plot area in Dompu, owned by the Livestock Services, has been observed to be growing *Stylosanthes guianensis* cv Cook, which has shown excellent growth performance. *Clitoria ternatea* had been tried by some colleges in Lombok but found no promising growth compared with that in East Nusa Tenggara.

South Sulawesi: In South Sulawesi, evaluation of herbaceous legumes was conducted using 62 accessions from 16 genera, all consisting of 50 species, for the introduced ones, while native origins consisted of 29 accessions of 6 genera (*Alysicarpus*, *Atylosia*, *Desmodium*, *Smithia*, *Uraria*, and *Vigna*) were tested (Hunt et al., 1991; Salam, 1991) starting in 1983. In Maiwa, South Sulawesi, *Centrosema pubescens* (syn. *C. molle*), and *Stylosanthes guianensis* cv Cook were evaluated on a three-year grazing trial, indicating the adaptability of the species in the province (Hunt et al., 1991). In Gowa, when eight legumes were tested (*Desmodium heterophyllum*, *Desmodium triflorum* ex Gowa, *Arachis* sp. Ex Maiwa, *Clitoria ternatea* CPI 50973, *Macroptilum atropurpureum* cv Siratro, *Neonotonia wightii*, *Centrosema pubescens*, and *C. plumeri*), the highest legume biomass was *Clitoria ternatea* in the wet season and *Arachis* sp. in the dry season. While the best combination of yield and Rumen Bag Digestibility (RBD) result was found in *Arachis* sp., it showed its potential to be further evaluated (Bulo et al., 1994). Now it is also common practice in the region to use *Arachis pintoi* as a cover crop in the farming system (Dr. Andi Ella, personal communication). However, the most used line was *Arachis* sp. Ex. Maiwa.

North Sulawesi: An adaptation trial at Gorontalo found that herbaceous legumes that have good yield and persistence included *Arachis* (ex. Maiwa), *Centrosema pubescens* (syn. *C. molle*), *Desmodium heterophyllum*, and *Stylosanthes guianensis* (Ibrahim and Tuhulele, 1998).

Maluku and Papua: A reference mentioned three herbaceous legumes tested in Manokwari: *Arachis glabrata*, *Centrosema pubescens*, and *Clitoria ternatea* (Sawen et al., 2023), while no reference has been found yet on herbaceous and shrub legumes being introduced or tested in Maluku. Currently, forage to feed animals mostly depends on natively available forages from the existing natural pastures (Fatmona and Gunawan, 2022). There is still a high potential to introduce forage legumes into the region, as there are > 100 thousand cattle and > 16 thousand buffaloes (Maluku, 2024) available in the province to warrant better quality forages.

Tree legumes

East Nusa Tenggara: Tree legumes adapted to the region included: *Leucaena leucocephala* (Nulik, 1998; Nulik et al., 2004; Piggin and Nulik, 2005), *Gliricidia sepium*, *Acacia angustissima*, and *Indigofera zollingeriana* (just recently being introduced). Some locally or native available tree legumes included: *Acacia leucophloea*,
A. nilotica, and *Sesbania grandiflora* (Bamualim et al., 1990; Nulik and Bamualim, 1998; Ngongo et al., 2022).

Though has been considered native, actually *Acacia nilotica* was recorded to be introduced into Java and the Lesser Sunda Islands, Indonesia in 1850 from India (Wulijarni-Soetjipto and Lemmens, 1991). In a Dutch Government letter in 1939, there was a mention of the existence of the plant in Indonesia, and a reference that the plant was introduced to Baluran, East Java, in 1969 to be grown for the purpose of making a fire break, and may then enter into East Nusa Tenggara. Therefore, *A. nilotica* is not a native plant of Timor, but was considered naturalized and local due to its long existence in the region. As ruminants eat the pods of the plants, it further spreads widely in the region and is now becoming an invasive plant that has negative effects on reducing the area of grazing lands.

Adaptation evaluation after the arrival of the Psyllid attack identified some species and cultivars (Piggin and Mella, 1987; Piggin et al., 1987) of Leucaena, including *Leucaena leucocephala* cv Tarramba (Shelton and Nulik, 2008) (adapted to most of the agroecology of the region, from sea level up to about 1,000 m asl), *Leucaena pallida*, *Leucaena diversifolia*, and one hybrid Leucaena named "KX_2" (a cross between *Leucaena leucocephala* and *Leucaena diversifolia*), more suitable for high-altitude sites. KX_2 performed well, even better than Tarramba in the lowland during the wet season; however, Tarramba performed better compared to KX_2 during the dry season. Tarramba has even been successfully developed around villages in the Kupang District of West Timor with rocky marginal land and turned the unproductive land into a source of high-quality fodder all year round (in wet and dry seasons) for cattle fattening (Nulik et al., 2019). *Leucaena collinsii* was also found growing well in West Timor, free from psyllid; however, it did not produce much viable seed, making it difficult to multiply. *Sesbania grandiflora* has long been grown in the province, though it does not tolerate harsh treatments such as *Leucaena leucocephala*. *Sesbania grandiflora* is native to Southeast Asia. In Timor, it is cultivated as part of the fallow cycle, mainly for corn production, which has proven to lead to higher yields than alternatives (Kieft, 2010). Flowers and beans are consumed as vegetables, while the leaves are fed to livestock.

An adaptation evaluation on 15 provenances of *Gliricidia sepium* was conducted in East Nusa Tenggara, which had been identified as promising provenances, including "Retalhuleu" and "Belen". However, both species rarely flowered during the evaluation period in West Timor (Fernandez et al., 1995). The same evaluation was conducted in Bali with a similar promising result (Sukanten et al., 1995a; Sukanten et al., 1995b). Thus, planting development may be done through vegetative means using cuttings.

West Nusa Tenggara: As in East Nusa Tenggara, several Leucaena species and cultivars have been tested, including *Leucaena diversifolia*, *Leucaena pallida*, Leucaena KX2, Leucaena collinsii, and *Leucaena leucocephala* cv. Tarramba. The latter was the most promising one and was widely distributed in the province, especially on Sumbawa Island. Before the introduction of "Tarramba" Leucaena into West Nusa Tenggara, farmers in Sumbawa Island had also been using *Leucaena leucocephala* for cattle fattening since the 1980s (Panjaitan et al., 2014), which were most likely the giant El Salvador and Hawaiian varieties. The introduction of Tarramba Leucaena has boosted the province to promote "Lamtoro Beef" (Wulandani et al., 2022).

Sesbania grandiflora has been naturalized and heavily used for cattle fattening in Lombok Island of West Nusa Tenggara (Catchpoole and Blair, 1990; Dahlanuddin et al., 2013). The species is usually grown along the paddy rice field's bunds, where branches are lopped to obtain forage for cattle feeding.

South Sulawesi: When *Leucaena leucocephala* was planted in a mixture with *Panicum maximum* cv Riverdale produced 901 kg N per ha compared with 103 kg/ha by grass in monoculture, showing the potential of Leucaena in contributing to the provision of high-quality fodder (Catchpoole and Blair, 1990). *Leucaena leucocephala* is also well used in coffee plantations as a shade tree species (Dr. Andi Ella, personal communication).

Central Sulawesi: Tree legumes evaluated under coconut trees in central Sulawesi indicated that the best-performing species was *Indigofera zollingeriana* (Takdir et al., 2019).

North Sulawesi: Some genera of tree legumes have also been tested in North Sulawesi (in Gorontalo) by the project "Forages for Smallholders," including *Calliandra*, *Desmodium*, *Flemingia*, *Gliricidia,* *Leucaena,* and *Sesbania*, and found that the most promising were *Flemingia* and *Gliricidia* (Ibrahim and Tuhulele, 1998). Though *Flemingia* and *Desmodium* (*D. rensonii)* would be better included as shrub legumes (Shelton, 2001), as both may just have reached 2 to 3 meters in height, similar to the variety of *Desmanthus virgatus* encountered in West Timor (2 m height) (Kana Hau and Nulik, 2016b).

Maluku and Papua: There are some records available on tree legume introduction and usage in these provinces. However, a local tree legume with the local name "Dema" (*Ormocarpum orientale*) was mentioned (Sawen and Abdullah, 2020). Some references showed that Gliricidia sepium and *Leucaena leucocephala* were cultivated in the region. *Gliricidia sepium* was being planted at the University Khairun of Maluku (Salim et al., 2023), while *Leucaena leucocephala* cv Tarramba was recently developed in Buru Island for wood chip production and has shown promise to grow there, as rainfall was higher in the province of Maluku, the growth of Tarramba was excellent, with 1 tree at 1-year-old producing, on average, 10 kg of wood and 5 kg of leaf

(Dr. Simon Field, Personal Information) compared to that in Timor.

Forage legumes (tree, shrubs and herbaceous) cultivation

Forage legume cultivation research began with selecting species to be used in the forage cultivation systems based on methods of feeding, whether for direct grazing or cut-and-carry purposes (fed to confined animals in individual pens). Selection of legumes for direct grazing requires the species to have good grazing removal tolerance, i.e., a deep and strong rooting system to withstand grazing removal, as well as the ability to survive prolonged droughts (7 to 9 months) in semi-arid regions. If used in a cut-and-carry system, the species must have the capacity to withstand repeated cuttings and also have good regrowth ability, as well as good capacity in seed production, so that further development may continue by planting seeds. Thirty to forty percent of the total land area in West and East Nusa Tenggara (Bamualim et al., 1993; Wirdahayati and Bamualim, 1994) of the semi-arid region in Eastern Indonesia is native grassland. However, with the current increase in cattle population and land use changes, there is an increasing need for forage cultivation is becoming more urgent. Almost no efforts have been made to improve the quality of the forage in the native grasslands. in many cases, only a small amount of native and naturalized herbaceous legumes is found in the composition (less than 5%), e.g. *Alysicarpus* spp., *Aeschynomene americana*, *Desmanthus virgatus*, *Desmodium intortum*, *Vigna trilobata*, *Uraria* sp., *Centrosema pubescens* (syn. *C. molle*), and *Macroptilium atropurpureum* cv Siratro.

Tree legume cultivation and adoption

The cultivation of tree legumes in the semi-arid region started with the introduction of the small bushy Hawaiian type of *Leucaena leucocephala* (Piggin and Nulik, 2005; Salim et al., 2023), introduced in the 1920s during the colonial Dutch period in Indonesia. Leucaena was introduced to address land degradation, the invasive weed Lantana camara, and most probably because of overgrazing by cattle (*Bos sondaicus* or *Bibos banteng*), which was introduced by the colonial Dutch into West Timor in 1912 (Hilmiati et al., 2024). The King of the kingdom of Amarasi, near Kupang, requested his community to plant *Leucaena leucocephala* (Bamualim et al., 1990; Nulik, 1998). The species produced abundant seed, and as a result, spread throughout the area. Farmers, realizing the value of *Leucaena leucocephala* as a cattle feed, developed an innovative cut-and-carry system called Paron in the 1970s (Metzner, 1983). Farmers started to improve by planting the giant type of Leucaena species cultivars (both Hawaiian and Peruvian types). The use of *Leucaena leucocephala* for cattle fattening in the area was then well known by the name “The Amarasi System”. By 1986-1987, however, there was an insect invasion attacking the previously introduced *Leucaena leucocephala* named *Heteropsylla cubana* (psyllid insect) (Nulik et al., 2004), which significantly impacted any further development of tree legumes in Timor for livestock production. Farmers were reluctant to plant *Leucaena leucocephala* for either regreening programs or fodder.

Research began to focus on approaches to minimize the impact of the psyllid through identifying resistant accessions or identifying predators (Fernandez et al., 1995; Nulik et al., 2004). The adaptation and evaluation of tree legumes for replacing the former susceptible cultivars have identified some promising Leucaena species, including (i) *Leucaena leucocephala* cv Tarramba, *Leucaena diversifolia*, *Leucaena pallida*, *Leucaena collinsii*, and a hybrid Leucaena, namely Leucaena KX_2. *Leucaena diversifolia* and *L. pallida* were found to be more suitable for higher altitude locations, while *L. collinsii*, though, was found to have a low tannin content (Shelton, 1998) and is well adapted to the soil and climate but could not produce viable seeds.

To plant tree legumes such as *Leucaena leucocephala* in the semi-arid region it is recommended to prepare the seedlings in polybags before the rainy season (at least 1 month before the rain) and transplant them into the field when rain is already evenly distributed, at the time when soil moisture is sufficient for the plant to grow (Nulik et al., 2013; Nulik and Kana Hau, 2019). This can be done when water is available to prepare the seedlings in the nursery. In case water is difficult to get for the seedlings, the seedlings can be prepared as soon as the rain comes, such as in January, and be transplanted in February (Nulik and Kana Hau, 2019). Bare stem and direct seeding of *Leucaena leucocephala* have also been assessed and are more cost-effective compared to developing seedlings; however, the establishment rate is considerably smaller (Nulik and Kana Hau, 2019). Field (Field, 1991b), found that *Leucaena leucocephala* seed can be directly planted with the planting of the maize crop.

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When the maize crop is harvested 120 days after planting, the *Leucaena leucocephala* will continue to grow into the dry season on residual soil moisture, and after two years, will have a similar growth performance and yield to *Leucaena leucocephala* seedlings (Field and Yasin, 1991). Farmers have adopted the practice of planting the *Leucaena leucocephala* crop at the same time as the maize crop. Tree legume species were cultivated in many ways to suit the needs of the farming systems as well as their usage as livestock feed. Tree legumes can be planted in monoculture plots (in several plant densities) (Kana Hau et al., 2022; Kana Hau et al., 2024), to establish a living fence or hedge, in a mixture with food crops as well as with other forages (grasses and herbaceous or shrub legumes). A standard recommended plant density when planting *Leucaena leucocephala* in East Nusa Tenggara is 1 m x 2 m, giving a total plant density of 5,000 plants/ha, while planting densities can be up to 10,000 to 20,000 plants/ha. The higher the plant density, the lower the biomass production per individual plant; however, with a higher forage biomass per land size. *Leucaena leucocephala* can also be planted in an alley cropping pattern, with an alley width of 4 m to 6 m or even wider.

The alley formed can be planted with either forage crops (grasses and herbaceous or shrub legumes) or with food crops (corn, sorghum, dryland rice, mung bean, peanut, or pigeon pea).

Establishing tree legumes in the house garden and ladang areas is common in Eastern Indonesia (Pellokila et al., 1991). Regular pruning of the tree legume, especially species like *Leucaena leucocephala* that readily coppice, minimizes any impact on the dry-season maize crop. The pruned biomass subsequently improves crop productivity by increasing soil nitrogen (Field and OeMatan, 1990). The other advantage of the tree legume intercropped with maize is a reduction in weeds (Field, 1991a).

Once the wet season garden is abandoned after cropping for two to three years, the tree legumes dominate the fallow. The subsequent fallow period reduces the types of weeds that invade the abandoned garden (Field and Yasin, 1991). The tree legume fallow system has become a major opportunity for developing tree legumes for livestock production in Eastern Indonesia.

Gliricidia sepium was introduced primarily to assist in developing a living fence hedgerow in the 1980s. The plant readily establishes through the planting of 1-2m long cuttings to form the fence line and create a barrier. In the drier areas of Indonesia, *Gliricidia sepium* flowers and produces seeds. The seed is then broadcast throughout the abandoned garden and germinates in the following wet season, forming a dense *Gliricidia sepium* forest that displaces other weeds and increases soil fertility. Farmers have observed a significant increase in maize production after a *Gliricidia sepium*. Kieft (Kieft, 2023) found that in the district of Timor Tengah Selatan, tree cover has increased by over 7000 ha, mainly due to *Gliricidia sepium* forests established in the abandoned gardens. As *Gliricidia sepium* is not readily combustible in forest fires, the incidence of forest fires has also reduced in the district.

Besides their adaptation, the selected tree legume species were also noticed for their palatability and acceptability by animals, especially cattle breed in the semi-arid region (Dahlanuddin et al., 2019).

The adoption of tree legumes by farmers, especially in the case of *Leucaena leucocephala* in Eastern Indonesia, seems to be escalating and still being expanded in its cultivation and usages for cattle fattening and for all ruminants in general (Kana Hau and Nulik, 2019) either without or under the support from the districts and provincial livestock services as many farmers and users have realized the benefits of the species (Shelton et al., 2023).

Shrub legume cultivation and adoption

Shrub legumes, in general, have upright growth habits with relatively hard woody stems and deep-rooting systems that enable them to survive prolonged drought and forage removal by direct grazing animals. In contrast, herbaceous legumes may be uprooted by the forced removal of grazing animals.

Shrub legumes tested during the project's experiments included *Desmanthus virgatus* (Syn. *D. pernambucanus*), and *Stylosanthes seabrana* (Syn. *S. scabra*) (Nulik, 1987; Kana Hau and Nulik, 2017). *Desmanthus virgatus* has survived prolonged (> 10 years) direct grazing in Chinchilla, Australia, when grown in a mixture with *Panicum coloratum*. *Desmanthus* species' ability to survive grazing may most probably be related to its ability to survive grazing removal (employing strong and deep rooting systems) and its capacity to produce abundant seed. When frequently grazed, *Desmanthus* species tended to develop prostrate growth to the ground and were still able to produce abundant seed. Heavy grazing usually reduces seed banks in semi-arid conditions (Tessema et al., 2012); thus, selecting proper species such as *Desmanthus* to be used in a mixture pasture (grass-legume) may be recommended for heavy grazing conditions in semi-arid regions. The species may survive grazing by developing prostrate branches to the ground surface, which can produce sufficient seeds for regeneration (Jones and Brandon, 1998). A local *Desmanthus virgatus* with plant height reaching up to 2 m or more has been found in the native pastures in the three larger islands (Timor, Flores, and Sumba). The species has the potential to be grown in mix with improved grasses and may be spread into the native grasslands in the region to improve the forage quality of the native grasses grazed by animals. On Java Island, different species of *Desmanthus virgatus* with a plant height of about 40 cm were found in the wild (Mountara et al., 2021). There is a possibility to proceed with further works with the local *Desmanthus virgatus* noted in Timor by conducting some gamma irradiation treatments to modify the genetic traits to obtain mutants (Álvarez-Holguín et al., 2022) with less woody character. *Stylosanthes* may be grown in relay mode with corn crops, in rotational mode, or in intercropping when planted at the same time as food crop planting (Dalgliesh et al., 2014). However, many shrub legumes may experience great competition for light and nutrients with companion corn when planted at the same time and will only start to grow well when corn is harvested (Nulik et al., 2013). In India, under rotational relay, *Stylosanthes* was classified as a weak competitor compared to *Cajanus cajan* (Akanvou et al., 2002). Further grass-legume mixture experiments were divided into taller growing grasses with taller growing legumes, and lower growing grasses mixed with a lower growing legume. The taller species mixtures were meant for cut-and-carry forage use, while the lower-growing mixture was for forage direct grazing use (Nulik, 1987).

Herbaceous legume cultivation and adoption

Herbaceous legumes can be planted in monoculture or mixtures with grasses or food crops, as they may contribute to the improvement of soil fertility and thus may contribute to the N supply for their companion crops. In monoculture, herbaceous legumes may be grown for rotational modes (subsequently grow the land with cereal crops, such as corn, sorghum, or upland rice), to be rotated every 2 to 4 years or to keep growing in monoculture every year. Planting in the relay, the herbaceous legumes were usually planted when crops such as corn had reached an adult knee height or before the corn reached anthesis (Nulik et al., 2013; Dalgliesh et al., 2014). On the other hand, planting in rotational mode is usually conducted during the subsequent growing season, when cereal crops (maize or rice) can be planted (Hosang et al., 2016; Bell et al., 2022) to make use of the increasing soil Nitrogen. Planting in rotation can have higher N contributions when the legume is retained in the plot than when the legume is removed (Bell et al., 2022). However, when livestock is integrated into farming, then forage legume will certainly be taken for feeding the animals, thus the N contribution will be less. This may need further experiments to study what the optimum level of legume can be taken so that more contribution can still be able to be achieved. Planting herbaceous legumes in monoculture just to provide forage, in many cases, may induce the invasion of weeds as the soil nitrogen increases.

Planting in monoculture can be done using a planting distance of 20 cm x 20 cm. Plant densities of herbaceous legumes will be significantly related to the land surface coverage capacity. The higher the density, the quicker the land surface cover will be, which will further be related to the possibility of suppressing the growth of weeds (Kobayashi et al., 2003; Kana Hau and Nulik, 2016a; Nulik, 2021).

When planted during the dry season on sandy vertisol soil at Naibonat village, using a planting distance of 20 cm x 20 cm and watered to keep the soil moist, *Clitoria ternatea* can produce an average of 15 tons of fresh biomass/ha/harvest, or approximately 4.5 tons of Dry Matter. Harvest can be done every 2 to 3 months, so there could be potential to produce 18 tons of DM per year. Harvest was conducted at the time when plants started to flower, when the stem was about 90 cm to 120 cm in length. In the lowlands in the region, however, *Clitoria ternatea* may sometimes get damaged by caterpillars (larvae) from the *Catopsilia* sp butterfly, especially during the end of the wet season or early dry season, which may destroy almost all the leaves in a relatively short time. To overcome this, it is recommended to harvest the biomass immediately before the attack is noticed, when some butterflies are present in the area (Nulik et al., 2013). The biomass will then regrow and be free from the attack as the insect's life cycle changes.

Planting in a relay usually happens for farmers who have only one piece of land and want to make more efficient use of the land. Farmers in semi-arid conditions can make use of the remaining rain in the growing season (March to April, even to May) when there can be some occasional rains, thus also making use of the remaining soil moisture to grow the herbaceous legumes provide more high-quality forage biomass rather than let weeds grow in the plot towards the end of the rainy season and early dry season (Dalgliesh et al., 2014; Bell et al., 2022).

Planting in rotational modes. Rotation of forage legumes with food crops can be done in upland conditions or lowland conditions. In upland conditions, such as in West Timor, when planting of food crops such as maize and upland rice happens every rainy season thus rotation can happen in the subsequent year after legumes. However, in rainfed areas, planting can also be done with the help of irrigation from bore water planting of herbaceous legumes can be done during the dry season using irrigation (June to October), harvesting the forage before the rainy season (can be one or two harvests), making hay and used for feed cattle during the wet season (December to May) when forages around the rainfed area is difficult to obtain as most of the land is planted with rainfed rice (Nulik, 2021).

Adoption: Despite the potential adaptation of the herbaceous legumes mentioned above, especially in East Nusa Tenggara, West Nusa Tenggara and Bali, however it was rarely seen that herbaceous legumes are adopted by farmers in eastern Indonesia and cultivated in large areas in the farming systems owing to various reasons, such as the scarcity of good quality seed at planting season, while most of the legumes may need to be planted every year as they are short lived, and still there is lack of knowledge of their cultivation techniques in the farming systems and livestock farming. There are, however, some species noted to spread in the region (i.e., on the roadsides, border of forests and agriculture fallow lands by themselves which may need more intervention to encourage their use as high-quality fodder, such as *Centrosema pubescens*, *Macroptilium atropurpureum*, *Aeschynomene americana*, *Desmanthus virgatus*, *Desmodium intortum*, *Desmodium triflorum*, *Mucuna pruriens*, *Alysicarpus vaginalis*, and *Vigna trilobata*.

Combination of tree legumes, grasses and herbaceous legumes

To provide sufficient forage with proper nutrient supplies, ruminants will need sufficient bulk biomass consisting proper amount of crude fiber, sugar, starch, and crude protein (Villalba et al., 2021) before considering minerals and vitamin supplies. High-quality fodder will certainly supply sufficient minerals and vitamins for the animals, while fiber will be needed by the rumen bacteria for their multiplication. Thus, a combination of fiber, protein, vitamins, and minerals may be available through the combination of legume leaves (can be from tree legumes, or herbaceous legumes) combined with high-quality grass species as good sources of fiber. Growing herbaceous legumes with grasses may help the grass to obtain N fixed by the legumes, as well as provide higher crude protein through the high quality of herbaceous legumes (Nulik, 1987; Nulik et al., 2013; Bell et al., 2022).

The combination can be started from the mixed planting of the forages (Tree legumes, grasses, and herbaceous or shrub legumes). Tree legumes are important for the semi-arid conditions, such as in East Nusa Tenggara, with a prolonged dry season where only tree legumes (such as *Leucaena leucocephala*) can provide high-quality fodder while most grasses cannot survive drought, except that some irrigation can be provided during the dry season (Nulik et al., 2024). Thus, a model of feed provision through the combination of planting of *Leucaena leucocephala* – Improved grass (such as *Pennisetum purpureum*, *Panicum maximum* (Catchpoole and Blair, 1990), *Tripsacum laxum*, etc.) – Herbaceous or Shrub legume (such as *Clitoria ternatea*, *Pueraria phaseoloides*, *Centrosema pascuorum*, *C. pubescens* or *Desmanthus virgatus*) can be arranged. In the demonstration forage plot of mixture between *Leucaena leucocephala* and grass of either *Pennisetum purpureum* cv Mott or Pennisetum purpureum var. Biograss on sandy vertisol soil, it was observed that naturalized herbaceous legumes from early introduction, such as *Centrosema pubescens* and *Macroptilium atropurpureum,* and the newly introduced species, such as *Clitoria ternatea*, showed excellent coexistence of all the species within the base mixture, showing their good potential of compatibility, able to improve soil fertility and improve forage quality and diversity.

Grass-legume mixtures were found to grow well, with the grass consistently displaying green leaves, unlike when grasses were grown on their own. It appeared that even adding organic fertilizer gave no significant contribution to biomass production when planted in the mixture, while planting grass in monoculture with the application of organic fertilizer gave better biomass production compared to without organic fertilizer (Yan et al., 2023). In some experiments in East Nusa Tenggara, planting maize in rotation with legumes increased the production of grain corn significantly compared to planting maize without rotation with legumes (Hosang et al., 2016; Bell et al., 2022). Thus, the inclusion of legumes significantly contributed to the improvement of grass biomass or grain yields of maize and rice even under semi-arid conditions.

Oversowing legumes into native grasslands

Shrubs and herbaceous legumes can be oversown into native grasslands (Shaw, 1979) to improve the quality of forage production by the native grasslands. Though oversowing legumes into the native pastures has been widely conducted in many countries and sites (Durant and Doublet, 2022). This mode of improving the native grasslands was not being done in the region by intention. However, patches of native herbaceous and shrub legumes are found occasionally in the communal native grazing lands, which may have escaped from experimental or forage plots, indicating the potential to do more work and experiment with oversowing legumes into the native pastures. An experiment was conducted in East Sumba to oversow herbaceous legumes into the native pasture by comparing the treatments of burning and no-soil soil disturbance with burning and soil disturbance (Nulik, 1987) has also shown the potential to oversow herbaceous legumes.

Potential species for oversowing native pastures would be *Desmanthus virgatus* either introduced or local ones, and from *Stylosanthes* spp. such as *S. seabrana* (syn. *S. scabra*), *S. hamata*, and *S. guianensis*. *Stylosanthes* spp were noticed to appear sometimes along the side roads in West Timor or on the edges of forest lands, most probably escaping from village nurseries through cattle dung. Those shrub legumes are recommended for their ability to survive grazing and competition with existing grass species in the native grasslands, though species such as stylo may have a slow establishment in the first year (Nulik et al., 2013). The dominant native grasses in West Timor include *Heteropogon contortus*, *Bothriochloa pertusa*, *Ischaemum timorensis*, *Bothriochloa ischaemeum* of perennial ones, and *Sorghum timorense* and *Cenchrus polistachyon* (syn. *Pennisetum polistachyon*) of annual ones. In Sumba Island, the dominant native grasses include *Heteropogon triticeus*, *H. contortus*, *Sorghum nitidum*, *Bothriochloa pertusa*, *B. ischaemum*, *Appluda mutica*, and *Themeda triandra*.

Depending on the soil type and the level of degradation of a native grassland, there are examples of tree legumes like *Gliricidia sepium* invading degraded grasslands. Trials conducted by the Nusa Tenggara Timor Livestock Development project found high survival and the emergence of *Leucaena leucocephala* when the seed was broadcast or planted by dibble stick into native pastures, with a 50% survival rate (Piggin et al., 1995).

Legume seed production

In the cultivation of herbaceous legumes, the availability of seed is important, and thus selection of species needs to consider the species' seed production capacity. Species like *Clitoria ternatea* can produce double the amount when facilitated with a trellis compared to one without a trellis. When allowed the plant to climb on the trellis, it will provide more contact with incoming radiation, and thus plants produce more pods and hence seed production (Nulik et al., 2016). Seed production can be conducted by individual farmers or farmer groups (Nulik et al., 2013). Currently, the most demanding legume seed sold is *Leucaena leucocephala* cv Tarramba (Nulik et al., 2013; Kana Hau and Nulik, 2019), while *Clitoria ternatea* is occasionally requested. More research on seed production aspects still needs to be conducted to guarantee the availability of seeds for yearly planting and expansion of the market within the country and to meet export demand. *Gliricidia sepium* seed is now being sought after, as the tree is now in demand as a source of biomass, due to its high calorific value, to replace coal. Tree legume biomass plantations are now being established throughout Indonesia. Legume cultivation for seed production must also consider the characteristics of the species, such as flowering time. for instance, *Clitoria ternatea* may be flowering at any time; thus, it can be planted at any time too, provided that water is not a limiting factor. Other species, such as *Centrosema molle* (syn. C pubescens) and *Pueraria phaseoloides* (syn. *P javanica*), may only flower at a certain time, and thus, planting time has to be adjusted to the possibility of flowering too. Both later species in West Timor started flowering in the mid to end of May up to December, following shorter sunlight duration (11.30 hours) and lower night temperature of 18^0C. Because May to October would be the dry season in most of West Timor of Eastern Indonesia, planting these species for seed production must also consider providing watering facilities. The time of seed setting must also be considered to avoid insect invasion, such as *Clitoria ternatea*, which may be attacked by larvae of white butterflies from mid to the end of the wet season (Nulik et al., 2013), while

Leucaena leucocephala would experience a lot of pod damage if seeds are produced during the wet season, as observed in West Timor.

Key adaptive traits of forage legume species under drought conditions

To provide a comprehensive overview of the major characteristics influencing drought adaptability in forage legume species, a synthesis was conducted using global literature. Trait information was extracted and summarized with the assistance of ChatGPT (OpenAI, GPT-4.5, 2025 version), then cross-validated with field observations and research findings from Eastern Indonesia (Table 1). The table summarizes key drought adaptation traits of selected forage legume species relevant to the semi-arid conditions of the region.

Table-1. Adaptive traits of legume species summarized using ChatGPT which were found to be in accordance with field experiences in Eastern Indonesia.

Species	Drought Tolerance	Rooting Depth	Growth and Regrowth	Biomass Production	Protein Content	Disease Resistance
Aeschenomene americana	Moderate	Medium	Good but slow regrowth	Moderate (6-10 t/ha)	16-24%	Good resistance, susceptible to fungal disease
Centrosema pascuorum	High	Shallow to medium (0.5-1.2 m)	Fast early growth, moderate regrowth	Moderate (6-10 t/ha)	12-18%	Moderate but susceptible to rust and leaf spot diseases
Centrosema pubescens	Moderate to high	Medium to deep (1-1.5 m)	Vigorous growth, good regrowth	Moderate to high (8-12 t/ha)	18-25%	Moderate resistance to foliar diseases, but susceptible to rust in humid conditions
Clitoria ternatea	High	Medium to deep (1-1.5 m)	Vigorous initial growth, moderate regrowth	Moderate (5-9 t/ha)	15-25%	Good resistance to root and foliar diseases
Desmanthus virgatus	High	Deep (> 1.5 m)	Rapid growth, strong regrowth	Moderate to high (6-12 t/ha)	16-26%	Highly resistant to pests and diseases
Macroptilium atropurpureum	Moderate to high	Medium to deep	Rapid regrowth	Moderate (3-10 t/ha)	15-22%	Moderate resistance to diseases
Mucuna pruriens	High	Medium	Vigorous growth but annual	High (10-15 t/ha)	18-30%	Generally resistant to pests and diseases
Pueraria phaseoloides	Moderate to high	Deep (> 1.5 m)	Aggressive creeping growth, moderate regrowth	High (10-15 t/ha)	15-22%	Good resistance to most diseases, but may be susceptible to rust

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						in humid conditions
Stylosanthes hamata	High	Medium to deep (1-1.5 m)	Vigorous growth. Good regrowth	Moderate to high (8-12 t/ha)	12-18%	Moderate to high resistance to anthracnose and other foliar diseases
Stylosanthes seabrana	High	Deep (> 1.5 m)	Persistent growth, good regrowth	High (10-15 t/ha)	14-22%	High resistance to anthracnose and root diseases
Vigna luteola	Moderate to high	Medium to deep	Fast initial growth, moderate regrowth	Moderate to high (6-12 t/ha)	15-22%	Moderate resistance to diseases
Vigna trilobata	High	Medium to deep (1-1.5m)	Persistent growth, moderate regrowth	Moderate (5-10 t/ha)	18-24%	Good disease resistance; may be affected by root rot in waterlogged conditions
Indigofera zollingeriana	High	Deep (> 1.5 m)	Excellent regrowth, bushy growth habit	High (10-15 t/ha)	22-30%	Generally resistant, but susceptible to leaf spot and root rot in wet conditions
Leucaena leucocephala	High	Deep (> 2 m)	Excellent growth when properly weeded, Excellent regrowth	High (10-20 t/ha)	20-28%	High resistance, though susceptible to psyllid insect damage
Sesbania grandiflora	High	Deep (> 2 m)	Very fast growth, good regrowth.	High (12-20 t/ha)	25-30%	Generally resistant; susceptible to waterlogging and fungal diseases in humid conditions
Gliricidia sepium	High	Deep (> 2 m)	Excellent regrowth after pruning	High (10-25 t/ha)	18-30%	Generally resistant to pests and diseases, can be affected by root rot in waterlogged conditions

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Forage legume feeding strategies

Forage legumes can be fed in fresh form, hay, silage, pellets, and cube forms (Kana Hau, 2010). However, the more practical way is to be given in fresh or hay form by farmers (Nulik and Kana Hau, 2016).

Forage legume feeding in the semi-arid region is mainly targeted at (Jelantik et al., 2008, 2010) (i) reducing calf mortality in Bali cattle, (ii) achieving high calf crop and high calf birth weight, (iii) shortening calving intervals in Sumba Ongole cattle, and (iv) increasing daily body weight gain in fattening cattle (Wirdahayati and Bamualim, 1994; Wirdahayati, 2010; Nulik, 2021). Bali cattle are well known for their high fertility character, which can get estrus and be mated even under bad conditions (poor body condition, and low nutrition supply). Other breeds will not even get hit, especially noted in Australian Brahman and Sumba Ongole cattle.

Nevertheless, Bali cows usually give birth during the dry season when the scarcity of feed often occurs. Therefore, calf mortality can be as high as 30 to 50% (Jelantik et al., 2008, 2010) as the mother, who was poorly provided with sufficient feed in quantity and quality, was not able to produce enough milk to support the newborn calf. This may cause death or stunting with low birth weight and can be permanent (dwarfed) even if the surviving calf is fed high-quality feed after weaning. These stunting cases mostly occur in areas with high cattle populations and share the same native communal grassland areas, which are significantly overgrazed and thus provide insufficient forage to the grazing animals, including pregnant cows and the newly born calves.

Despite their high protein content in general, forage legumes have low sugar content (Ikhwanti et al., 2020) and high buffering capacity, making it difficult to produce silage (Chakrapong et al., 2017). To overcome this limitation, feeding a mixture of legumes and grasses becomes important in the feeding strategy. Wilting to 30% dry matter would be needed for silage making. In feeding, grasses will contribute more to the fiber supply by improving soluble sugar, while legumes in the protein supply

Feeding strategy to reduce calf mortality

To overcome the problem of high calf mortality, a strategy of feeding calves' high-quality legume leaves is recommended. A creep feeder system was trialed, where legume hay, such as *Clitoria ternatea* leaf hay, is placed in a creep feeder area only accessible by the calves through a small gate, and the calves can always come out to suckle from the mother cows (Mayberry et al., 2021). The idea for using legume hay to supplement the suckling calves came from the experience that concentrated feed is difficult for farmers in the region, especially in West Timor, to purchase (Jelantik et al., 2008; Mayberry et al., 2021). *Clitoria ternatea* hay can be accessible to farmers. They can grow the legume in their croplands or spare lands, whether in monoculture for rotation, as a relay crop, or in intercropping patterns in upland areas during the wet season to the early dry season, or in lowland areas during the dry season with irrigation. *Clitoria ternatea* supplementation can reduce calf mortality down to < 4% (Mayberry et al., 2021) and give better growth performance for the calves. *Clitoria ternatea* hay, for example, as a supplement for suckling calves in this way, was given in a creep feeding method, where access to the feed rack is provided through a small door or doors that only calves can enter.

A noticeable new practice in the semi-arid areas of Timor is that farmers, during the dry season, let cows with suckling calves graze in a plot planted with Leucaena leucocephala. The plant is cut at a height of 0.5 m to stimulate the growth of shoots that can be easily grazed by the calves and the suckling cows. In this way, not only can the calves get sufficient high-quality fodder, but also the suckling cows are provided with forage that is sufficient for both calves and the mothers. If forage availability is not sufficient to support the cows, the creep feeding model can also be applied to the forage plot. The forage supplement plot can be used during the afternoon until the next morning, when the cattle herd is brought back to the pens, which are near the nearby farmers' houses, after being free-grazing in the native grasslands during the day. The forage supplement using a *Leucaena leucocephala* plot would be more practical than if farmers had to plant *Clitoria ternatea* or other herbaceous legumes to make hay as a supplement. Leucaena can provide high-quality forage all year round, even under the peak of the dry season, when most of the native grasses have dried off, and can be grazed by the calves born during the dry season and the cows. The perennial shrub legumes, such as *Desmanthus* virgatus (Kana Hau and Nulik, 2016b), with proper management such as frequent pruning or grazing to stimulate new shoot regrowth, may have the opportunity to be used in the model to provide high-quality supplement fodder for the pre-weaning calves in this semi-arid short wet season area.

Feeding strategy for early weaning of calves

Early weaning of Bali cattle at 6 months of age is possible when using high-quality fodder (high in crude protein) such as leaves of *Leucaena leucocephala* and *Sesbania grandiflora* (Quigley and Poppi, 2009). Therefore, supplementing pre-weaning calves to reduce mortality rates, combined with early weaning in Bali cattle, is recommended to improve the productivity performance of Bali calves, such as higher birth weight and higher daily weight gain. If sufficient high-quality fodder is available, the combination of cow supplementation and pre-weaning calf supplementation can also be conducted for Ongole Cattle for better performance. Feeding strategy to shorten calving interval

Sumba Ongole cows should ideally be mated when the body condition score is equal to or above three (of the 5 scales) (Wirdahayati and Bamualim, 1994). This is difficult to achieve with free-grazing animals during the dry season with low-quality native grasses in native grasslands, as they have low body condition scores and need to get a better supply of good-quality forage. This can be done by supplementing the free-grazing cows with legume forages. The research found that supplementing cows with *Clitoria ternatea* hay can maintain cows' body condition at around three (Wirdahayati and Bamualim, 1994; Mayberry et al., 2021). This enables a cow to be conceived and produce a calf every year, compared to every 2-3 years (Wirdahayati, 1994; Bamualim and Wirdahayati, 2003).

Besides *Clitoria ternatea* hay, the Ongole cows can also, in the same way, be given hay of *Leucaena leucocephala* leaf for a supplement in the night yard pen. However, Ongole cows may need to be trained to consume the Leucaena hay, as they may not readily accept Leucaena leaf compared to *Clitoria ternatea* hay, as also conducted for fattening Ongole bulls (Kana Hau and Nulik, 2015).

Besides the strategy to feed legume hay supplement for free grazing cows to maintain body score condition to conceive, intensive feeding of legumes for cows in the pen three months before parturition and 3 months after parturition will result in a higher body weight of calf at birth and also higher calf survival (Wirdahayati and Bamualim, 1994; Bamualim and Wirdahayati, 2003).

Feeding strategy for cattle fattening

East Nusa Tenggara with its prolonged dry season and native grasslands with native grass species (both annuals and perennials) with a short growing season will only have quality forage during the wet season (November to March) with a crude protein content of 8 to 9% and will soon be depleted down to less than 4% during the early to the peak of the dry season (April to October). Dry season forage will not be sufficient to achieve any body weight gain in the cattle. With the problems of overgrazing and forage production fluctuation in quantity and quality in the native grasslands, the average weight gains of Bali Bulls only range between 0.2 to 0.3 kg/head/day. Thus, the provision of high-quality fodder, which can be obtained all year round, would be very important. During the dry season, it is common to observe cattle grazing in the native grassland, losing weight. To be able to supply sufficient feed of high-quality Leucaena leucocephala is well known in the region. Generally, farmers in the semi-arid region in eastern Indonesia feed up to 100% of Leucaena during the dry season, but often not enough to meet the animals' dietary needs. Feeding cattle with sufficient amounts of forage is significantly influenced by the availability of forage legume plants. Nulik and Kana Hau (2015) found that farmers with the lowest number of Leucaena plants available fed the least to their animals and received the lowest animal body weight gain in a year of feeding, while higher gains were achieved by farmers who cultivated more Leucaena plants. The findings make a strong suggestion for the importance of providing sufficient *Leucaena* forage by planting more plants to meet the animals' requirements.

Feeding 100% legume: Many farmers in the fattening area of Amarasi in West Timor and now more widespread in East Nusa Tenggara feed up to 100% of *Leucaena leucocephala* (Halliday et al., 2013; Panjaitan et al., 2014; Halliday, 2017) leaf, as also recorded in Sumbawa district of West Nusa Tenggara (Halliday et al., 2014; Panjaitan et al., 2014). Some farmers mixed with the skin (bark) of leucaena, which, in their observation, gave better weight gains to the fattening beef cattle. Normally, when offered the fully intact pruned leucaena branches, animals (cattle and goats) would strip off the skin (bark) also. In this way, the animal will have sufficient protein from the leaf and fiber from the skin parts, thus having a balanced ration. Feeding Leucaena leaf at a proportion of > 30% to animals, new to consuming the forage, may need some time to cope with the toxicity problem of mimosine in the forage. In our experience, animals new to the forage may need 1 to 2 months to adjust to developing mimosine tolerance. Animals new to consuming Leucaena may show signs such as over-salivation, and loss of hair, especially on the tail, but may recover after (when rumen degrading bacteria increase), showing shiny skin and better daily weight gain. Other abundant tree legume fodder is available, especially during the wet season (December to April) and even during the early dry season (June), i.e., *Gliricidia sepium* appeared to be less utilized as animals, especially cattle, preferring *Leucaena leucocephala* to *Gliricidia*. There is potential to process the abundant fodder into hay or pellets and cubes, and be used for dry season feeding (Kana Hau, 2010).

Feeding grass-legume mix: However, according to the feeding experiments, it is recommended that the feed is in the form of a mixture of grass and legume at 60% grass and 40% legume, or with an additional small amount of cassava tuber (as readily available carbohydrate), which gave better live weight gain of fattening Bali Bulls (Nulik and Kana Hau, 2015), and would be best if added with mineral mix (Wahyuni and Amin, 2020). Grasses would be expected to provide fiber for the ruminants. Fiber type, quality, and length will influence the health and productivity of the animals (Parish, 2007). The best feeding at the farmer level can achieve an average daily weight gain of > 0.8 kg/head/day, i.e., in Bali Cattle weight of 400 kgs can be achieved at the age of 2 years, close to the genetic potential of Bali Cattle. Daily Weight Gain Capacity (Mastika, 2003).

Feeding on agricultural waste: There is potential to mix the tree legume leaves with agricultural by-products such as rice straw and corn stover, as it has been shown in many demonstrations feeding in the region. There is plenty of biomass produced as agricultural waste to be used as livestock feed in Indonesia in general, as well as in West and East Nusa Tenggara, in terms of the Bioeconomy approach (Matitaputty et al., 2021; Priyanti, 2022).

Discussion

Trajectories, adaptation and future pathways of forage legume integration

The forty-year trajectory of forage legume development in the semi-arid regions of eastern Indonesia (Table 2) demonstrates how technology introduction, adaptation, and utilization follow a gradual process of ecological and socio-economic integration. This process aligns with the concept of *agroecosystem resilience*, where innovations that enhance resource-use efficiency, soil fertility, and drought tolerance contribute to system stability under climate variability (Altieri and Nicholls, 2017). The successful establishment of *Leucaena leucocephala* in the Amarasi system and further boosted with the successful introduction and use of the Tarramba cultivar (Shelton et al., 2023) exemplifies a locally adapted innovation that improved feed quality and livestock productivity through social learning and participatory adaptation. However, subsequent challenges—such as pest outbreaks, species invasiveness, and seed system limitations—illustrate the dynamic interactions between ecological adaptation and institutional support that shape the long-term sustainability of forage innovations.

The evolution from single-species introduction (such as *Leucaena leucocephala*) to diversified legume–grass mixtures and integrated crop–livestock systems also reflect the *diffusion of innovation theory* (Rogers, 2003). Early adoption was driven by visible economic benefits in smallholder fattening enterprises, while later adoption phases depended on farmer networks, government programs, and market incentives. This progression underscores the importance of collective action, farmer field schools, cross visits and community seed enterprises to enhance adoption and maintenance of improved pastures. Furthermore, the coexistence of native and introduced legumes supports the *ecological complementarity theory*, suggesting that species diversity enhances resource capture, nitrogen cycling, and resilience against climatic stress (Tilman et al., 2006). The naturalization of several introduced species, such as highly palatable species such as *Centrosema pubescens* and *Macroptilium atropurpureum*, indicates positive ecological assimilation, while less palatable accessibility species, which pose into invasive risk, warrant monitoring to propose approaches to reduce their spread, as observed with *Acacia nilotica*.

Table-2. Forty-year trajectory of forage legume introduction, adaptation, and utilization in semi-arid eastern Indonesia.

Period	Major Development / Innovation	Key Species Involved	Adaptive Use or Integration in Farming Systems	Key Outcomes / Notes
1920s–1970s	Early introduction of *Leucaena leucocephala* (small weedy type) by Dutch; followed by giant types in the 1970s	*Leucaena leucocephala*	Basis of Amarasi cattle fattening system (cut-and-carry feeding)	Boosted cattle growth and income; foundation of "Amarasi system"
1980s	Psyllid (*Heteropsylla cubana*) outbreak; search for alternative species	*Leucaena diversifolia*, *L. pallida*, *Gliricidia sepium*, *Sesbania grandiflora*	On-farm trials for pest-resistant tree legumes	Identified *L. leucocephala* cv. Tarramba as resistant and high-yielding
1983–1995	Large-scale introduction of herbaceous and shrub legumes from Australia (ACIAR, NTTLDP)	*Clitoria ternatea*, *Centrosema pascuorum*, *Stylosanthes spp.*, *Macroptilium atropurpureum*, *Desmanthus virgatus*	Village trials and pasture improvement plots	Demonstrated drought tolerance and palatability under local soils
2000–2010	Integration of legumes in crop–livestock systems; legume rotation and relay cropping trials	*Clitoria ternatea*, *Pueraria phaseoloides*, *Desmanthus virgatus*	Mixed cropping with maize, intercropping, and alley farming	Improved soil nitrogen and subsequent maize yields
2010–2020	Adoption of *Leucaena leucocephala* cv. Tarramba and *Gliricidia sepium* for fattening and biomass energy	*Leucaena leucocephala* cv. Tarramba, *Gliricidia sepium*, *Indigofera zollingeriana*	Cut-and-carry and integrated agroforestry systems	Enhanced dry-season feeding and income diversification
2020–present	Focus on climate-resilient and sustainable legume-based systems	*Desmanthus virgatus* (local), *Clitoria ternatea*, *Centrosema pubescens*	Community seed systems, drone-based oversowing, and native pasture enrichment	Supports bioeconomic approaches and climate change adaptation

Looking ahead, forage legume development should transition from species introduction toward landscape-level integration that supports both productivity and ecosystem services. Climate-resilient pastures and farming systems in semi-arid regions will benefit from combining drought-tolerant legumes, such as *Desmanthus virgatus* and *Clitoria ternatea*, with precision technologies like drone-assisted seeding (Marzuki et al., 2021) and soil nutrient monitoring. Future research should quantify the contribution of legume-based systems to carbon sequestration, water-use efficiency, and adaptive capacity under projected climate scenarios. The excellent potential of tree legumes to provide high quality forage as well as provide wood chip for wood-based electricity (Narendra et al., 2020) with potential caloric value (Nordin et al., 2016), needs further research. Strengthening local seed production, farmer cooperatives, and policy frameworks for sustainable land management will be crucial to ensure widespread, lasting impacts of these innovations on livestock and smallholder livelihoods.

To translate these forage legume innovations into tangible benefits for smallholder farmers, locally adapted and participatory strategies are essential. First, the establishment of community-based seed systems and smallholder seed cooperatives can ensure a consistent supply of quality legume seed, reducing dependency on external distribution networks. Second, promoting on-farm demonstration plots and farmer field schools can accelerate knowledge sharing and build confidence in legume management, particularly in mixed pastures or alley-cropping systems. Third, integrating forage legumes into existing crop–livestock cycles—for instance, by intercropping *Clitoria ternatea, Centrosema pascuorum* or *Desmanthus virgatus* with maize or planting *Leucaena leucocephala* on field boundaries—can improve land-use efficiency without displacing staple crops. Fourth, mechanized and drone-assisted oversowing could be tested to enhance pasture rejuvenation at landscape scale. Finally, coordinated extension–research partnerships should focus on evaluating economic returns, animal performance, and soil benefits under farmer conditions, providing a feedback loop that supports sustainable adoption and scaling across diverse agro-ecological zones.

Conclusion and Recommendation

Over the past four decades, extensive efforts to introduce and evaluate forage legumes have significantly advanced livestock feeding and pasture improvement in the semi-arid regions of eastern Indonesia. Tree legumes such as *Leucaena leucocephala* cv. Tarramba and *Gliricidia sepium*, together with herbaceous and shrub species like *Clitoria ternatea*, *Desmanthus virgatus*, and *Centrosema pascuorum*, have proven well adapted to the region's soils and climatic conditions, contributing to improved feed quality, soil nitrogen enrichment, and livestock productivity. At the same time, native palatable forages—including *Aeschynomene americana, Alysicarpus spp.*, *Desmodium intortum*, and *Vigna trilobata*—remain important components of natural pastures that sustain grazing ecosystems and provide opportunities for rehabilitation through enrichment planting and legume reseeding. The naturalized species of herbaceous legumes, such as *Centrosema pubescens* and *Macroptilium atropurpureum,* have spread by themselves and have enriched the biodiversity of palatable herbaceous legume species in the region.

The integration of these forage innovations into traditional crop–livestock systems requires strategies that are both participatory and locally feasible. Strengthening community-based seed systems, promoting farmer field schools, cross visits between farmer groups, and encouraging on-farm demonstrations are key to building farmer confidence and capacity. Integrating legumes into existing cropping systems (such as alley cropping or boundary planting with *Leucaena*) and testing drone-assisted oversowing for pasture rejuvenation can enhance scalability and efficiency. Sustained collaboration among research institutions, local governments, and farmer cooperatives will be crucial to ensure long-term adoption, adaptation, and dissemination of these technologies.

Future work should emphasize the ecological balance between introduced and native forage species to maintain biodiversity while improving productivity. Quantifying their combined contributions to soil fertility, water-use efficiency, and carbon sequestration will provide a scientific foundation for developing climate-resilient and economically viable farming systems in the semi-arid landscapes of eastern Indonesia.

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Contribution of Authors

Kana Hau D: Conceived the idea for the review and served as the lead author in drafting the manuscript.
Nulik J: Contributed to the conceptualization, provided critical input, and supervised the overall development of the manuscript.
Ella A: Contributed to data compilation and writing.
Field SP, Kieft J, Bahar S, Husni A, Sutedi E, Tiesnamurti B, Sirait J, Herdiawan I & Matitaputty PR: Provided insights from international project experience and contributed to the writing and editing of the manuscript.

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