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Performance of Legume Crops under Different Agroforestry Systems: A Comprehensive Review

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ABSTRACT

Grain legumes and agroforestry are each promoted as routes to sustainable intensification, but the agronomic consequences of combining them remain inadequately synthesised. This review compares the grain yield, biological nitrogen fixation, soil response and economic return of ten major food legumes, namely chickpea, pigeonpea, cowpea, mungbean, urdbean, lentil, field pea, soybean, groundnut and faba bean, grown under six agroforestry models, namely agrisilviculture, alley cropping, agrihorticulture, silvopastoral systems, boundary plantation and multistrata systems. Peer-reviewed literature published from 2010 to 2025, together with landmark earlier studies, was retrieved from Scopus, Web of Science, ScienceDirect and Google Scholar and screened against defined inclusion criteria. Qualifying studies were arranged in a legume by model matrix and in a nitrogen and soil matrix and were interpreted qualitatively within the competition and facilitation framework of tree-crop interaction. Legume performance was determined more consistently by the interaction between understorey radiation and soil water supply than by the land use system studied. Facilitation predominated on humid and fertile soils, where trees added nitrogen and moderated the microclimate, whereas in semi-arid environments below-ground competition for water cause yield loss. Soybean, groundnut and the cool-season pulses were the most shade-sensitive species, while cowpea, pigeonpea and several mungbean genotypes maintained yield under moderate shade. Reported fixation ranged from approximately 20 to 400 kg N ha^{-1} and declined when canopy shading limited the supply of photosynthate to the nodules. Legume-inclusive agroforestry raised soil organic carbon and ecosystem-service delivery in most reported comparisons. Across the humid to semi-arid gradient, the evidence identifies widely spaced agrisilviculture and boundary plantations carrying deciduous or regularly pruned nitrogen-fixing trees, sown to plastic warm-season legumes such as cowpea, mungbean and pigeonpea, as the configuration most reliably matched to grain legume production. Future research should replace comparisons between system labels with factorial genotype by tree by environment experiments.

Key words: Agroforestry models, Biological nitrogen fixation, Grain legumes, Land equivalent ratio, Shade tolerance, Soil organic carbon.

Food legumes occupy a central position in tropical and subtropical cropping systems by supplying major source of dietary protein. Their symbiotic association with rhizobia also represents the principal biological pathway through which atmospheric nitrogen fixed into the soils (Stagnari *et al.*, 2017; Peoples *et al.*, 1995). The nitrogen fixed in this way is not confined to the legume crop itself. A proportion remains in root and nodule residues and becomes available to the following crops in rotation (Herridge *et al.*, 2008; Giller, 2001). The nitrogen fixation depends on the rate of applied nitrogen, which suppresses nodulation and on the availability of soil carbon, which sustains the rhizobial population. Where legumes are intercropped rather than grown in sequence, fixation of the order of 125 kg N ha^{-1} per season has been reported together with an increase of roughly one third in main-crop-equivalent yield (Akchaya *et al.*, 2025).

Agroforestry, in which woody perennials are grown with crops or livestock on the same unit of land, offers a means of intensifying legume cultivation without withdrawing land from arable use (Nair, 1993; Sanchez, 1995; Nair *et al.*, 2021). Trees contribute nutrients cycle through litter fall and prunings, moderate the temperature and vapour pressure deficit experienced by the understorey, recover nutrients from below the crop rooting zone and accumulate carbon in biomass and soil (Jose, 2009; Nair *et al.*, 2009). In addition, nitrogen-fixing tree species enrich soil nitrogen through symbiotic biological nitrogen fixation (Nair *et al.*, 2009). These contributions are not obtained without cost, because trees and crops draw on the same light, water and nutrients. The net interaction is facilitative in some conditions and competitive in others, according to the species combined, the spatial arrangement adopted, the management applied and the biophysical conditions of the site (Ong and Huxley, 1996; Cannell *et al.*, 1996; Kumar *et al.*, 2020).

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This review compares ten legumes across six agroforestry models and addresses why the reported results so often conflict, ranging from substantial success to complete failure.

This review follows a structured narrative design. A documented literature search combined with interpretive synthesis within the competition and facilitation framework of tree and crop interaction. This approach was adopted because the evidence base is heterogeneous in design, duration and reporting and does not support quantitative pooling. Scopus, Web of Science, ScienceDirect and Google Scholar were searched using Boolean combinations of terms for the ten focal legumes, the six agroforestry models and the response variables of interest. The search was restricted to peer-reviewed sources in English published from 2010 to 2025 and earlier landmark studies were retained where they established the concepts on which later work depends. Studies qualified for inclusion when they reported an explicit tree and crop association involving one of the focal legumes together with at least one quantitative response, namely grain yield, biomass, the proportion of plant nitrogen derived from the atmosphere (%Ndfa), the quantity of nitrogen fixed, a soil indicator, the land equivalent ratio (LER) or an economic output. Studies of pure forestry, experiments conducted only in pots without a field comparator, duplicated reports and studies lacking a sole-crop or open-field control were excluded. The retained evidence was arranged in a legume by model matrix (Table 4) and in nitrogen and soil matrix (Table 5) and divergent results were reconciled by reference to environment, tree functional type and management. Two syntheses of the resulting interpretation are presented as Fig 1 and 2.

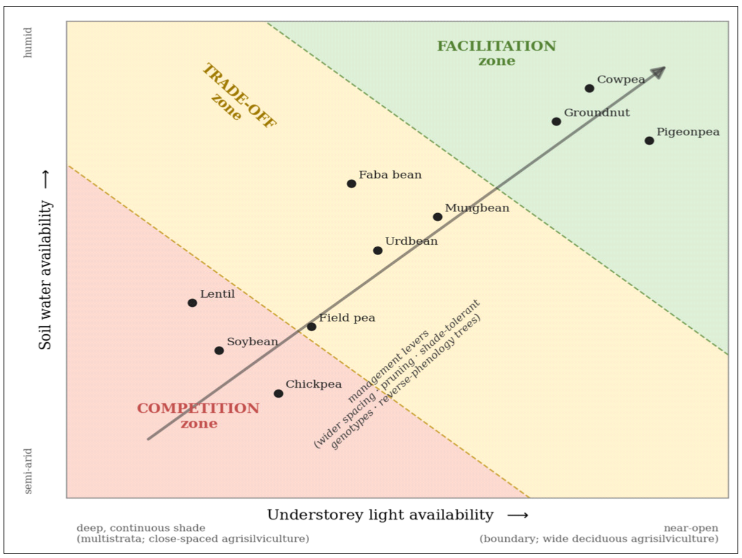

Fig 1: Conceptual framework: predicted suitability of grain legumes as a function of understorey light availability (x-axis) and soil water availability (y-axis).

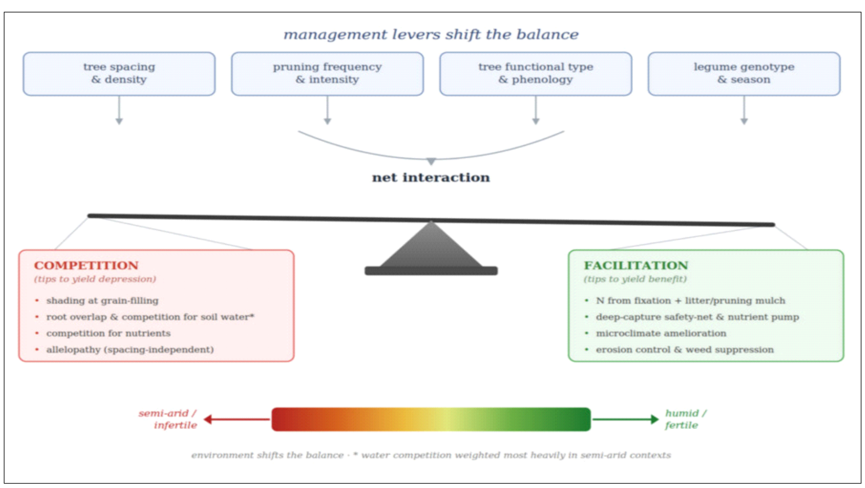

Fig 2: Conceptual diagram of the competition-facilitation continuum in tree-legume systems.

Agroforestry and legume components

Two properties of a tree and legume association predict legume performance more reliably than the model under which the association is classified. The first is the phenology and architecture of the tree canopy, which determine how much radiation reaches the understorey during flowering and grain filling. The second is the water status of the site, which determines whether the nitrogen and microclimate benefits conferred by the tree exceed the soil moisture it withdraws from the crop rooting zone (Garrity *et al.*, 2010; Bayala *et al.*, 2014). The components considered in this review are catalogued in Table 1 to 3.

When the six models are classified by structure and by spatial and temporal arrangement following Nair (1985), they form a gradient of understorey radiation rather than a set of discrete categories (Table 1). Agrisilviculture and boundary plantation lie at the permissive end of this gradient. In boundary plantations the trees are confined to bunds, field margins and windbreaks, so that competition is restricted to the outer crop rows while the interior of the field remains effectively an open-field environment (Dhyani *et al.*, 2013). Agrisilviculture spans a wider range, because the same class includes scattered trees at low density and improved fallows at high density and understorey radiation consequently varies from near-full sunlight to deep shade within a single model. Alley cropping occupies an intermediate position and its outcome depends less on the initial hedgerow spacing than on the frequency of pruning, since each pruning simultaneously removes the shading canopy and returns nitrogen-rich mulch to the alley (Kang *et al.*, 1981; Kang *et al.*, 1985). Agrihorticulture imposes moderate and seasonally variable shade that increases as the orchard canopy closes, which restricts legume cultivation largely to the establishment phase. Silvopastoral systems retain scattered trees but are managed for forage and grazing rather than for grain, so grain legumes are uncommon within them. Multistrata systems lie at the restrictive end, because several stacked canopy layers transmit so little continuous radiation that grain legumes become marginal and shade-adapted or climbing species are favoured instead (Kumar and Nair, 2004).

Tree and legume functional traits

The identity of the woody component is the strongest single determinant of legume performance among the factors that can be selected at establishment (Table 2). Trees that facilitate the understorey crop share a common physiological property, in that they minimise the overlap between their own period of maximum resource demand and that of the crop. *Faidherbia albida* is the clearest example, because it sheds its canopy at the onset of the rainy season and carries leaves through the dry season, so that the crop grows beneath a leafless canopy and

Table 1: Status of legumes under agroforestry models.

Agroforestry model	Structure and arrangement	Woody components	Status of legumes	References
Agrisilviculture	Trees and arable crops on the same unit; spacing from wide (scattered trees) to dense (improved fallows); spatial or temporal overlap.	*Populus, Eucalyptus, Gliricidia, Grevillea, Acacia, Melia, Dalbergia*	Grain legume as the arable component; benefits or losses highly context-dependent.	Nair (1985); Rizvi *et al.* (2020)
Alley cropping (hedgerow intercropping)	Crops in alleys between regularly pruned hedgerows; pruning controls shade and supplies N-rich mulch.	*Leucaena leucocephala, Gliricidia sepium, Cajanus cajan, Sesbania* spp.	Legume as alley crop and/or as the hedgerow itself (woody legume).	Kang *et al.* (1985); Lawson and Kang (1990)
Agrihorticulture	Fruit/horticultural trees with field crops; moderate, seasonal shade; strong market orientation.	*Mangifera, Citrus, Psidium, Emblica, Prunus*, apple	Legume as interspace crop during the orchard establishment phase.	Nair (1985, 1993)
Silvopastoral	Trees with pasture and grazing livestock; understorey managed for forage and grazing pressure.	*Acacia, Prosopis, Faidherbia*; scattered timber/fodder trees	Mainly herbaceous forage legumes; grain legumes uncommon.	Bayala *et al.* (2014); Garrity *et al.* (2010)
Boundary plantation	Trees on bunds, margins and as windbreaks; minimal cropped-area loss; competition concentrated at edges.	*Populus, Eucalyptus, Casuarina, Dalbergia, Melia*	Field-interior legume largely shielded; edge rows affected.	Nair (1993); Dhyani *et al.* (2013)
Multistrata (home garden, shaded perennial)	Several stacked canopy layers; low, continuous understorey light; high species richness.	Fruit, timber and palm overstorey; diverse mid- and under-storey	Grain legumes marginal; shade-adapted and climbing legumes favoured.	Kumar and Nair (2004); Nair (1993)

receives the nitrogen released by litter decomposition without the accompanying shade (Garrity *et al.*, 2010). Deep-rooted species with light crowns achieve a comparable separation in the vertical dimension by drawing water from horizons below the crop rooting zone (Rao *et al.*, 1998), while frequently pruned nitrogen-fixing species such as *Leucaena leucocephala* and *Gliricidia sepium* achieve it through management rather than phenology, since each pruning restores understorey radiation and adds mulch. Suppression arises where these separations are absent. Dense evergreen species with high transpirational demand compete for water and radiation throughout the cropping season and species such as walnut and *Eucalyptus* add chemical interference to that competition, so that three suppressive mechanisms operate at once (Jose *et al.*, 2004).

Table 2: Functional traits of the principal agroforestry trees and dominant effect on legumes.

Tree (common; binomial)	Family/type	Canopy and phenology	Rooting and water use	Dominant effect on understorey legumes	References
Apple-ring acacia; *Faidherbia albida*	Fabaceae; N-fixer	Reverse phenology; leafless in cropping season	Very deep; little dry-season competition	Strongly facilitative; raises associated crop yields	Garrity *et al.* (2010); Bayala *et al.* (2014)
Leucaena; *Leucaena leucocephala*	Fabaceae; N-fixer	Dense if unpruned; managed by pruning	Moderate; competes if unpruned	Facilitative as pruned hedgerow (N mulch); suppressive unpruned	Kang *et al.* (1985); Lawson and Kang (1990)
Gliricidia; *Gliricidia sepium*	Fabaceae; N-fixer	Open, pruned hedgerow	Shallow-moderate	Facilitative *via* N-rich mulch in humid zones	Sileshi *et al.* (2008); Kang *et al.* (1985)
Sesbania; *Sesbania* spp.	Fabaceae; N-fixer	Fast, short-lived; improved fallow	Shallow-moderate (2010)	Facilitative in rotational/ improved-fallow use Garrity *et al.*	Sileshi *et al.* (2008);
Pigeonpea; *Cajanus cajan*	Fabaceae; N-fixer (woody legume)	Open shrub; slow early growth	Deep tap-root; low early competition	Dual role-often the woody component; low penalty on companions	Daniel and Ong (1990)
Parkland acacias / mesquite; *Vachellia, Senegalia, Prosopis* spp.	Fabaceae; N-fixer	Open parkland canopy	Deep; ameliorates microclimate	Generally facilitative in dry parklands (groundnut, cowpea)	Bayala *et al.* (2014)
Poplar; *Populus deltoides*	Salicaceae; non-fixer	Deciduous; leafless in winter	Vigorous; competitive when dense or aged	Facilitative at wide spacing; loss rises with age and density	Chauhan *et al.* (2012); Chavan and Dhillon (2019)
Eucalyptus; *Eucalyptus* spp.	Myrtaceae; non-fixer	Evergreen, dense	Very high water use; allelopathic	Suppressive: shading + water competition + allelopathy	Jose *et al.* (2004)
Silver oak; *Grevillea robusta*	Proteaceae; non-fixer	Light, open canopy	Deep-rooted; relatively complementary	Comparatively legume-friendly; light shade, deep roots (1998)	Ong and Huxley (1996); Rao *et al.*
Shisham / Casuarina; *Dalbergia sissoo, Casuarina* spp.	Fabaceae / Casuarinaceae; N-fixer (incl. actinorhizal)	Open boundary timber	Deep; edge competition only	Boundary use: minimal interior effect; adds N	Dhyani *et al.* (2013); Nair (1993)
Walnut; *Juglans* spp.	Juglandaceae; non-fixer	Deciduous; temperate	Allelopathic (juglone)	Suppressive *via* allelopathy, independent of spacing	Jose *et al.* (2004)

The legumes divide along the same axis of temporal overlap (Table 3). The warm-season group, comprising pigeonpea, cowpea, mungbean, urdbean, soybean and groundnut, is sown when deciduous trees are in full leaf and therefore incurs the largest proportional reduction in intercepted radiation. The cool-season pulses, comprising chickpea, lentil, field pea and faba bean, are grown under low winter radiation, so that a given proportional reduction in transmitted light represents a larger absolute constraint even where the canopy above them is leafless. Within the warm-season group the responses differ according to growth habit and duration. Pigeonpea is frequently the woody component of the system rather than the understorey crop, an arrangement that removes interspecific competition for the legume altogether (Daniel and Ong, 1990). Cowpea and several mungbean genotypes are short in duration and morphologically plastic and adjust specific leaf area and internode length under shade in a manner that partly maintains light capture. Soybean and groundnut are the most shade-sensitive of the ten species and soybean is further penalised by lodging as stems elongate under a reduced red to far-red ratio. Faba bean and field pea fix the largest quantities of nitrogen but are also sensitive to reduced radiation, because fixation depends on the current supply of photosynthate. Shade tolerance is therefore a quantitative rather than a categorical trait and several species retain a substantial proportion of their open-field yield under moderate shade before declining sharply beyond a threshold (Umesh *et al.*, 2023; Pang *et al.*, 2019).

Table 3: Functional traits of legumes under agroforestry.

Legume (common; binomial)	Season / growth habit	Photoperiod and shade response	Typical N fixed / %Ndfa	Agroforestry niche	References
Chickpea; *Cicer arietinum*	Cool-season; erect annual	Low winter radiation; shade-sensitive at podding	~0-60 kg; low-moderate %Ndfa	*Rabi* interspace under deciduous/boundary trees	Herridge *et al.* (2008)
Pigeonpea; *Cajanus cajan*	Warm-season; woody perennial/ shrub	Deep-rooted; tolerant; slow early growth	~40-400 kg; high %Ndfa	Often the woody/hed gerow component itself	Daniel and Ong (1990); Herridge *et al.* (2008)
Cowpea; *Vigna unguiculata*	Warm-season; spreading annual	Relatively shade-adaptable; fast cycle	~8-200 kg; moderate-high	Alley and relay crop; living-mulch use	Herridge *et al.* (2008); Pang *et al.* (2019)
Mungbean; *Vigna radiata*	Warm-season; short-duration annual	Genotype-dependent plasticity; short cycle aids fit	~30-80 kg; moderate	Catch crop in tree interspaces	Herridge *et al.* (2008); Umesh *et al.* (2023)
Urdbean; *Vigna mungo*	Warm-season; short-duration annual	Moderately shade-tolerant; sparse AF data	~30-60 kg; moderate	Interspace/relay; under -studied under trees	Herridge *et al.* (2008);
Lentil; *Lens culinaris*	Cool-season; short erect annual	Low-light winter crop; shade-sensitive	~35-100 kg; moderate	*Rabi* boundary/wide-spaced agrisilviculture	Herridge *et al.* (2008)
Field pea; *Pisum sativum*	Cool-season; climbing/semi-leafless	Cool-tolerant; sensitive to deep shade	~50-150 kg; moderate-high	Temperate silvoarable; *rabi* interspace	Herridge *et al.* (2008); Pang *et al.* (2019)
Soybean; *Glycine max*	Warm-season; determinate annual	Strongly photophilic; lodging and yield loss under shade	~20-350 kg; high (esp. Brazil)	Wide-spaced/young-orchard interspace only	Cheng *et al.* (2022); Nasar *et al.* (2022)
Groundnut; *Arachis hypogaea*	Warm-season; geocarpic annual	C3; sensitive at pod fill; widely intercropped	~45-190 kg; moderate-high	Parkland and wide agrisilviculture	Herridge *et al.* (2008); Ghosh (2004)
Faba bean; *Vicia faba*	Cool-season; erect annual	Cool-moist tolerant; sensitive to deep shade	~75-220 kg; high %Ndfa	Temperate silvoarable; high-N contributor	Herridge *et al.* (2008); Peoples *et al.* (1995)

Legume productivity across agroforestry models

Reported legume yield declines with proximity to the tree row and with increasing canopy closure, but both the magnitude and the direction of the response vary with rainfall, tree functional type and management (Table 4; Fig 1). Cowpea, mungbean and pigeonpea retain a substantial proportion of their open-field yield under moderate shade, whereas soybean and groundnut sustain the largest losses, because pod filling coincides with the period of maximum canopy demand for radiation and water (Umesh *et al.*, 2023; Cheng *et al.*, 2022). This penalty is not fixed, since both the selection of shade-tolerant cultivars and the adjustment of nutrition recover part of it (Cheng *et al.*, 2022; Nasar *et al.*, 2022).

Facilitation is reported consistently where the tree is leafless during the cropping season or is pruned to that effect. Beneath *Faidherbia albida* in Malawi, maize yield has increased by up to approximately 280 per cent and legumes grown in the same parklands share that gain because the mechanism, namely nitrogen released from decomposing litter in the absence of shade, is not specific to the associated species (Garrity *et al.*, 2010). The alley cropping literature illustrates the same principle over a longer period and provides a useful historical benchmark. The early experiments of Kang *et al.* (1981, 1985) at Ibadan, conducted on humid and inherently fertile soils with frequent pruning of *Leucaena* hedgerows, established that companion crop yields could be sustained without fertiliser nitrogen. Later work in the same system showed that this outcome was contingent on those conditions rather than general, since yields declined as hedgerow density increased and pruning intervals lengthened (Lawson and Kang, 1990). The pattern that emerges across four decades is that the reported success of alley cropping tracks rainfall and the availability of pruning labour rather than the design itself.

Spatial arrangement modifies the magnitude of the response in a predictable manner. Understorey radiation falls steeply with proximity to the tree row and competition intensifies as stand age and density increase, but a large proportion of the resulting yield loss is recovered by widening the spacing between tree rows (Lawson and Kang, 1990; Chauhan *et al.*, 2012; Chavan and Dhillon, 2019). Spacing therefore functions as the principal management lever available after establishment and its effect operates through the same two variables that govern the system as a whole, namely transmitted radiation and the degree of root overlap.

Water availability determines whether these arrangements yield a net gain at all. In humid environments, nitrogen-fixing trees raise the yield of associated crops and meta-analytic evidence from sub-Saharan Africa supports this as a general result (Sileshi *et al.*, 2008). In semi-arid environments the same tree functional types compete with the crop for soil moisture during grain filling and the nitrogen benefit is offset or exceeded by that competition. Alley cropping and closely spaced agrisilviculture have accordingly failed to produce yield advantages in semi-arid India (Singh *et al.*, 1989; Doddabasawa *et al.*, 2021). These observations conform to the central agroforestry hypothesis, which states that a net production gain arises only where the tree acquires resources that the crop could not otherwise have captured (Cannell *et al.*, 1996).

Table 4: Comparative summary of legume productivity responses under agroforestry model.

Legume	Agrisilviculture	Alley cropping	Agrihorti-culture	Silvopastoral	Boundary plantation	Multistrata	References
Chickpea	↔ wide	↓	↔ estab.	-	↑ interior	↓↓	Umesh *et al.* (2023); Singh *et al.* (1989)
Pigeonpea	↑ (acts as tree)	↔ / hedge	↔	↔ fodder	↑	↔ shade-adapt	Daniel and Ong (1990)
Cowpea	↔-↑	↔ (humid ↑)	↑ estab.	↑ forage	↑	↓	Kang *et al.* (1985); Lawson and Kang (1990)
Mungbean	↔ wide	↔	↑ catch	-	↑	↓↓	Umesh *et al.* (2023)
Urdbean	↔	↔	↔	-	↑	↓↓	Sathiya *et al.* (2025)
Lentil	↔ wide	↓	↔ estab.	-	↑ interior	↓↓	Umesh *et al.* (2023)
Field pea	↔ wide	↓	↔	-	↑	↓↓	Pang *et al.* (2019); Umesh *et al.* (2023)
Soybean	↓ (↔ wide)	↓↓	↓ estab.	-	↔ -↓ edge	↓↓	Cheng *et al.* (2022); Nasar *et al.* (2022)
Groundnut	↔ parkland	↓	↔ estab.	↔	↑	↓↓	Ghosh (2004); Garrity *et al.* (2010)
Faba bean	↔ wide	↓	↔	-	↑	↓↓	Umesh *et al.* (2023)

↑ = Generally maintained or enhanced under good management; ↔ = Neutral or strongly context-dependent (sign varies with rainfall, tree type and management); ↓ = Generally reduced; ↓↓ = Typically strongly reduced; - = Little direct field evidence.

Nitrogen fixation, nutrient cycling and soil health

Biological nitrogen fixation is the principal reason for including legumes beneath trees, yet the evidence indicates that fixation does not proceed unaffected under a canopy. Reported inputs are large but variable, ranging from approximately 20 to 400 kg N ha^{-1} across the ten species, with pigeonpea and faba bean in the upper part of that range and chickpea in the lower part (Table 5; Herridge *et al.*, 2008; Peoples *et al.*, 1995).

The response of fixation to shade follows from its energetic cost. Nodule function is supplied by current photosynthate, so the reduction of nitrogenase activity under a canopy is a direct consequence of reduced carbon assimilation rather than an independent effect of low light. Under moderate shade on soils of low mineral nitrogen status the proportion of nitrogen derived from the atmosphere may be maintained or may rise, because scarce soil nitrogen sustains nodulation even as total plant biomass declines, while the quantity of nitrogen fixed per hectare nevertheless falls in proportion to that biomass. Under deep shade both the proportion and the quantity decline, because carbon limitation becomes severe enough to restrict nodule formation as well as nodule activity. Adequate phosphorus and micronutrient supply relaxes part of this constraint (Nasar *et al.*, 2022). Two mechanisms are therefore confounded in most reported comparisons, namely carbon limitation imposed by shade and nitrogen sparing imposed by low soil nitrogen and because they act in opposite directions on %Ndfa they cannot be separated without isotopic measurement.

Nitrogen entering the system from the tree component partly compensates for the reduction in fixation. Litter fall and prunings from nitrogen-fixing trees deliver nitrogen to the soil surface in quantities that substitute for a substantial part of the fertiliser requirement (Garrity *et al.*, 2010) and the deep root systems of trees intercept nutrients leached below the crop rooting zone and return them to the surface through litter, a process described as the safety-net function (Schroth, 1999; van Noordwijk and Lusiana, 1999).

Table 5: Nitrogen-fixation values for the focal legumes and reported soil and soil-organic-carbon (SOC) responses in legume-inclusive agroforestry.

Legume	%Ndfa (typical)	N fixed (kg ha^{-1})	Response of fixation under canopy / in AF	Reported soil / SOC effect of legume inclusion	References
Chickpea	Low-mod (≈20-60%)	0-60	Modest fixation; nitrate-sparing; sensitive to deep shade	Raises SOM and aggregate stability; reliable rotational N	Herridge *et al.* (2008); Peoples *et al.* (1995)
Pigeonpea	High (≈70-90%)	40-400	Maintained when acting as woody component; deep N capture	Strong litter/root C inputs; improves fertility and structure	Daniel and Ong (1990); Herridge *et al.* (2008)
Cowpea	Mod-high (≈30-80%)	8-200	Often maintained under moderate shade (N-sparing)	Fast residue turnover; good cover/green-manure C	Herridge *et al.* (2008); Peoples *et al.* (1995)
Mungbean	Moderate (≈50-70%)	30-80	Short cycle limits exposure; genotype-dependent	Modest but rapid residue C; weed suppression	Herridge *et al.* (2008)
Urdbean	Moderate	30-60	Sparse data; presumed similar to mungbean	Residue C and cover benefits; under-studied	Herridge *et al.* (2008)
Lentil	Moderate	35-100	Low-light winter crop; fixation curtailed by shade	Improves rotational N and structure on light soils	Herridge *et al.* (2008); Peoples *et al.* (1995)
Field pea	Mod-high	50-150	Cool-season fixation; sensitive to deep shade	High residue N; valuable temperate silvoarable C input	Herridge *et al.* (2008); Peoples *et al.* (1995)
Soybean	High (≈40-80%)	20-350	Falls with shade *via* C-limitation and lodging	Large residue/root C when yields maintained	Herridge *et al.* (2008); Cheng *et al.* (2022)
Groundnut	Mod-high (≈40-70%)	45-190	Maintained in parklands; sensitive at pod fill	Haulm C; improves P cycling and surface soil	Herridge *et al.* (2008); Ghosh (2004)
Faba bean	High (≈70-80%)	75-220	Among highest; cool-season; deep-shade sensitive	Largest cool-season N and residue C contributor	Herridge *et al.* (2008); Peoples *et al.* (1995)

Cumulative organic inputs from both components raise soil organic carbon. The largest relative gains occur on arid and degraded land, where the initial carbon stock is low (Shi *et al.*, 2018; Pan *et al.*, 2025) and further accumulation follows the conversion of cropland to agroforestry (De Stefano and Jacobson, 2018). Long-established systems accumulate carbon below the plough layer and Barman *et al.* (2025) reported enrichment of subsoil carbon pools under agroforestry in the Indian Himalaya, which indicates that accumulation is not confined to surface litter. The associated physical and biological changes, including improved aggregate stability, infiltration, erosion control and soil faunal activity, are reported consistently and are compatible with continued cropping under appropriate management (Muchane *et al.*, 2020; Rizvi *et al.*, 2020).

Resource-use efficiency and ecological interactions

Systems combining trees and legumes frequently return a land equivalent ratio above unity even where legume yield per unit area declines, because the tree produces output from resources the legume did not capture (Mead and Willey, 1980). In poplar-based systems in northern India the land equivalent ratio reaches approximately 1.75 to 2.28 and rises with wider tree spacing (Chavan and Dhillon, 2019) and optimised land configuration raises pigeonpea-equivalent yield above that of sole stands (Garud *et al.*, 2021). The distinction between yield per unit area and productivity per unit of land is therefore material to the interpretation of this literature, since a reported reduction in legume yield is fully compatible with an increase in total system output.

The position of a given system on the competition and facilitation continuum (Fig 2) is set by two measurable quantities, namely the proportion of incident radiation transmitted to the understorey and the degree of overlap between tree and crop root systems. Where root distributions are complementary in depth the tree draws on water and nutrients unavailable to the crop and where they overlap the two components compete, most severely where water is limiting (Ong and Huxley, 1996; Schroth, 1999). Process-based models such as WaNuLCAS represent these interactions explicitly and have been used to identify the spacings and pruning regimes that maximise complementarity for a given rainfall regime (van Noordwijk and Lusiana, 1999). Microclimate amelioration constitutes a separate facilitative mechanism, since the reduction in canopy temperature and vapour pressure deficit beneath scattered trees protects legumes from heat stress in hot and dry conditions (Bayala *et al.*, 2014; Sudhalakshmi *et al.*, 2022). Allelopathy is distinct from resource competition and, because it is mediated by chemical inhibition rather than resource capture, it cannot be relieved by increasing spacing alone (Jose *et al.*, 2004).

Legume-inclusive agroforestry delivers provisioning, regulating, supporting and cultural services within a single working landscape (Jose, 2009). Meta-analytic evidence indicates that it raises overall service provision relative to conventional agriculture, with consistent gains in erosion control and soil fertility but weaker and more variable biodiversity responses (Torralba *et al.*, 2016), while the most comprehensive global synthesis to date confirms multifunctionality and reports greater biodiversity, with the largest gains in carbon storage and regulating services under drier conditions (Mathieu *et al.*, 2025). For climate change mitigation, carbon is stored both in woody biomass and in soil and the nitrogen fixed by the legume displaces the emissions associated with fertiliser manufacture and application. The mitigation dividend is largest on arid and degraded land (Pan *et al.*, 2025) and smallest and may be negative, where agroforestry replaces natural forest rather than cropland (De Stefano and Jacobson, 2018).

Table 6: Economic and sustainability indicators for legume agroforestry systems, with time profile/risk.

System	Reported economic indicator	Time profile / risk	References
Poplar-based agroforestry (Indo-Gangetic Plains, India)	LER typically ≈1.75-2.28; benefit-cost ratio favourable vs sole cropping	Multi-year payback; tree-market price risk; benefits rise with wide spacing	Chavan and Dhillon (2019)
Pigeonpea-based systems (*e.g.*, pigeonpea-yam, West Africa)	Higher profitability than monocropping in smallholder analyses	Legume is the perennial - short lag; low input cost	Owusu Danquah *et al.* (2023)
Groundnut-cereal association (semi-arid India)	Improved gross returns and land-use efficiency	Water-limited years erode advantage	Ghosh (2004)
Nutri-cereal–legume intercrop (urdbean, pigeonpea; Tamil Nadu)	Improved economic returns and climate resilience	Rainfed; benefit varies with season and market	Sathiya *et al.* (2025)
Fertiliser-tree / evergreen agriculture (southern Africa)	Large maize-yield gains (up to ~280% under Faidherbia) at low cash cost	Establishment lag; benefits build over years	Garrity *et al.* (2010)
Alley cropping (humid and semi-arid tropics)	Agronomic gains possible but labour cost often exceeds benefit	Pruning labour decisive; fails where water-limited	Kang *et al.* (1985); Singh *et al.* (1989)

In marginal environments the adaptive value of these systems, expressed through buffered microclimate and diversified production, is likely to exceed their mitigation value (Bayala *et al*., 2014; Garrity *et al*., 2010).

Economic and sustainability perspectives

Adoption is determined ultimately by economic return (Table 6). Commercial poplar-based agroforestry in northern India is profitable across a range of configurations, with favourable benefit to cost ratios and land equivalent ratios above unity (Chavan and Dhillon, 2019). Pigeonpea-based systems derive an advantage from the legume itself constituting the perennial component, which shortens the interval between establishment and first return (Owusu Danquah *et al*., 2023; Pandey *et al*., 2021). Groundnut and cereal associations and nutri-cereal and legume associations, raise returns and stabilise them against seasonal variation where water supply permits (Ghosh, 2004; Sathiya *et al*., 2025), which is consistent with the broader gains in resource-use efficiency, soil fertility and income reported for legume intercropping (Akchaya *et al*., 2025). India recognised the sector in policy through the National Agroforestry Policy of 2014, the first national policy of its kind (National Agroforestry Policy, 2014).

Three constraints recur across the economic literature and qualify these returns. Returns lag during the establishment phase, which bears most heavily on resource-poor cultivators who cannot forgo income for several seasons. Labour requirements and particularly the timely pruning on which alley cropping depends, constitute a decisive cost and account for much of the limited adoption of that model beyond experimental stations. Profitability is also exposed to price risk in tree products, which are marketed at longer intervals and through less regulated channels than annual crops. Sustainability assessment carries a further temporal dimension, because gains in soil carbon, fertility and resilience accrue over years to decades and are not detected by appraisals conducted over a single season.

Agroforestry configurations best matched to grain legume production

The evidence assembled in Table 4 to 6 supports a narrower set of recommendations than the range of systems reported in the literature. In the humid and sub-humid zone, alley cropping with regularly pruned *Leucaena* or *Gliricidia* hedgerows and agrisilviculture with widely spaced deciduous nitrogen-fixing trees both sustain legume yield, so that the choice between them rests on the availability of pruning labour rather than on agronomic performance. Where labour is constrained, widely spaced agrisilviculture is preferable, because it delivers a comparable nitrogen benefit without a recurrent pruning requirement.

In the semi-arid zone the systems that perform reliably are those that minimise root overlap during grain filling. Boundary plantation is the most consistent of these, because it confines competition to the outer rows and leaves the field interior at close to open-field productivity while still returning litter and providing windbreak protection. Scattered-tree parkland systems based on reverse-phenology species, of which *Faidherbia albida* is the type example, are the only within-field configuration for which facilitation is reported consistently under low rainfall, because the tree is leafless during the cropping season and its water use is displaced to the dry season. Dense alley cropping and closely spaced agrisilviculture should not be recommended for grain legume production in this zone, since the reported outcome is yield loss (Singh *et al*., 1989; Doddabasawa *et al*., 2021).

In both zones the legume component should be selected for morphological plasticity and short duration. Cowpea, mungbean and pigeonpea maintain yield under the moderate shade characteristic of these configurations, whereas soybean, groundnut and the cool-season pulses should be confined to boundary plantations or to the widest agrisilvicultural spacings. Pigeonpea occupies a particular position, because it can serve as the woody component itself and thereby eliminates interspecific competition for the legume while retaining the nitrogen and soil benefits of a perennial.

Taken together, the evidence identifies one system as best matched to grain legume production, namely widely spaced agrisilviculture in which the woody component is a deciduous or regularly pruned nitrogen-fixing tree, inter-row spacing is wide enough to maintain understorey radiation through grain filling and the arable component is a plastic, short-duration warm-season legume. This system is placed first because it is the only configuration that satisfies the three requirements identified above simultaneously, since wide spacing maintains radiation during grain filling, it also limits root overlap during the period of peak crop water demand and the nitrogen-fixing tree retains the litter and prunings on which the soil benefits of agroforestry depend. Boundary plantation ranks second and becomes the preferred option below approximately 750 mm of annual rainfall, because confining the trees to bunds and field margins removes competition for soil water from the field interior while retaining litter return and windbreak protection. Pruned-hedgerow alley cropping ranks third, being highly productive in the humid zone but only where pruning labour is reliably available. Agrihorticulture is suitable only during the orchard establishment phase, before canopy closure. Multistrata systems, silvopasture and closely spaced agrisilviculture are not recommended for grain legume production, the first two because understorey radiation is insufficient for grain filling and the third because root competition for water outweighs the nitrogen benefit in all but the most humid and fertile sites.

Knowledge gaps and future research priorities

The evidence assembled here is uneven in four respects and each gap constrains the generality of the conclusions above. Coverage is concentrated on soybean, groundnut, cowpea and pigeonpea grown beneath fast-growing tropical trees, so that cool-season pulses and temperate silvoarable systems are represented by few studies and the conclusions drawn for them rest on inference from physiology rather than on direct measurement. Experimental designs are predominantly single-factor, comparing spacings or species in isolation, whereas the interactions identified in this review require factorial genotype by tree by environment experiments; the genotype axis of such designs is now tractable, since shade-tolerance markers derived from genome-wide association studies are available in soybean (Jia *et al.*, 2024). Nitrogen fixation under canopies remains poorly resolved, because carbon limitation and nitrogen sparing are rarely separated and because the belowground transfer of fixed nitrogen between the legume and the tree has seldom been quantified. Long-term, whole-system evidence integrating agronomic, soil, ecosystem-service and economic outcomes is scarce and the standardised reporting of tree spacing, pruning regime, rainfall, soil type and land equivalent ratio that would permit meta-analysis is not yet routine.

CONCLUSION

Legume performance in agroforestry depends less on the agroforestry model itself than on the interactions among the crop, tree and environment. The functional traits of both trees and legumes, their spatial and temporal arrangement, management practices and site conditions together determine whether tree-crop interactions are facilitative or competitive. Among these factors, the balance between understorey light availability and soil water supply is often the primary determinant of performance. Where soil moisture is adequate, trees can enhance legume productivity by contributing biologically fixed nitrogen, recycling nutrients through litter and mulch, moderating the microclimate and accessing water and nutrients from deeper soil layers. Under water-limited conditions, however, competition for soil moisture frequently outweighs these benefits, leading to reductions in legume growth and yield. These contrasting outcomes largely reflect differences in legume physiology. Soybean, groundnut and most cool-season pulses are generally the most shade-sensitive species, whereas cowpea, mungbean and pigeonpea are more tolerant of partial shade and therefore integrate more successfully into tree-based systems. Similarly, tree species selection and canopy management strongly influence the balance between facilitation and competition. Wide tree spacing, regular canopy pruning, deciduous nitrogen-fixing trees and the use of shade-tolerant legume cultivars generally promote complementary interactions, whereas dense evergreen canopies, deep-rooted tree species, or species with strong allelopathic effects are more likely to intensify competition and reduce legume productivity.

Evidence accumulated over the past fifteen years across environments ranging from humid to semi-arid regions indicates that successful grain legume production depends on matching agroforestry design to local environmental conditions. In most situations, the most effective configuration is a widely spaced agrisilvicultural or boundary plantation system with deciduous or regularly pruned nitrogen-fixing trees, combined with adaptable, short-duration warm-season legumes such as cowpea, mungbean, or pigeonpea. In humid regions, where pruning can be carried out regularly, these systems can be further intensified through pruned-hedgerow alley cropping without substantially reducing crop productivity. In contrast, semi-arid environments require more conservative designs. Boundary plantations and reverse-phenology species such as *Faidherbia albida* are generally more suitable, whereas dense within-field tree arrangements should be avoided because they intensify competition for soil moisture. When appropriately designed and managed, legume-based agroforestry systems not only sustain crop production but also enhance soil organic carbon, contribute biologically fixed nitrogen, increase carbon storage in biomass and soil and diversify farm income. Future research should move beyond single-factor evaluations towards factorial experiments that integrate legume genotype, tree species and environmental conditions to better explain variation in system performance. Greater attention is also needed to quantify the fate and long-term contribution of biologically fixed nitrogen within agroforestry systems.

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Disclaimers

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Informed consent

This article is a review based entirely on previously published literature and did not involve any new studies with human participants or animals performed by the author.

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References

Akchaya, K., Parasuraman, P., Pandian, K., Vijayakumar, S., Thirukumaran, K., Mustaffa, M.R.A.F., Rajpoot, S.K. and Choudhary, A.K. (2025). Boosting resource use efficiency, soil fertility, food security, ecosystem services and climate resilience with legume intercropping: A review. *Frontiers in Sustainable Food Systems*. **9:** 1527256. doi: 10.3389/fsufs.2025.1527256.

Barman, S., Bhattacharyya, R., Singh, C., Rathore, A.C., Singhal, V., Biswas, D.R., Ahmed, N., Das, S. *et al.* (2025). Long-term agroforestry enhances soil organic carbon pools and deep soil carbon sequestration in the Indian Himalayas. *Frontiers in Environmental Science*. **13:** 1568564. doi: 10.3389/fenvs.2025.1568564.

Bayala, J., Sanou, J., Teklehaimanot, Z., Kalinganire, A. and Ouedraogo, S.J. (2014). Parklands for buffering climate risk and sustaining agricultural production in the Sahel of West Africa. *Current Opinion in Environmental Sustainability*. **6:** 28-34.

Cannell, M.G.R., van Noordwijk, M. and Ong, C.K. (1996). The central agroforestry hypothesis: The trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems*. **34(1):** 27-31. doi: 10.1007/BF00129630.

Chauhan, S.K., Brar, M.S. and Sharma, R. (2012). Performance of poplar (*Populus deltoides* Bartr.) and its effect on wheat yield under agroforestry system in irrigated agro-ecosystem, India. *Caspian Journal of Environmental Sciences*. **10(1):** 53-60.

Chavan, S.B. and Dhillon, R.S. (2019). Doubling farmers' income through Populus deltoides-based agroforestry systems in north-western India: An economic analysis. *Current Science*. **117(2):** 219-227.

Cheng, B., Wang, L., Liu, R., Wang, W., Yu, R., Zhou, T. and Yang, W. (2022). Shade-tolerant soybean reduces yield loss by regulating its canopy structure and stem characteristics in the maize-soybean strip intercropping system. *Frontiers in Plant Science*. **13:** 848893. doi: 10.3389/fpls.2022.848893.

Daniel, J.N. and Ong, C.K. (1990). Perennial pigeonpea: A multipurpose species for agroforestry systems. *Agroforestry Systems*. **10(2):** 113-129. doi: 10.1007/BF00115360.

De Stefano, A. and Jacobson, M.G. (2018). Soil carbon sequestration in agroforestry systems: A meta-analysis. *Agroforestry Systems*. **92(2):** 285-299. doi: 10.1007/s10457-017-0147-9.

Dhyani, S.K., Handa, A.K. and Uma. (2013). Area under agroforestry in India: An assessment for present status and future perspective. *Indian Journal of Agroforestry*. **15(1):** 1-11.

Doddabasawa, Chittapur, B.M. and Mahadeva Murthy, M. (2021). Productivity of pigeonpea [*Cajanus cajan* (L.) Millsp.] under teak (*Tectona grandis*) based agroforestry systems in semiarid tropics. *Legume Research*. **44(9):** 1092-1096. doi: 10.18805/LR-4214.

Garrity, D.P., Akinnifesi, F.K., Ajayi, O.C., Weldesemayat, S.G., Mowo, J.G., Kalinganire, A., Larwanou, M. and Bayala, J. (2010). Evergreen agriculture: A robust approach to sustainable food security in Africa. *Food Security*. **2(3):** 197-214. doi: 10.1007/s12571-010-0070-7.

Garud, H.S., Asewar, B.V., Chavan, A.A., Gokhale, D.N. and Narkhede, W.N. (2021). Production potential of pigeon pea based intercropping systems under various land configurations in Marathwada region of Maharashtra. *Legume Research*. **44(8):** 947-951. doi: 10.18805/LR-4398.

Ghosh, P.K. (2004). Growth, yield, competition and economics of groundnut/cereal fodder intercropping systems in the semi-arid tropics of India. *Field Crops Research*. **88(2-3):** 227-237. doi: 10.1016/j.fcr.2004.01.015.

Giller, K.E. (2001). Nitrogen Fixation in Tropical Cropping Systems. 2nd edn. CABI Publishing, Wallingford, UK.

Herridge, D.F., Peoples, M.B. and Boddey, R.M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil*. **311(1-2):** 1-18. doi: 10.1007/s11104-008-9668-3.

Jia, Q., Hu, S., Li, X., Wei, L., Wang, Q., Zhang, W., Zhang, H., Liu, X., Chen, X., Wang, X. and Chen, H. (2024). Identification of candidate genes and development of KASP markers for soybean shade-tolerance using GWAS. *Frontiers in Plant Science*. **15:** 1479536. doi: 10.3389/fpls.2024.1479536.

Jose, S. (2009). Agroforestry for ecosystem services and environmental benefits: An overview. *Agroforestry Systems*. **76(1):** 1-10. doi: 10.1007/s10457-009-9229-7.

Jose, S., Gillespie, A.R. and Pallardy, S.G. (2004). Interspecific interactions in temperate agroforestry. *Agroforestry Systems*. **61(1-3):** 237-255. doi: 10.1023/B:AGFO.0000029002.85273.9b.

Kang, B.T., Grimme, H. and Lawson, T.L. (1985). Alley cropping sequentially cropped maize and cowpea with leucaena on a sandy soil in southern Nigeria. *Plant and Soil*. **85(2):** 267-277. doi: 10.1007/BF02139631.

Kang, B.T., Wilson, G.F. and Sipkens, L. (1981). Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* Lam.) in southern Nigeria. *Plant and Soil*. **63(2):** 165-179. doi: 10.1007/BF02374595.

Kumar, B.M. and Nair, P.K.R. (2004). The enigma of tropical homegardens. *Agroforestry Systems*. **61(1-3):** 135-152.

Kumar, M., Larkin, A. and Daniel, S. (2020). Effect of silver oak (*Grevillea robusta*) and poplar (*Populus deltoides*) based agroforestry systems on growth and yield attributes of different varieties of wheat (*Triticum aestivum*) in Dehradun region. *Ecology, Environment and Conservation*. **26(Suppl.):** S256-S262.

Lawson, T.L. and Kang, B.T. (1990). Yield of maize and cowpea in an alley cropping system in relation to available light. *Agricultural and Forest Meteorology*. **52(3-4):** 347-357. doi: 10.1016/0168-1923(90)90091-J.

Mathieu, A., Martin-Guay, M.O. and Rivest, D. (2025). Enhancement of agroecosystem multifunctionality by agroforestry: A global quantitative summary. *Global Change Biology*. **31(5):** e70234. doi: 10.1111/gcb.70234.

Mead, R. and Willey, R.W. (1980). The concept of a 'land equivalent ratio' and advantages in yields from intercropping. *Experimental Agriculture*. **16(3):** 217-228. doi: 10.1017/S0014479700010978.

Muchane, M.N., Sileshi, G.W., Gripenberg, S., Jonsson, M., Pumarino, L. and Barrios, E. (2020). Agroforestry boosts soil health in the humid and sub-humid tropics: A meta-analysis. *Agriculture, Ecosystems and Environment*. **295:** 106899. doi: 10.1016/j.agee.2020.106899.

Nair, P.K.R. (1985). Classification of agroforestry systems. *Agroforestry Systems*. **3(2):** 97-128. doi: 10.1007/BF00122638.

Nair, P.K.R. (1993). An Introduction to Agroforestry. Kluwer Academic Publishers (in cooperation with ICRAF), Dordrecht.

Nair, P.K.R., Kumar, B.M. and Nair, V.D. (2009). Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*. **172(1):** 10-23. doi: 10.1002/jpln.200800030.

Nair, P.K.R., Kumar, B.M. and Nair, V.D. (2021). An Introduction to Agroforestry: Four Decades of Scientific Developments. 2nd edn. Springer, Cham. doi: 10.1007/978-3-030-75358-0.

Nasar, J., Wang, G.Y., Zhou, F.J., Gitari, H., Zhou, X.B., Tabl, K.M., Hasan, M.E., Ali, H., Waqas, M.M., Ali, I. and Jahan, M.S. (2022). Nitrogen fertilization coupled with foliar application of iron and molybdenum improves shade tolerance of soybean under maize-soybean intercropping. *Frontiers in Plant Science*. **13:** 1014640. doi: 10.3389/fpls.2022.1014640.

National Agroforestry Policy (2014). National Agroforestry Policy 2014. Department of Agriculture and Cooperation, Ministry of Agriculture, Government of India, New Delhi.

Ong, C.K. and Huxley, P. (1996). Tree-Crop Interactions: A Physiological Approach. CAB International, Wallingford, UK.

Owusu Danquah, E., Dissanayake, H.G., Danquah, F.O., Weebadde, C., Acheampong, P.P. and Ennin, S.A. (2023). Financial analysis of pigeon pea-yam cropping system options and implications on profitability of smallholder farmers in Ghana. *Agroforestry Systems*. **97(1):** 69-79. doi: 10.1007/s10457-022-00788-x.

Pan, J., Chen, S., He, D., Zhou, H., Ning, K., Ma, N., Li, K., Liao, D., Mi, W., Wu, Q., Zhang, C. and Dong, Z. (2025). Agroforestry increases soil carbon sequestration, especially in arid areas: A global meta-analysis. *Catena*. **249:** 108667. doi: 10.1016/j.catena.2024.108667.

Pandey, I.B., Tiwari, S. and Singh, R.S. (2021). Production potential and economic feasibility of planting pattern and nutrient management in pigeonpea (*Cajanus cajan*) based inter cropping system under rainfed condition. *Legume Research*. **44(11):** 1284-1292. doi: 10.18805/LR-4226.

Pang, K., Van Sambeek, J.W., Navarrete-Tindall, N.E., Lin, C.H., Jose, S. and Garrett, H.E. (2019). Responses of legumes and grasses to non-, moderate and dense shade in Missouri, USA. II. Forage quality and its species-level plasticity. *Agroforestry Systems*. **93(1):** 25-38. doi: 10.1007/s10457-017-0068-7.

Peoples, M.B., Herridge, D.F. and Ladha, J.K. (1995). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant and Soil*. **174(1-2):** 3-28. doi: 10.1007/BF00032239.

Rao, M.R., Nair, P.K.R. and Ong, C.K. (1998). Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems*. **38(1-3):** 3-50. doi: 10.1023/A:1005971525590.

Rizvi, R.H., Handa, A.K., Sridhar, K.B., Singh, R.K., Dhyani, S.K., Rizvi, J. and Dongre, G. (2020). Spatial analysis of area and carbon stocks under populus deltoides-based agroforestry systems in Punjab and Haryana states of the Indo-Gangetic Plains. *Agroforestry Systems*. **94(6):** 2185-2197.

Sanchez, P.A. (1995). Science in agroforestry. *Agroforestry Systems*. **30(1-2):** 5-55. doi: 10.1007/BF00708912.

Sathiya, K., Nirmalakumari, A., Shri Rangasami, S.R., Vanitha, C., Harisudan, C., Ayyadurai, P., Karthikeyan, R. and Ajaykumar, R. (2025). Econometric analysis and intercropping nutri-cereals with legumes (urad bean, arhar) on climate resilience in North Eastern Zone of Tamil Nadu. *Legume Research*. **48(1):** 117-123. doi: 10.18805/LR-5399.

Schroth, G. (1999). A review of belowground interactions in agroforestry, focussing on mechanisms and management options. *Agroforestry Systems*. **43(1-3):** 5-34. doi: 10.1023/A:1026443018920.

Shi, L., Feng, W., Xu, J. and Kuzyakov, Y. (2018). Agroforestry systems: Meta-analysis of soil carbon stocks, sequestration processes and future potentials. *Land Degradation and Development*. **29(11):** 3886-3897. doi: 10.1002/ldr.3136.

Sileshi, G., Akinnifesi, F.K., Ajayi, O.C. and Place, F. (2008). Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant and Soil*. **307(1-2):** 1-19. doi: 10.1007/s11104-008-9547-y.

Singh, R.P., Ong, C.K. and Saharan, N. (1989). Above and below ground interactions in alley-cropping in semi-arid India. *Agroforestry Systems*. **9(3):** 259-274.

Stagnari, F., Maggio, A., Galieni, A. and Pisante, M. (2017). Multiple benefits of legumes for agriculture sustainability: An overview. *Chemical and Biological Technologies in Agriculture*. **4:** 2. doi: 10.1186/s40538-016-0085-1.

Sudhalakshmi, C., Rani, S., Sathyamoorthi, N.K., Meena, B., Ramanathan, S.P. and Geethalakshmi, V. (2022). Microclimate modification through groundnut-pigeon pea intercropping system and its effect on physiological responses, disease incidence and productivity. *Legume Research*. **45(9):** 1122-1129. doi: 10.18805/LR-4747.

Torralba, M., Fagerholm, N., Burgess, P.J., Moreno, G. and Plieninger, T. (2016). Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis. *Agriculture, Ecosystems and Environment*. **230:** 150-161. doi: 10.1016/j.agee.2016.06.002.

Umesh, M.R., Angadi, S., Begna, S., Gowda, P. and Prasad, P.V.V. (2023). Shade tolerance response of legumes in terms of biomass accumulation, leaf photosynthesis and chlorophyll pigment under reduced sunlight. *Crop Science*. **63(1):** 278-292. doi: 10.1002/csc2.20851.

van Noordwijk, M. and Lusiana, B. (1999). WaNuLCAS, a model of water, nutrient and light capture in agroforestry systems. *Agroforestry Systems*. **43(1-3):** 217-242. doi: 10.1023/A:1026417120254.