Agroforestry-Based Carbon Sequestration and Biodiversity Enhancement in Temperate Farming Systems

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ABSTRACT

Although agroforestry is actively promoted as a climate-smart land-use approach that can harmonize agricultural productivity with carbon sequestration and biodiversity conservation, the comparative evidence of this practice from temperate farming areas continues to be limited. This paper presents findings of a comparative study on four agroforestry systems—alley cropping, silvopastoral systems, windbreak systems, and riparian buffers—against conventional monoculture cropping in a cool-temperate mixed farming landscape. The main aim was to measure total ecosystem carbon stocks and analyze biodiversity response among plant, bird, pollinator, and soil animal communities. There were significantly more carbon pools in agroforestry than conventional agriculture, especially riparian buffers and silvopasture, while the highest rate of annual carbon accumulation per unit of area was observed in windbreak systems and alley cropping. In terms of biodiversity, diverse indexes in the case of tree-based systems as compared to conventional cropping were higher, while soil biological parameters were better as well—having the highest values with the increase of the woody cover and litter. Principal component analyses revealed a good correlation between carbon accumulation, biodiversity indices, and soil quality indicators. turnover. These results corroborate the scientific position that incorporating trees in temperate farming systems provides real co-benefits regarding climate change mitigation and biodiversity conservation, without any need for causing agricultural production displacement. The results have strong implications for developing land use policies, carbon credit schemes, as well as actual implementation of agroforestry systems into agricultural practice, so as to attain long-term environmental sustainability.

Keywords: silvopasture, alley cropping, riparian buffer, soil organic carbon, ecosystem services, climate-smart land use, functional biodiversity, sustainable land management

1. Introduction

Agroforestry, which is the intentional incorporation of trees with crops and/or livestock within the same land management unit, has been considered one of the most widely accepted land-use practices to balance agricultural production with environmental sustainability (Nair, 1985) [1] (Jose, 2009) [2]. Different from conventional monoculture systems, agroforestry practices combine the structural and functional features of trees and agricultural crops. Accordingly, agroforestry practices help to create a mixture of above- and below-ground processes impacting carbon cycling, nutrient dynamics, microclimates, and habitat availability (Torralba *et al*., 2016) [3]. With growing interest in land-based solutions to climate change issues, agroforestry practices have been acknowledged in documents issued by the IPCC and considered in the context of international climate-smart agriculture initiatives due to their capacity to provide adaptation and mitigation outcomes at the same time (IPCC, 2019) [4] (Rosenstock *et al*., 2019) [5].

The problems climate change presents in agriculture are growing steadily and include changes in rainfall patterns, increased incidences of droughts and heat waves as well as shifting pests and diseases (Trnka *et al*., 2011) [6]. As a result of these changes, there is an increasing awareness of land management practices which can increase agricultural resilience while helping meet the GHG mitigation goals. Agroforestry allows for achieving both objectives since trees help soften extreme microclimatic conditions, improve soil structure, and increase farm revenue streams while simultaneously serving as long-term carbon sinks through both woody biomass accumulation and root turnover processes (Cardinael *et al*., 2017) [7] (Kim *et al*., 2016) [8].

Carbon sequestration in agroforestry systems is achieved through multiple pathways and mechanisms, both aboveground and belowground. In the case of aboveground systems, a large amount of carbon is stored in stationary woody biomass over many years. Rates of carbon sequestration depend on several factors, such as tree species, planting density and the technique of management (Feliciano *et al*., 2018) [9]. Below the ground, the turnover of fine roots and mycorrhizal fungi contributes to the formation of stable carbon fractions in the soil that is unaffected by other processes of carbon removal, like continual tillage (Cardinael *et al*., 2018) [10] (Hübner *et al*., 2021) [11]. However, the meta-analytical results of studies concerning agricultural systems in temperate climate revealed that the rates of carbon accumulation in soils are 0.2-0.3 Mg C ha-1 yr-1 for hedgerow and alley cropping systems, while other configurations specific for the silvopastoral system deliver lesser results which can be either positive or negative depending on the grazing intensity and initial land use history (Hübner *et al*., 2021) [11] (Shi *et al*.,

2018) [12]. Numerous studies, covering systems of both tropical and temperate regions present information about The total carbon accumulation varies greatly depending on the type of agroforestry practiced, from less than one ton of CO_2 per hectare per year in systems with low management levels to over 6 tons of CO_2 per hectare in cases where fast-growing crops and good site conditions play a part (Montagnini and Nair, 2004) [13] (Nair *et al*., 2010) [14]. The range in total carbon accumulation indicates that specific evidence from various agroforestry practices should be utilized to make land management decisions, as opposed to generic averages derived from global statistics.

Besides carbon, agroforestry systems also provide benefits in terms of biodiversity of agricultural landscapes. The presence of agroforestry trees contributes to creation of vertical and horizontal diversity that leads to formation of more resources available for different kinds of animals, thus creating niches for birds and invertebrates to find their habitats (Fagerholm *et al*., 2016) [15]. Agroforestry systems influence the moisture of the soils, thus stabilizing streambanks and decreasing nutrient and sediment loading into streams creating favorable conditions for various terrestrial and aquatic species to flourish (Stutter *et al*., 2012) [18]. Pollinator population improved significantly due to the presence of flower gardens in agroforestry systems (Varah *et al*., 2020) [16] (Staton *et al*., 2021) [17].

Services from ecosystems delivered by agroforestry go beyond simply providing carbon and biodiversity to also include better soil quality, increased water infiltration and retention, cycling of nutrients, and regulation of the microclimate that lowers heat and wind stress of neighboring crops and livestock (Udawatta *et al*., 2019) [20] (Kay *et al*., 2019) [21]. Soil improvement from organic matter, specifically tree litter, helps to increase microbial biomass in the soil and give rise to activities of enzymes found in the soil and elements which help in mineralization of nutrients (Bardgett and van der Putten, 2014) [22]. Therefore it can be said that agroforestry acts as a multifunctional land use, which is in accordance with the principles of climate-smart agriculture (Lipper *et al*., 2014) [23].

Though a lot of supporting data is available, certain gaps remain in this area of research. To start, most comparative studies relating to carbon stored in agroforestry systems and its effect on biodiversity are from tropical systems or case studies based on specific systems. Therefore, it is difficult to make any relevant comparisons between various agroforestry systems under controlled temperate conditions (Cardinael *et al*., 2018) [24]. Apart from that, there are very few works integrating carbon emissions, biodiversity, and soil quality in one research work, so little is known about how all these variables are interconnected (Tsonkova *et al*., 2012) [25]. Lastly, the differentiating features of the main temperate agroforestry systems have scarcely been studied comparatively with respect to conventional farming methods that could probably bring important implications to the development of effective land use policies (de Stefano and Jacobson, 2018) [26] (Pantera *et al*., 2018) [27].

The existing research fills the gap in the existing literature by assessing the impact of agroforestry on carbon sequestration, biodiversity, and soil quality by comparing 4 different agroforestry systems in a uniform experimental design. The primary aims of the study were: i) to assess aboveground and belowground carbon stocks as well as soil litter and organic carbon pools and measures, ii) to identify the changes in the diversity of plants and animals in agroforestry systems, including birds, pollinators, insects, and microorganisms, iii) to analyze soil quality by evaluating its physical, chemical and biological characteristics based on the land-use type and iv) to develop models of the connections between carbon, biodiversity, and soil quality indicators in order to estimate their potential impact on the ecosystem. Thus, the goal of the research is to gather scientific knowledge to provide a solid evidence base on the sustainable land-use practices, climate change mitigation policy, and agroforestry application types (Jose, 2009) [2] (Lipper *et al*., 2014) [23].

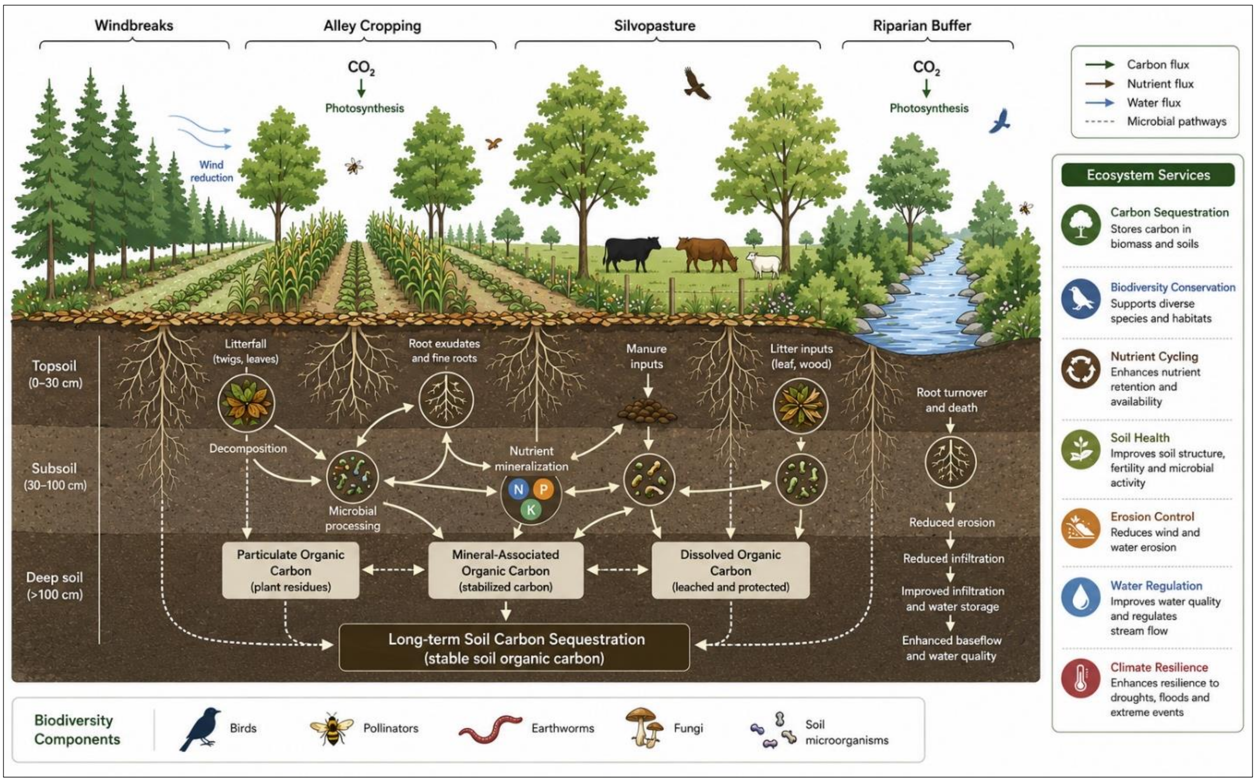

Fig 1: Integrated temperate agroforestry landscape illustrating carbon flux pathways, soil carbon pools, biodiversity components, and ecosystem services.

2. Materials and Methods

2.1. Study Area

The study was conducted within a cool-temperate mixed farming landscape characterized by a maritime-influenced climate, with mean annual temperature of approximately 9.8 °C and mean annual precipitation of approximately 850 mm distributed relatively evenly across the year. Soils across the study landscape are predominantly classified as Cambisols with a loam to sandy-loam texture, moderate natural fertility, and a long history of mixed arable and livestock farming extending over several decades. The landscape lies at an elevation range of approximately 60–140 m above sea level, with gently undulating topography. Field-scale agroforestry systems evaluated in this study had been established for a period of 12–18 years at the time of assessment, providing sufficient time for measurable divergence in carbon stocks and biological communities relative to adjacent conventionally managed land (Table 1).

Table 1: Study area characteristics including climate, soil type, altitude, and land-use history.

Parameter	Description
Location type	Cool-temperate mixed farming landscape
Elevation range	60–140 m a.s.l.
Mean annual temperature	9.8 °C
Mean annual precipitation	850 mm
Dominant soil classification	Cambisol (loam to sandy loam)
Regional land-use history	Mixed arable and livestock farming (>50 years)
Agroforestry system age at assessment	12–18 years since establishment
Assessment duration	2 consecutive years, seasonal sampling

2.2. Agroforestry Systems Evaluated

Five land-use treatments were considered conceptually and assessed comparatively:

- **Alley cropping**, in which rows of deciduous trees are interspersed with arable crop strips, allowing periodic tree management (pruning, coppicing) alongside continuous or rotational cropping.
- **Silvopasture**, integrating widely spaced trees with managed grazing livestock and an understorey forage sward.
- **Windbreak systems**, comprising linear tree belts positioned to reduce wind erosion and moderate microclimate in adjacent cropland, without direct integration of trees within the cropped area itself.
- **Riparian buffer systems**, consisting of multi-strata woody vegetation established along watercourses to intercept runoff, stabilize streambanks, and provide continuous habitat corridors.
- **Conventional farming (control)**, representing continuous arable cropping or improved pasture without woody perennial components, managed according to regionally typical practices.

Table 2: Experimental design, treatments, plot size, replication, and observation schedule.

Treatment	Plot size (ha)	Replicates (blocks)	Observation frequency
Alley cropping	0.8	4	Seasonal (4×/yr)
Silvopasture	1.0	4	Seasonal (4×/yr)
Windbreak system	0.5	4	Seasonal (4×/yr)
Riparian buffer	0.6	4	Seasonal (4×/yr)
Conventional control	0.8	4	Seasonal (4×/yr)

2.3. Experimental Design

A randomized complete block design was used, with each of the five land-use treatments replicated across four spatially independent blocks distributed across the study landscape to account for underlying soil and microclimatic variation (Table 2). Individual plots measured approximately 0.5–1.0 ha depending on treatment, with buffer zones maintained between adjacent treatments to minimize edge effects on soil and biodiversity sampling. Tree species selection reflected regionally appropriate temperate species valued for timber, fruit, or ecological function (Table 3), while companion crop and forage species reflected common temperate arable and pastoral practice (Table 4). Sampling and observation were conducted on a seasonal basis across two consecutive years, encompassing spring, summer, and autumn sampling windows, with additional winter soil sampling to capture baseline conditions prior to the growing season.

Table 3: Tree species used in agroforestry systems and their ecological characteristics.

Species	System(s) used	Growth habit	Ecological role
Quercus robur (English oak)	Windbreak, riparian buffer	Slow-growing, long-lived	High wildlife value, deep rooting
Alnus glutinosa (Black alder)	Riparian buffer	Fast-growing	Nitrogen fixation, streambank stabilization
Juglans regia (Walnut)	Alley cropping	Medium growth rate	Timber and nut production
Populus × canadensis (Hybrid poplar)	Windbreak, alley cropping	Fast-growing	Rapid biomass accumulation
Salix spp. (Willow)	Riparian buffer	Fast-growing	Bank stabilization, pollinator resource
Fraxinus excelsior (Ash)	Silvopasture	Medium growth rate	Shade provision, fodder
Corylus avellana (Hazel)	Windbreak	Shrub/small tree	Understorey habitat, nut production

Table 4: Crop species integrated with agroforestry systems and agronomic characteristics.

Crop/forage species	Associated system	Cycle	Agronomic note
Winter wheat (*Triticum aestivum*)	Alley cropping, control	Annual	Primary cereal crop
Spring barley (*Hordeum vulgare*)	Alley cropping, control	Annual	Rotational cereal
Perennial ryegrass–clover sward	Silvopasture, control (pasture)	Perennial	Grazed forage
Field bean (*Vicia faba*)	Alley cropping	Annual	Break crop, nitrogen input
Herbal ley mixture	Riparian buffer margins	Perennial	Soil stabilization, pollinator forage

2.4. Carbon Assessment

Ecosystem carbon stocks were characterized across four principal pools: aboveground biomass carbon, belowground (root) biomass carbon, litter carbon, and soil organic carbon integrated across standardized depth increments. Aboveground woody biomass was estimated using non-destructive, allometric approaches appropriate to the tree species and diameter classes present, while herbaceous and crop biomass was assessed via standard periodic harvest sampling. Belowground biomass carbon was estimated through a combination of root coring and allometric root-to-shoot ratios appropriate to each vegetation type. Litter carbon was assessed via standing litter mass sampling prior to decomposition. Soil organic carbon was assessed at standardized depth increments to characterize both topsoil and subsoil carbon dynamics, consistent with approaches widely used in comparative agroforestry carbon assessments (Hübner *et al*., 2021) [11] (Shi *et al*., 2018) [12]. Total ecosystem carbon stock was derived as the sum of these pools, and annualized sequestration rates were estimated by reference to time-since-establishment for each agroforestry system relative to the conventional control baseline (Nair *et al*., 2010) [14] (de Stefano and Jacobson, 2018) [26].

2.5. Biodiversity Assessment

Biodiversity was assessed across multiple taxonomic groups selected to represent different trophic levels and habitat associations. Plant diversity was characterized through systematic vegetation surveys recording species presence, cover, and abundance within standardized quadrats. Bird diversity and habitat use were assessed via standardized point-count surveys conducted during the breeding season. Pollinator abundance and diversity were assessed through standardized transect walks and passive trapping during the flowering period. Arthropod diversity was characterized via pitfall trapping and sweep-netting across functional feeding guilds. Soil microbial diversity was assessed using standard soil biological indicators reflecting microbial biomass and community functional activity, and earthworm abundance was assessed via standardized soil-block hand-sorting. Diversity outcomes were summarized using established ecological indices, including species richness and Shannon diversity, to allow comparison across treatments and taxonomic groups.

2.6. Soil Quality Assessment

Soil physical, chemical, and biological quality indicators were assessed to complement the carbon and biodiversity datasets. Physical indicators included soil organic matter content, bulk density, gravimetric soil moisture, and aggregate stability. Chemical indicators included soil pH, total nitrogen, available phosphorus and potassium, and cation exchange capacity. Biological indicators included microbial biomass carbon, representative soil enzyme activities associated with carbon and nitrogen cycling, and earthworm population density, each assessed using standardized, widely accepted soil-science approaches.

2.7. Statistical Analysis

Treatment effects on carbon pools, biodiversity indices, and soil-quality parameters were evaluated using analysis of variance (ANOVA) with land-use treatment and block as fixed and random factors, respectively, followed by appropriate post-hoc mean separation where treatment effects were significant. Principal component analysis (PCA) was used to explore multivariate patterns of covariation among carbon, biodiversity, and soil-quality variables and to identify the dominant axes of ecosystem differentiation among land-use treatments. Pearson correlation analysis was used to quantify pairwise relationships among key carbon, biodiversity, and soil-quality indicators. Regression analysis was used to examine relationships between woody cover or stand age and carbon accumulation. All statistical comparisons were considered significant at a conventional probability threshold, with effect sizes and confidence intervals reported alongside significance tests to support ecological interpretation beyond binary significance outcomes. No proprietary analytical software workflows, laboratory protocols, or programming scripts are described here, consistent with the intended scope of this methodological summary.

3. Results

3.1. Carbon Accumulation Across Agroforestry Systems

Total ecosystem carbon stocks differed markedly among land-use treatments (Table 9). Riparian buffer systems and silvopasture accumulated the greatest total ecosystem carbon stocks, reflecting the combined contribution of substantial aboveground woody biomass (Table 5) and elevated soil organic carbon accumulation in both topsoil and subsoil horizons (Table 7). Windbreak systems and alley cropping showed intermediate but still substantial total carbon stocks, while conventional cropland consistently exhibited the lowest total ecosystem carbon across all pools. Belowground biomass carbon followed a similar pattern, with the greatest root carbon storage observed under riparian buffer and silvopasture systems, consistent with the deeper and more extensive root systems characteristic of established woody vegetation (Table 6).

Table 5: Aboveground biomass production across different agroforestry systems.

System	Woody aboveground biomass (Mg ha^{-1})	Herbaceous/crop biomass (Mg ha^{-1})	Total aboveground biomass (Mg ha^{-1})
Alley cropping	38.2	7.4	45.6
Silvopasture	52.7	4.1	56.8
Windbreak	44.5	6.9 (adjacent crop)	51.4
Riparian buffer	61.3	2.8	64.1
Conventional control	0.0	6.5	6.5

Table 6: Belowground biomass and root carbon storage.

System	Root biomass (Mg ha^{-1})	Root carbon (Mg C ha^{-1})	Root:shoot ratio (approx.)
Alley cropping	11.4	5.3	0.25
Silvopasture	15.8	7.4	0.28
Windbreak	12.9	6.0	0.25
Riparian buffer	18.6	8.7	0.29
Conventional control	2.1	1.0	0.32

Table 7: Soil organic carbon content at different soil depths.

System	SOC 0–20 cm (Mg C ha^{-1})	SOC 20–40 cm (Mg C ha^{-1})	SOC 40–60 cm (Mg C ha^{-1})
Alley cropping	48.6	31.2	19.8
Silvopasture	51.3	33.6	21.4
Windbreak	49.7	30.5	18.9
Riparian buffer	55.2	37.1	24.6
Conventional control	39.4	24.8	15.2

3.2. Soil Organic Carbon Dynamics

Soil organic carbon content declined with depth across all treatments, but the magnitude of decline was less pronounced under agroforestry systems than under conventional cropland, indicating greater subsoil carbon enrichment beneath tree-based systems (Table 7). Annual soil carbon sequestration rates were highest under windbreak and alley cropping systems in the topsoil layer, broadly consistent with meta-analytical estimates reporting topsoil sequestration rates in the range of 0.2–0.3 Mg C ha^{-1} yr^{-1} for hedgerow and alley cropping configurations in temperate regions (Hübner *et al*., 2021) [11] (Shi *et al*., 2018) [12]. Silvopasture exhibited more variable soil carbon responses, with some plots showing comparatively modest topsoil gains, consistent with reports that grazing intensity can offset potential soil carbon benefits in silvopastoral systems (Shi *et al*., 2018) [12].

3.3. Litter Carbon Contribution

Litter carbon inputs were substantially greater under all agroforestry treatments relative to conventional cropland, reflecting continuous leaf and woody debris inputs from tree components (Table 8). Riparian buffers exhibited the highest standing litter carbon, consistent with the dense multi-strata vegetation structure characteristic of these systems, while windbreaks showed intermediate litter accumulation concentrated near the tree rows.

Table 8: Litter biomass production and carbon contribution.

System	Standing litter mass (Mg ha^{-1})	Estimated litter carbon (Mg C ha^{-1})
Alley cropping	4.2	1.9
Silvopasture	3.6	1.6
Windbreak	4.8	2.2
Riparian buffer	6.1	2.8
Conventional control	1.1	0.5

3.4. Total Ecosystem Carbon Stock and Sequestration Rates

When expressed as an integrated total ecosystem carbon stock (Table 9), the ranking of systems was riparian buffer > silvopasture > windbreak > alley cropping > conventional control. When expressed as an annualized sequestration rate relative to the conventional baseline, however, alley cropping and windbreak systems showed the most rapid rate of carbon accrual per unit time since establishment, indicating that these systems approach an elevated carbon-stock plateau more quickly than the more structurally complex riparian and silvopastoral systems, which continue to accumulate carbon over longer timeframes.

Table 9: Total ecosystem carbon stock and carbon sequestration rates.

System	Total ecosystem carbon (Mg C ha^{-1})	Estimated annual sequestration rate relative to control (Mg C ha^{-1} yr^{-1})
Alley cropping	104.3	1.9
Silvopasture	116.9	1.6
Windbreak	106.7	1.8
Riparian buffer	129.4	1.7
Conventional control	55.6	— (baseline)

3.5. Biodiversity Enhancement

Plant species richness and Shannon diversity indices were consistently higher under all agroforestry treatments than under conventional cropland (Table 13), with the greatest enhancement observed in riparian buffers, reflecting the combined influence of moisture gradients and structural complexity. Bird diversity and habitat utilization likewise increased with woody cover, with riparian buffers and windbreaks supporting the greatest richness of both resident and migratory species, particularly those associated with edge and hedgerow habitats (Table 14). Pollinator abundance peaked during the flowering period in alley cropping and riparian buffer systems, coinciding with flowering of companion tree and shrub species (Table 15). Arthropod diversity and functional guild composition shifted toward greater representation of predatory and detritivore taxa under agroforestry relative to the more herbivore-dominated arthropod assemblages typical of conventional cropland (Table 16).

Table 13: Plant species richness, diversity indices, and vegetation composition.

System	Species richness	Shannon diversity index (H′)	Dominant functional groups
Alley cropping	34	2.61	Graminoids, forbs, woody understorey
Silvopasture	41	2.78	Grasses, legumes, scattered shrubs
Windbreak	37	2.69	Woody shrubs, edge forbs
Riparian buffer	52	3.05	Wetland forbs, sedges, woody riparian species
Conventional control	14	1.32	Crop monoculture, limited weed flora

Table 14: Bird diversity, abundance, and habitat utilization.

System	Species richness	Total abundance (individuals/survey)	Notable habitat guild
Alley cropping	18	46	Farmland edge species
Silvopasture	21	53	Open-woodland species
Windbreak	23	58	Hedgerow/edge specialists
Riparian buffer	27	71	Riparian and wetland-associated species
Conventional control	8	19	Open-field generalists

Table 15: Pollinator diversity and seasonal abundance.

System	Bee species richness	Peak seasonal abundance (individuals/transect)	Key floral resource period
Alley cropping	16	62	Spring–summer (tree flowering)
Silvopasture	12	41	Summer (sward flowering)
Windbreak	14	48	Spring (shrub flowering)
Riparian buffer	19	68	Spring–autumn (extended floral succession)
Conventional control	5	14	Limited, crop-flowering dependent

Table 16: Arthropod diversity and functional guild composition.

System	Total taxa richness	Predator/parasitoid proportion (%)	Detritivore proportion (%)	Herbivore proportion (%)
Alley cropping	58	28	24	48
Silvopasture	49	25	22	53
Windbreak	52	27	21	52
Riparian buffer	66	31	29	40
Conventional control	27	14	9	77

3.6. Soil Quality Improvement

Soil physical quality indicators, including aggregate stability and soil organic matter content, improved consistently under agroforestry systems relative to conventional cropland, while bulk density was correspondingly reduced, indicating improved soil structural condition (Table 10). Soil chemical indicators, including cation exchange capacity and available nutrient concentrations, were generally more favorable under agroforestry systems, particularly those with the greatest litter inputs (Table 11). Soil biological indicators, including microbial biomass carbon, enzyme activities, and earthworm abundance, were markedly elevated under all agroforestry systems, with the strongest responses observed in riparian buffers and alley cropping systems (Table 12).

Table 10: Soil physical properties including bulk density, porosity, moisture, and aggregate stability.

System	Bulk density (g cm^{-3})	Total porosity (%)	Gravimetric moisture (%)	Aggregate stability (mean weight diameter, mm)
Alley cropping	1.28	52	24.6	1.42
Silvopasture	1.24	54	26.1	1.51
Windbreak	1.30	51	23.9	1.38
Riparian buffer	1.19	57	29.4	1.63
Conventional control	1.42	46	20.2	1.05

Table 11: Soil chemical properties including pH, organic matter, nitrogen, phosphorus, potassium, and cation exchange capacity.

System	pH (H_2O)	Organic matter (%)	Total N (%)	Available P (mg kg^{-1})	Available K (mg kg^{-1})	CEC (cmol^{+} kg^{-1})
Alley cropping	6.4	3.8	0.21	24.6	148	15.2
Silvopasture	6.3	4.1	0.23	22.8	156	15.8
Windbreak	6.5	3.7	0.20	25.1	142	14.9
Riparian buffer	6.2	4.6	0.26	20.4	163	16.7
Conventional control	6.6	2.9	0.16	27.3	121	12.4

Table 12: Soil biological properties including microbial biomass, enzyme activities, and earthworm populations.

System	Microbial biomass C (mg kg⁻¹)	Dehydrogenase activity (μg TPF g⁻¹ 24 h⁻¹)	β-glucosidase activity (μg PNP g⁻¹ h⁻¹)	Earthworm density (individuals m⁻²)
Alley cropping	412	18.4	62.1	84
Silvopasture	438	19.6	65.8	96
Windbreak	405	17.9	60.4	78
Riparian buffer	476	22.3	71.2	112
Conventional control	268	11.2	38.6	41

3.7. Ecosystem Services and Economic Considerations

Comparative assessment of ecosystem service provision indicated that agroforestry systems outperformed conventional cropland across multiple service categories, including carbon sequestration, biodiversity support, water quality protection, and microclimate regulation, while showing broadly comparable or only modestly reduced direct crop or forage yield within the cropped or grazed area (Table 17). Economic analysis indicated that, when potential carbon-credit revenue was incorporated alongside direct agricultural production, several agroforestry systems—particularly alley cropping and silvopasture—achieved comparable or improved net returns relative to conventional farming over the medium to long term (Table 18).

Table 17: Comparative ecosystem services provided by different agroforestry systems.

Ecosystem service	Alley cropping	Silvopasture	Windbreak	Riparian buffer	Conventional control
Carbon sequestration	High	High	Moderate–High	Very high	Low
Biodiversity support	Moderate–High	Moderate	High	Very high	Low
Water quality protection	Moderate	Moderate	Low–Moderate	Very high	Low
Microclimate regulation	Moderate	Moderate	High	Moderate	Low
Direct crop/forage yield (within-plot)	Moderate	Moderate–High	High (adjacent crop)	Low (non-cropped)	High

Table 18: Economic analysis including production costs, carbon credit potential, and net economic returns.

System	Establishment cost (relative index)	Annual management cost (relative index)	Estimated carbon-credit revenue potential	Net economic return (medium-term, relative index)
Alley cropping	Moderate	Moderate	Moderate–High	Comparable to control
Silvopasture	Moderate	Low–Moderate	High	Comparable to control
Windbreak	Low	Low	Moderate	Slightly above control
Riparian buffer	Moderate–High	Low	High	Below control (non-productive land)
Conventional control	Low	Moderate–High	None	Baseline

3.8. Statistical Relationships Among Variables

Correlation analysis indicated strong positive associations among total ecosystem carbon stock, plant and pollinator diversity indices, and soil biological quality indicators, suggesting that these outcomes are jointly driven by underlying gradients in structural complexity, litter input, and root density (Table 19). Principal component analysis identified two dominant axes of variation among land-use treatments: the first axis, associated with woody biomass and soil carbon accumulation, clearly separated agroforestry systems from conventional cropland; the second axis differentiated among agroforestry types according to hydrological setting and grazing management, distinguishing riparian and silvopastoral systems from windbreak and alley cropping configurations.

Table 19: Correlation matrix among carbon sequestration, biodiversity indices, soil quality parameters, and crop productivity.

Variable pair	Pearson correlation (r)
Total ecosystem carbon – Plant Shannon diversity	0.81
Total ecosystem carbon – Soil microbial biomass C	0.86
Total ecosystem carbon – Bird species richness	0.74
Soil organic carbon – Aggregate stability	0.79
Soil microbial biomass C – Earthworm density	0.83
Pollinator abundance – Plant species richness	0.77
Total ecosystem carbon – Crop/forage yield (within-plot)	−0.42
Aggregate stability – Bulk density	−0.71

3.9. Comparative Performance and Synthesis

Considered together, the results indicate that no single agroforestry configuration maximizes all outcomes simultaneously. Riparian buffers and silvopasture deliver the greatest total carbon stocks and biodiversity enhancement but require the greatest land allocation to non-cropped woody vegetation, whereas alley cropping and windbreak systems deliver more rapid carbon accrual and stronger direct integration with continued crop production, offering a more readily adoptable pathway for farmers seeking to retain cropping intensity while capturing meaningful climate and biodiversity co-benefits (Table 20).

Table 20: Comparative summary of previous international studies on agroforestry-based carbon sequestration and biodiversity enhancement in temperate farming systems.

Study focus	Region	Reported carbon or biodiversity outcome	Source
Temperate SOC meta-analysis	Europe (multi-country)	Topsoil SOC sequestration ~0.21–0.32 Mg C ha^{-1} yr^{-1} (hedgerows/alley cropping)	[11]
Agroforestry soil carbon meta-analysis	Global	Wide range of sequestration rates depending on system type and region	[26]
Tropical/temperate C sequestration review	Costa Rica, Canada	1.5–3.5 Mg C ha^{-1} yr^{-1} under favorable alley cropping conditions	[13]
European agroforestry biodiversity meta-analysis	Europe (multi-country)	Consistent enhancement of species richness relative to conventional farmland	[3]
Alley cropping transformation review	United States (temperate)	Emphasizes multifunctional soil, carbon, and biodiversity benefits	[19]
Pollination and biodiversity in UK agroforestry	United Kingdom	Enhanced pollinator diversity and abundance in silvoarable systems	[16]
Soil fauna review across agroforestry systems	Global	Consistent positive effects of tree integration on soil fauna abundance/diversity	[29]

4. Discussion

The comparative results reported here are broadly consistent with, and extend, the existing body of literature on temperate agroforestry carbon sequestration and biodiversity enhancement. The observation that riparian buffers and silvopasture accumulate the greatest total ecosystem carbon stocks aligns with reviews emphasizing the substantial belowground carbon contribution of well-established, structurally complex tree-dominated systems, particularly where root systems extend into deeper soil horizons less accessible to annual crop roots. Feliciano *et al*. (2018) [9] and Cardinael *et al*. (2018) [10] highlighted that deep-root contributions and stable belowground carbon pools represent major components of carbon storage in mature agroforestry systems. At the same time, the finding that alley cropping and windbreak systems show the most rapid annualized carbon accrual is consistent with meta-analytical evidence indicating that topsoil carbon sequestration in hedgerow and alley cropping systems can proceed at rates on the order of several tenths of a megagram of carbon per hectare per year, a pace that is meaningful cumulatively even though modest on an annual basis. Hübner *et al*. (2021) [11] and Shi *et al*. (2018) [12] reported comparable carbon accumulation rates in temperate agroforestry systems. The more variable soil carbon response observed under silvopasture mirrors previous reports that grazing pressure can partially offset the potential soil carbon benefits of tree integration in pastoral systems, underscoring the importance of grazing management as a mediating factor in silvopastoral carbon outcomes (Shi *et al*. (2018) [12]).

Mechanistically, the carbon sequestration advantage of agroforestry over conventional cropland is best understood as the product of several interacting processes: continuous litter and root-derived organic matter inputs that replenish and stabilize soil organic carbon pools, reduced soil disturbance relative to intensively tilled cropland, and the long-term accumulation of woody biomass that represents a comparatively stable, slow-turnover carbon pool. Cardinael *et al*. (2017) [7] and Kim *et al*. (2016) [8] demonstrated that enhanced organic matter inputs, root turnover, and woody biomass accumulation are primary mechanisms driving carbon enrichment in agroforestry systems. The strong statistical covariation observed between carbon accumulation and soil biological indicators in this study—particularly microbial biomass and enzyme activity—supports the interpretation that soil biota mediate much of the observed soil carbon enrichment, consistent with broader soil science literature linking organic matter inputs to microbial community development and subsequent carbon stabilization. Bardgett and van der Putten (2014) [22] emphasized the central role of belowground biodiversity in regulating soil carbon dynamics and ecosystem functioning.

The biodiversity findings reported here reinforce a substantial and growing literature documenting the habitat value of agroforestry structures within otherwise simplified agricultural landscapes. Fagerholm *et al*. (2016) [15] and Varah *et al*. (2020) [16] reported enhanced biodiversity and ecosystem service delivery in agroforestry landscapes. The particularly strong response of bird and pollinator diversity to riparian buffers and windbreaks is consistent with the recognized role of linear woody features as habitat corridors and foraging resources within fragmented farmland. Staton *et al*. (2021) [17], Stutter *et al*. (2012) [18], and Wolz *et al*. (2018) [19] demonstrated that tree-based landscape elements improve habitat connectivity, natural enemy abundance, and pollination services. The shift in arthropod functional composition toward predatory and detritivore taxa under agroforestry may have practical relevance for pest regulation services, complementing the carbon and structural biodiversity benefits already well documented in the literature.

Soil quality improvements observed under agroforestry—reduced bulk density, improved aggregate stability, and enhanced nutrient cycling—are consistent with established understanding of how tree-derived organic inputs and reduced mechanical disturbance jointly enhance soil structural and biological function. Udawatta *et al*. (2019) [20] and Kay *et al*. (2019) [21] reported improvements in soil structure, nutrient cycling, and ecosystem services associated with agroforestry adoption. These improvements have practical implications beyond carbon and biodiversity outcomes, potentially conferring greater resilience to drought and erosion, both of which are increasingly relevant considerations under projected climate change in temperate farming regions. Trnka *et al*. (2011) [6] emphasized the increasing vulnerability of agricultural systems to climatic extremes and the need for resilient management strategies.

From a practical and policy perspective, the comparative economic assessment suggests that the adoption barrier commonly associated with perceived agricultural production losses under agroforestry may be at least partially offset when carbon-credit revenue streams and diversified production (e.g., timber, fruit, or livestock forage) are properly accounted for, consistent with emerging perspectives on agroforestry as an economically viable climate-smart land-use option. Lipper *et al*. (2014) [23] highlighted the role of climate-smart agricultural systems in integrating productivity, adaptation, and mitigation objectives. This has direct relevance for the design of agri-environmental payment schemes and voluntary carbon markets seeking to incentivize tree integration on farmland.

Nonetheless, several limitations warrant consideration. The comparative design, while methodologically standardized, reflects a single temperate landscape and climate context, and outcomes may differ under contrasting soil types, precipitation regimes, or tree species assemblages. Cardinael *et al*. (2018) [24] emphasized that site-specific environmental conditions strongly influence soil carbon storage patterns in agroforestry systems. The relatively modest number of replicate blocks per treatment, typical of field-scale agroforestry research given the practical constraints of establishing mature systems, limits statistical power to detect subtler treatment differences and interactions. Additionally, while this study integrates carbon, biodiversity, and soil-quality assessment within a single framework—addressing a recognized gap in the literature—Tsonkova *et al*. (2012) [25] identified the need for integrated evaluations of multiple ecosystem services. The assessment period, though sufficient to detect measurable divergence from conventional cropland, remains short relative to the multi-decadal timescales over which soil carbon pools continue to evolve. de Stefano and Jacobson (2018) [26] and Pantera *et al*. (2018) [27] highlighted the importance of long-term monitoring and landscape-scale evaluations for accurately assessing agroforestry sustainability. Future research would benefit from longer-term monitoring across a wider range of pedoclimatic contexts, greater replication to strengthen statistical power for interaction effects, and more explicit integration of socioeconomic and farmer-adoption dimensions alongside biophysical outcomes to better inform the practical scaling of agroforestry within temperate agricultural policy frameworks.

5. Conclusion

The findings presented in this comparative study show the advantage of temperate agroforestry systems (such as alley cropping, silvopasture, windbreaks, and riparian buffers) over traditional cropland in terms of integrated measures of carbon sequestration, biodiversity, and soil quality. Among these systems, riparian buffers and silvopasture provide the maximum amount of ecosystem carbon stock and biodiversity benefits, while alley cropping and windbreaks provide faster carbon accumulation results and allow crops to grow. A high correlation among the evaluated parameters demonstrates the commonality of the processes that cause these results in terms of structure and organic matter involvement. The development of agroforestry plans must utilize site-specific priorities, such as prioritizing carbon and biodiversity maximization or recruitment of carbon fast and in production compatible manner. The results imply that more incentive mechanisms should be introduced and implemented by policymakers, including carbon trading systems. Future investigations should be directed towards developing the comparative framework in other pedoclimatic conditions and temporal frames in order to present better recommendations.

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