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# Integrating Agroforestry Systems with Precision Agriculture Technologies: Optimizing Ecosystem Service Delivery and Productivity Trade-offs in Temperate Mixed Farming Landscapes

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## Abstract
Agroforestry — the deliberate integration of trees with crops and/or livestock — offers substantial potential for enhancing ecosystem service delivery in agricultural landscapes while maintaining economic productivity. However, the management complexity and productivity trade-offs associated with agroforestry adoption have limited uptake, particularly in high-input temperate farming systems where monoculture specialization is economically entrenched. This study examined the potential for precision agriculture technologies — including unmanned aerial vehicles (UAVs), satellite multispectral remote sensing, soil electrical conductivity mapping, and variable rate application systems — to optimize agroforestry system management and quantify ecosystem service delivery across 12 operational temperate silvoarable agroforestry farms in Western Europe. A mixed-methods approach combining on-farm field measurements, remote sensing analysis, farmer surveys, and ecosystem service valuation was employed over a four-year period (2019–2023). Results demonstrated that UAV-based canopy monitoring enabled spatially targeted management interventions that maintained crop yields within 8.3% of adjacent monoculture controls in tree alleys, substantially reducing the perceived productivity penalty associated with agroforestry adoption. Precision soil mapping revealed significant spatial heterogeneity in crop response to agroforestry-induced soil microclimate modification, enabling variable rate fertilizer adjustments that reduced nitrogen input by 17.4% while maintaining equivalent yields. Total ecosystem service value, including carbon sequestration (3.8–9.2 t $CO_2$-eq $ha^{-1}$ $yr^{-1}$), biodiversity (farmland bird species richness +34%), water regulation (peak flow reduction 24–38%), and microclimate regulation, exceeded the monetary value of crop production yield gaps in 10 of 12 farms studied when valued using established ecosystem service monetary metrics. Farmer adoption modeling indicates that targeted precision technology subsidies and ecosystem service payment schemes could increase temperate agroforestry adoption rates by 38–55% within a decade. These findings support the development of integrated agroforestry-precision agriculture management frameworks as a transformative pathway toward sustainable, multifunctional temperate farming landscapes..

## Keywords
agroforestry; silvoarable; precision agriculture; ecosystem services; UAV remote sensing; carbon sequestration; biodiversity; temperate farming; multifunctionality.

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## INTRODUCTION
The transformation of agricultural landscapes from structurally diverse, heterogeneous farming systems to simplified, large-scale monocultures over the past century has delivered substantial productivity gains but at profound ecological cost, including widespread declines in farmland biodiversity, soil health degradation, disruption of hydrological cycles, and loss of landscape-scale ecosystem service provision (Tilman et al., 2002; Foley et al., 2011). As the limitations of high-input monoculture approaches become increasingly apparent in the context of climate change, resource constraints, and ecosystem service demand, there is growing scientific and policy recognition of the need for agricultural system redesign that restores ecological complexity while

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maintaining economic viability for farming enterprises (Gliessman, 2015).

Agroforestry — defined broadly as land-use systems that intentionally combine trees or shrubs with crops and/or livestock on the same land management unit — represents a time-tested approach to integrating productive and ecological functions in agricultural landscapes (Nair, 1993). In temperate contexts, silvoarable systems (trees + arable crops) offer particularly compelling opportunities: tree rows provide windbreak and microclimate buffering effects that can reduce crop water stress during drought events; deep tree root systems access subsoil nutrients and water unavailable to annual crops; tree canopies intercept rainfall and facilitate preferential infiltration, reducing peak runoff; and the structural diversity provided by trees supports far greater farmland biodiversity than monoculture equivalents (Plieninger et al., 2015; Torralba et al., 2016).

Despite this substantial body of evidence supporting agroforestry's ecological and agronomic potential, the adoption of agroforestry in European and North American temperate farming contexts remains remarkably low — estimated at less than 3% of arable land in Western Europe (den Herder et al., 2017). Barriers to adoption are multiple and interacting: the complexity of managing tree-crop interactions in competition for light, water, and nutrients; uncertainty about long-term productivity trade-offs and return on investment; incompatibility with large-scale machinery logistics; and the absence of adequate payment mechanisms for the non-market ecosystem services provided (Kay et al., 2019).

Precision agriculture technologies — including global navigation satellite system (GNSS)-guided machinery, UAV-based remote sensing, multi-layer digital soil mapping, crop growth simulation models, and variable-rate input application systems — have transformed the management of uniform monoculture fields by enabling spatially explicit, data-driven optimization of inputs and operations (Gebbers & Adamchuk, 2010). However, the application of precision technologies to the inherently spatially heterogeneous, structurally complex environment of agroforestry systems has received comparatively limited systematic investigation (Moreno et al., 2018). This represents a critical missed opportunity: the spatial variability in light availability, soil moisture, nutrient dynamics, and microclimate conditions created by tree-crop spatial arrangements is precisely the context in which precision spatial data and variable-rate management have the greatest potential to deliver agronomic benefits.

The present study addresses this research gap through a comprehensive, multi-farm assessment of precision technology integration with operational temperate silvoarable agroforestry systems. Specific objectives were to: (i) evaluate the effectiveness of UAV-based multispectral monitoring for characterizing spatial crop performance variability within agroforestry alleys; (ii) assess the potential for precision soil mapping and variable-rate fertilizer application to optimize nitrogen use efficiency in agroforestry-managed fields; (iii) quantify the ecosystem service delivery of agroforestry farms relative to monoculture comparators using field measurements and remote sensing-derived indicators; (iv) determine the economic conditions under which agroforestry ecosystem service values exceed crop productivity trade-off costs; and (v) model the potential impact of policy interventions (precision technology subsidies; ecosystem service payments) on agroforestry adoption rates.

## MATERIALS AND METHODS

### Study Farm Network and Agroforestry System Characterization

Twelve operational silvoarable agroforestry farms were recruited through the European Agroforestry Federation (EURAF) network, spanning a latitudinal gradient from southern England (51°N) to northern France (48°N) and including farms in Belgium, Netherlands, and Germany. Farm size ranged from 48 to 340 ha, with agroforestry components comprising 15–85% of total farm area. Tree species represented included: hybrid poplar (*Populus* × *euramericana*), common walnut (*Juglans regia*), field maple (*Acer campestre*), wild cherry (*Prunus avium*), and mixed native broadleaf species. Tree spacing ranged from 10 × 60 m to 15 × 100 m, with tree row age ranging from 4 to 22 years. Adjacent monoculture reference plots (minimum 5 ha) were identified on each farm for comparative measurements.

**UAV-Based Multispectral Monitoring**

Each farm was surveyed six times annually using multirotor UAV platforms (DJI Matrice 300 RTK) equipped with Micasense RedEdge-MX multispectral cameras capturing reflectance in blue, green, red, red-edge, and near-infrared bands at 5–8 cm ground sampling distance. Flights were conducted at key crop growth stages: tillering, stem elongation, flag leaf, heading, and grain fill for cereal crops; V6, V12, tasseling, and silking for maize. Orthomosaic processing and reflectance calibration were performed in Agisoft Metashape Pro (version 1.8) using calibrated reflectance panels. Vegetation indices calculated included: NDVI, NDRE (normalized difference red-edge index), MCARI (modified chlorophyll absorption ratio index), and LAI estimates from NDRE following Delegido et al. (2011). Spatial gradient analysis was employed to characterize the distance-dependent effects of tree rows on crop vigor at 2 m resolution.

**Precision Soil Mapping**

Electromagnetic induction (EMI) soil electrical conductivity (ECa) mapping was conducted using a Geonics EM38-MK2 instrument mounted on a field vehicle at 12–15 m transect spacing across agroforestry alleys and reference monoculture fields. ECa maps were used as a stratification framework for targeted soil sampling at 30–40 points per field, collected at 0–30 cm and 30–60 cm depths. Laboratory analysis included: texture, organic carbon, total nitrogen, available phosphorus and potassium, pH, CEC, and bulk density. Soil data were interpolated to field-scale maps using ordinary kriging in ESRI ArcGIS Pro 3.0. Variable-rate nitrogen prescription maps were generated using a commercially adapted algorithm (Yara N-Sensor approach) integrating soil N supply maps with UAV-derived crop demand indices.

**Crop Yield Monitoring**

Combine harvesters were equipped with calibrated yield monitors and GNSS receivers to capture spatially continuous yield maps for all cereal and oilseed crops harvested on the study farms. Yield maps were processed to remove edge effects, headland data, and machine speed artifacts following established protocols (Blackmore, 1999). Mean alley crop yields were calculated for five distance bands from tree rows (0–5, 5–10, 10–15, 15–20, >20 m) to characterize the spatial yield gradient associated with tree competition and facilitation.

**Ecosystem Service Quantification**

A suite of ecosystem services was quantified using field measurements and remote sensing analysis:

- **Carbon sequestration**: Tree biomass carbon was estimated using allometric equations for each species (following Forrester et al., 2017), combined with soil organic carbon measurements (0–30 cm and 30–100 cm) and litter input estimates. Net annual carbon sequestration rates were calculated accounting for timber harvesting cycles.
- **Biodiversity**: Farmland bird species were surveyed using point-count methodology at 10 points per farm in spring and summer. Vascular plant diversity was assessed in tree rows, alley crop areas, and monoculture reference fields using 1 $m^2$ quadrats. Pollinating insect abundance and diversity were assessed using pan-trap arrays during crop flowering.
- **Water regulation**: Peak runoff coefficients were estimated from rainfall-runoff event data collected from farm drainage outlets during significant precipitation events (>20 mm in 24 h), compared between agroforestry and monoculture catchments using a paired watershed approach where topographic conditions permitted.
- **Microclimate regulation**: Air temperature, relative humidity, wind speed, and solar radiation were monitored continuously at meteorological stations installed within agroforestry alleys at multiple distances from tree rows and in monoculture reference fields.

### Ecosystem Service Valuation and Economic Analysis

Ecosystem services were monetarily valued using published transfer functions and market-based approaches: carbon sequestration at the EU Emissions Trading System shadow price (EUR 65 $t^{-1}$ $CO_2$-eq, 2022 values); biodiversity improvement using European habitat valuation equivalencies; water regulation using avoided downstream flood damage cost data; and microclimate regulation through energy demand substitution values. Farm-level financial performance was assessed through partial enterprise budgets incorporating agroforestry establishment costs, ongoing management, crop yield changes, timber revenue projections, and ecosystem service payment scenarios.

### Farmer Survey and Adoption Modeling

Semi-structured interviews and structured questionnaires were administered to the 12 study farm operators and 48 non-agroforestry farmers in the same regions. Questions addressed: awareness and attitudes toward agroforestry; perceived barriers and enabling factors for adoption; willingness to adopt under alternative policy scenarios (technology subsidies, ecosystem service payments, technical advisory support). Multinomial logistic regression was used to identify predictors of agroforestry adoption intention. An agent-based model (ABM) was parameterized using survey data to simulate adoption dynamics under alternative policy scenarios over a 10-year horizon.

### Statistical Analysis

Crop yield data were analyzed using spatial linear mixed models in R (spaMM package), accounting for spatial autocorrelation structures in yield monitor data. Ecosystem service metrics were compared between agroforestry and monoculture systems using paired t-tests or Wilcoxon signed-rank tests. Ecosystem service monetization values were expressed as mean ± 95% confidence intervals incorporating both measurement uncertainty and valuation parameter uncertainty through Monte Carlo simulation (n = 10,000 iterations).

## RESULTS

### UAV-Based Crop Monitoring and Spatial Yield Gradients

UAV multispectral surveys revealed pronounced spatial gradients in crop vigor within agroforestry alleys, with NDRE values declining significantly within 8–12 m of tree rows, indicating light and/or resource competition effects. However, the magnitude and spatial extent of competition effects varied substantially with tree species, row orientation, tree age, and alley width. North-facing shading from east-west oriented tree rows (predominantly in older systems with 15–22 year tree rows) generated the most pronounced crop vigor reduction zones. In contrast, north-south oriented rows showed minimal light competition effects. UAV-guided precision interventions — including targeted late-season nitrogen top-dressing applications in lower-vigor competition zones based on real-time NDRE maps — maintained mean alley crop yields within 8.3% of adjacent monoculture controls (range: 2.1–18.4% depending on farm characteristics), compared to 15.2% without precision management.

### Precision Soil Management and Nitrogen Use Efficiency

ECa mapping revealed significant spatial heterogeneity in soil properties within agroforestry alleys, largely attributable to soil organic matter accumulation under tree canopy drip lines, preferential root water uptake patterns, and litter decomposition gradients. Variable-rate nitrogen prescription maps, integrating ECa-derived soil N supply estimates with UAV crop demand indicators, enabled nitrogen input reductions of 17.4% (range: 11.2–24.8% across farms) relative to uniform-rate applications, while maintaining equivalent crop yields based on precision yield monitoring. Economic analysis of precision nitrogen management indicated annual savings of EUR 38–87 $ha^{-1}$, partially offsetting precision technology operating costs.

### Ecosystem Service Quantification

**Carbon**: Annual tree carbon sequestration ranged from 2.1 to 6.8 t $CO_2$-eq $ha^{-1}$ $yr^{-1}$ across species and tree age classes. Combined with measured soil organic carbon increases in agroforestry areas

(0.08–0.24% SOC $yr^{-1}$ above monoculture reference), total net carbon sequestration was 3.8–9.2 t $CO_2$-eq $ha^{-1}$ $yr^{-1}$ for the agroforestry component. **Biodiversity**: Farmland bird species richness was 34% higher on agroforestry farms than monoculture reference farms ($p < 0.001$), with tree rows constituting critical nesting and foraging habitat. Pollinator abundance during crop flowering was 62% higher in agroforestry alleys adjacent to tree rows than in monoculture centers. Vascular plant diversity in tree rows was threefold higher than in monoculture field margins. **Water**: Peak runoff coefficients during intensive rainfall events were 24–38% lower in agroforestry micro-catchments compared to monoculture, attributable to enhanced canopy interception, improved soil infiltration, and increased surface roughness. **Microclimate**: Air temperatures within agroforestry alleys were 1.2–2.8°C lower than monoculture during summer heat events, with reduced water vapor pressure deficit reducing potential evapotranspiration and crop heat stress.

**Economic and Ecosystem Service Trade-off Analysis**

Total monetized ecosystem service values (EUR $ha^{-1}$ $yr^{-1}$, mean ± 95% CI): carbon sequestration EUR 247 ± 89; biodiversity improvement EUR 184 ± 67; water regulation EUR 128 ± 54; microclimate regulation EUR 96 ± 41; totaling EUR 655 ± 251 $ha^{-1}$ $yr^{-1}$. Mean crop yield value gap between agroforestry and monoculture (accounting for land occupied by tree rows) was EUR 412 ± 184 $ha^{-1}$ $yr^{-1}$. Ecosystem service values exceeded the yield gap in 10 of 12 farms, with a mean net benefit of EUR +243 $ha^{-1}$ $yr^{-1}$ (range: −EUR 87 to +EUR 618). When precision technology-enabled yield improvements were incorporated, the net benefit position improved by EUR 89–124 $ha^{-1}$ $yr^{-1}$ across all farms.

**Adoption Modeling**

Farmer survey analysis identified five principal barriers to agroforestry adoption: (i) insufficient financial return certainty (85% of non-adopter respondents); (ii) long establishment period before tree-derived revenues materialize (72%); (iii) machinery incompatibility concerns (68%); (iv) lack of technical knowledge and advisory support (61%); and (v) regulatory uncertainty around cross-compliance and CAP payment eligibility (54%). Agent-based modeling of adoption dynamics under alternative policy scenarios projected that a combined policy package of 60% precision technology cost subsidies plus EUR 300 $ha^{-1}$ $yr^{-1}$ ecosystem service payments would increase temperate agroforestry adoption rates by 38–55% within a 10-year simulation horizon.

## DISCUSSION

This multi-farm, multi-year study provides novel empirical evidence that precision agriculture technology integration can meaningfully reduce the primary agronomic barriers to agroforestry adoption in temperate farming systems — namely, the uncertainty surrounding within-alley crop productivity and nitrogen management complexity — while simultaneously enabling quantification of the substantial ecosystem service benefits that represent agroforestry's most compelling societal justification.

The finding that UAV-guided crop management maintained yields within 8.3% of monoculture controls is particularly significant. Previous studies without spatially adaptive management have typically reported yield penalties of 10–30% in the competition zones adjacent to tree rows (Graves et al., 2010; Dupraz et al., 2019), suggesting that precision management substantially narrows the actual productivity gap beyond what has been captured in earlier unmanaged agroforestry yield comparisons. The spatial resolution and temporal frequency of UAV monitoring enables detection of early crop stress indicators and targeted intervention before yield losses are fully realized.

The ecosystem service valuation findings, demonstrating that total ES values exceed the crop yield gap in 10 of 12 farms, provide a compelling economic case for agroforestry from a whole-system perspective. However, a critical policy challenge is that these ecosystem service benefits accrue largely as public goods to society — improved water quality, biodiversity, climate regulation — while the productivity costs are borne privately by the farming enterprise. This fundamental market failure explains the persistent underadoption of agroforestry despite its apparent social optimality, and underscores the necessity of well-designed public payment mechanisms to internalize ecosystem service values into farm-level economic decision-making.

The adoption modeling results suggest that a combined precision technology subsidy and ecosystem service payment policy package could substantially accelerate agroforestry uptake. Current EU Common Agricultural Policy (CAP) provisions for agroforestry under the European Green Deal framework represent encouraging initial steps, but payment rates in current schemes (EUR 80–150 $ha^{-1}$ $yr^{-1}$) fall substantially short of the EUR 300 $ha^{-1}$ $yr^{-1}$ threshold identified in our modeling as necessary to trigger broad-scale behavioral change.

## CONCLUSION

This study demonstrates that the integration of precision agriculture technologies — particularly UAV-based multispectral monitoring and precision soil mapping — with temperate silvoarable agroforestry systems can substantially reduce perceived productivity penalties while enabling more efficient input management. Ecosystem service delivery from agroforestry, including significant carbon sequestration, biodiversity enhancement, water regulation improvement, and microclimate buffering, has substantial monetary value that exceeds crop yield gaps in most farm contexts studied. Targeted policy interventions combining precision technology adoption support with meaningful ecosystem service payment mechanisms are modeled to significantly accelerate agroforestry adoption rates. These findings support the development of an integrated agroforestry-precision agriculture paradigm as a transformative pathway for temperate agricultural landscape sustainability.

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