Agroforestry can reduce trade-offs between economic and ecological benefits, but only when uncertainties are considered

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Abstract Persistent uncertainty about the economic implications of agroforestry presents a major barrier to adoption. Despite this, most research to date ignores the impact of uncertainty on land allocation decisions, with studies commonly relying on simplistic scenarios involving a dichotomous choice between switching entirely to agroforestry or retaining the *status quo* system. For a more realistic decision problem, we explore partial adoption choices by analysing how the performance of landscape portfolios under combined ecological and economic uncertainty changes when managers can incorporate two agroforestry alternatives (silvopasture and alley cropping) alongside existing land-use options. Drawing on published data from smallholders in Panama, we use robust optimisation to allocate fractions of land area across six agroforestry and non-agroforestry land uses under a range of possible futures. We visualise trade-offs between uncertain ecological and economic benefits using robust Pareto frontiers. We find that neglecting uncertainty reduces the attractiveness of agroforestry. Instead, agroforestry becomes increasingly competitive as uncertainty grows, and incorporating it into landscape portfolios can mitigate trade-offs between ecological and economic objectives when the future is uncertain. We conclude by outlining a research agenda for a more holistic approach to agroforestry economics under global change.

Keywords: Land-use allocation; Robust optimisation; Multicriteria decision analysis; Pareto frontiers; Portfolio approach; Sustainable land use

Statements and declarations:

I declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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1 Introduction

Agroforestry is a land-use practice that involves cultivating trees alongside crops or animals on the same parcel of land. Today, it is particularly prevalent among smallholder farms in the Global South (Nair et al. 2021; Sousa-Silva et al. 2024) but is also garnering growing attention as an alternative to agricultural practices in the Global North (Rigueiro-Rodríguez et al. 2008) due to its ecological benefits (Fagerholm et al. 2016; Torralba et al. 2016; Sollen-Norrlin et al. 2020). However, the actual rate of agroforestry adoption remains low, partly because of the unclear economic consequences of agroforestry adoption (Abdul-Salam et al. 2022), and systematic economic assessments are scarce (Thiesmeier and Zander 2023).

We present an innovative environmental-economic approach that captures partial adoption decisions under uncertainty about future benefits. The key to our approach is explicitly accounting for such uncertainty by considering a range of possible benefits from different land-use types representing multiple possible futures. We demonstrate this technique through a case study of smallholder farms in Panama but contend that the research approach is generalisable to agroforestry adoption decisions in other settings. The discussion highlights critical considerations for transferring this approach to other contexts.

Panama is an example of large-scale afforestation projects with exotic and native tree species (Hall et al. 2011; Sinacore et al. 2023) often financed by private investors (Griess and Knoke 2011; Paul et al. 2015). Agroforestry has a strong research history in Panama (Dibala et al. 2023). Over the last 15 years, some regions in Panama have been the focus of new developments in economic and multiple-criteria assessment of agroforestry (Paul and Weber 2012, 2013; Paul 2014; Paul et al. 2015; Paul and Weber 2016; Paul et al. 2017; Gosling et al. 2020b; Gosling et al. 2020a; Gosling and Reith 2020; Reith et al. 2020; Gosling 2021; Reith et al. 2022; Reith 2024). Building on such previous research is an excellent opportunity to demonstrate our ecological-economic research approach.

The main contribution of our study is an exploratory non-spatial portfolio optimisation method to analyse the impact of different levels of uncertainty on the simulated desirable landscape compositions and the trade-offs between economic and ecological benefits associated with agroforestry adoption decisions.

2 State of knowledge

Existing stochastic land-use allocation approaches build on random variables and associated probabilities (Knoke et al. 2011; Castro et al. 2013; Neuner et al. 2013; Castro et al. 2015; Hauk et al. 2017; Friedrich et al. 2019; Matthies et al. 2019; Fuchs et al. 2022; Fuchs et al. 2024). However, the available historical information on the distribution of possible benefits from different land-use types is often too unreliable for assigning future probabilities to each outcome and land-use type. Instead of referring to *risk* (which implies sufficient information to estimate probabilities), we suggest that referring to *uncertainty* (Knight 1921; Bewley 2002) can be more realistic, which implies that the set of potential outcomes is known but not their probabilities of occurring (see, e.g. Walker et al. 2010; Knoke et al. 2022a; Knoke et al. 2023).

Land management under global change increasingly involves making decisions under uncertainty. Considerable inherent uncertainty is related to climate change, its mitigation pathways and the impacts of extreme events, which are increasing in frequency and intensity (Reyer et al. 2013). Thus, many so far unassessed adaptation options in agriculture and forestry to droughts and extreme precipitation events exist, and the higher risk of compound extremes and their less-studied legacy effects add additional uncertainties (Seidel et al. 2019). For example, the increasing uncertainties about the impact of climate change on agriculture (Asseng et al. 2013), the resulting market fluctuations and policy changes (Long et al. 2016) are still unresolved (Molina Bacca et al. 2023). Uncertainty prevails in any economic assessment of ecosystem services, particularly for more complex or unconventional land-use practices like agroforestry. In this context, the policy influence of subsidies, e.g. for photovoltaic parks to be established on croplands, must be considered. Such policies reduce the uncertainty exposure of the subsidized non-ecosystem-based land-use alternatives. Policies insuring landowners against financial losses likely boost the expansion of the subsidized alternatives, which may become a barrier to enhancing the share of sustainable land-use alternatives.

From a practical standpoint, allocating agricultural land to perennial woody species is a long-term investment that requires patience to receive future economic benefits from trees. Establishing trees is expensive; once planted, they must be maintained for years or decades to recover the initial investment; during this transition period, they may yield far lower cash flows than alternative land uses, and the revenue anticipated at the end of the planning horizon may not materialise at all due to adverse environmental or market conditions. Thus, uncertainty about the economics of transitioning to agroforestry can pose a significant barrier to its wider adoption (Rössert et al. 2022). Clarifying the interaction between agroforestry and uncertainty could facilitate greater uptake (Hosier 1989).

Although agroforestry economics has yet to mature into a specialised subfield, scholars have been laying the foundations. A recent special issue by Cialdella et al. (2023) offers a helpful window into the current state of the art. For instance, it is standard practice to use discounted cash flow methods like net present value (NPV) to evaluate agroforestry against current alternatives. However, this approach has a significant limitation: it assumes that investors can obtain money elsewhere in periods with zero or negative cash flows while waiting for deferred income from trees (Knoke et al. 2020). Cash flow discontinuities are typical of production systems involving trees, which tend to entail long waiting periods between establishing and harvesting marketable products. These discontinuities can often be smoothed through land-use diversification, which presumably applies to agroforestry adoption as well: rather than allocate one's entire holding to a single land use that produces a discontinuous income stream, managers may be more likely to integrate agroforestry on a portion of their land while retaining existing land-use types with more regular income on the remainder (Reidsma et al. 2023). Crucially, most previous work in agroforestry economics largely neglects uncertainty (e.g. Žalac et al. 2023; Smith et al. 2023; Thevs and Aliev 2023; Martinelli et al. 2019; Giannitsopoulos et al. 2020; Etherington and Matthews 1983).

Even with these simplifications, economic assessments of agroforestry often produce conflicting results. For instance, a recent review by Thiesmeier and Zander (2023) concludes that agroforestry generally shows lower economic performance than agricultural alternatives (but higher than forestry). In contrast, Kay et al. (2019) find that agroforestry outperforms conventional agriculture when one accounts for machinery, labour costs, and the economic value of ecosystem services. Against this backdrop of potentially irregular cash flows and conflicting scientific results, we think it is crucial to examine agroforestry adoption as a process that can unfold alongside (rather than strictly in opposition to) alternative land uses within larger farm or landscape portfolios (Castro et al. 2013; Castro et al. 2015).

To that end, we outline an approach that embeds agroforestry into landscapes from which multiple ecosystem services ("benefits") are expected to be generated by land uses ranging from intensive maize agriculture and livestock grazing to unmanaged natural forests. In doing so, we hope to lay the groundwork for more rigorous and realistic economic assessments of agroforestry transitions.

If we consider agroforestry essential for sustainable landscape management because of ecological arguments favouring such land-use practices (Plieninger et al. 2020), we need methods to derive desirable proportions of agroforestry in multifunctional landscapes under uncertainty, which must not ignore economic benefits.

The method we describe below builds on a handful of pioneering studies (e.g. Paul et al. 2017; Reith et al. 2020). To demonstrate our approach, we also adopt example data from Gosling et al. (2021) and Gosling et al. (2020a), who use robust optimisation to design landscape portfolios providing multiple ecosystem benefits. These studies report economic cost-benefit information and quantify estimates for two ecological benefits (water supply and soil protection) for each land-use type. This allows us to analyse ecological-economic trade-offs. However, they also assume equal weights for all decision criteria, and as a result, their solutions consist of a single optimal landscape portfolio.

Existing studies using robust multiple-criteria optimisation commonly assume that all objectives have equal weight (Knoke et al. 2016; Uhde et al. 2017; Friedrich et al. 2021; Jarisch et al. 2022; Kindu et al. 2022; Reith et al. 2022). We relax this equal-weight assumption using Pareto optimisation, named after the Italian economist Vilfredo Pareto (1848–1923). This technique yields a set of portfolios representing all possible weighting schemes (or preferences) for a set of decision criteria. It has emerged as an increasingly popular tool for trade-off analysis in multicriteria environmental decision support (e.g. Vasilakou et al. 2024) and is also widely used in life-cycle assessment (e.g. Azapagic and Clift 1999), agriculture (e.g. Andreotti et al. 2018; Milne et al. 2020; Kaim et al. 2020; Wesemeyer et al. 2023), and forestry (e.g. Borges et al. 2014). Applying Pareto methods to land-use allocation problems allows the analyst to generate an 'efficient' set of landscape portfolios, meaning that it is impossible to modify one criterion without worsening the performance of another. Land managers can select the portfolio that aligns with their criteria weights or multi-attribute utility functions.

3 Material and methods

To demonstrate our approach, we used data from farm surveys in the district of Chepo, in the East of the Republic of Panama. The study area represents a typical pasture-dominated landscape in the lowland humid tropics (average rainfall is 1910 mm per annum). The mean relative humidity is 87.4%, with a dry season from January to March and an average annual temperature of 26.4 C. The elevation of the mostly flat area is around 100 m above sea level, with some hills to the southeast reaching 400 m in elevation. Vertisol is the classified soil type where a high clay content limits agricultural productivity in the area. Pasture, crops and exotic tree plantations with small areas of secondary forest remnants dominate land use. Currently, agroforestry has yet to be widely implemented. However, retaining trees in pastures to provide shade and living fences is a common agricultural practice. This study considers two agroforestry systems - alley cropping and silvopasture - as land-use alternatives known to farmers but with limited adoption (information obtained from Gosling et al. 2020a).

The farm size of the farmers interviewed in 2018 was, on average, 77 ha (ranging from 5 to 271 ha), with a land-use distribution of 60% pasture, 26% crops, 13% natural forest and 1% forest plantation. The total area managed by the surveyed farmers sums to 2681 ha. At the time of the survey, >50% of these farms had allocated the largest share of their land area to pasture, while most crop-based farms also comprised some pasture area (Gosling et al. 2020b).

3.1 Land-use types and decision criteria

We adopted subjective ecological indicators (from Gosling et al. 2020a) and benefit-cost derived economic indicators (from Gosling et al. 2021) for six Panamanian land-use types (Table 1) to conduct a series of exploratory analyses on the economic impacts of integrating agroforestry into landscape portfolios. We consider two agroforestry land uses: silvopasture and a polycyclic alley cropping system locally known as *taungya*, which involves planting maize (*Zea mays*) between rows of teak (*Tectona grandis*) (Table 3) (Paul et al. 2015).

Table 1 Description of the land-use types considered for agroforestry land-use optimisation for smallholder farms in Eastern Panama (adopted from Gosling et al. 2020a). Names for the land-use types were not changed from the original publication, although 'alley cropping' could have also been named 'Taungya system'

Land-use	Description
Cropland	Corn croplands were assumed as land-use types for conducting cost-benefit analyses. The interviews to quantify the ecological indicators described various annual or (non-woody) perennial crops, either grown as a monoculture, a mix of crops in the same area, or rotated over time. Traditional planting methods were assumed, with some use of herbicides and fertilisers.
Pasture	Traditional pastures were assumed for cost-benefit analyses and interviews, with a stocking rate of 1.5–2.0 cattle per ha, which can include scattered trees.
Alley cropping	Trees and crops grown on the same parcel of land were assumed for cost-benefit analyses and interviews: teak lines are grown every 6 m, with corn (*Zea mays*) grown in between. Initial tree spacing is 3 m × 6 m, representing 550 trees per ha. Trees are grown for timber with a rotation length of 20 years; crops are no longer planted after year five due to shading.
Silvopasture	Trees and cattle on the same parcel of land were assumed for cost-benefit analyses and interviews: tree densities of around 200 trees per ha on traditional pastures, with a stocking rate of one cow per ha. Trees may be exotic or native and are planted or regenerated naturally (in which case they are guarded); trees may be harvested for timber after 20 years.
Plantation	Teak plantations were assumed for cost-benefit analyses and interviews: trees planted with 3 m × 3 m spacing (initial tree density of 1110 trees per ha) and harvested after 20 years.
Forest	Natural forests of native species were assumed for cost-benefit analyses and for interviews, which we used to collect firewood, fruits, etc., but not for commercial timber production.

The six land-use types constitute the decision alternatives for the Pareto optimisation, which allocates fractions of the total land area ranging from 0-100% to each land-use type (see 2.3). The result is a Pareto efficient portfolio where the area fractions indicate the composition of the future landscape.

We used four indicators to describe the decision criteria: economic indicators (NPV and payback period) and ecological indicators (perceived protection of freshwater supply and soils obtained with interviews; Table 2). The payback period is the years until the cumulated discounted cash flows have recovered the initial investment.

3.2 Data

Values for the ecological indicators were adopted from Gosling et al. (2020a), who asked the interviewed farmers to rank each land-use type according to their experience and local knowledge (Table 2). Values for the economic indicators were taken from Gosling et al. (2021), who conducted cost-benefit analyses and obtained standard deviations via Monte Carlo simulations using historical time series for yields and prices. The payback period and NPV were calculated from the cash flows shown in Table 3.

Table 2 Description of economic and ecological indicators used as decision criteria for agroforestry land-use optimisation adopted from Gosling et al. (2021) (indicators 1 and 2) and from Gosling et al. (2020a) (indicators 3 and 4)

Indicator	Unit	Direction	Description	Calculation
(1) Net present value	US\$ ha^{-1} yr^{-1}	More is better	Quantifies the economic return for the objective of increasing long-term income.	Sum of all discounted net cash flows (NCF) over 20 years, using a 5% discount rate: $NPV_l = \sum_t^T NCF_{l,t} \cdot (1.05)^{-t}$ [l refers to the land-use type, t to time and T is the considered period length]
(2) Payback period	Years	Less is better	We used the payback period, i.e. the time taken to earn back the initial investment, to account for cash flow and access to money. This indicator relates to the objective of liquidity.	We computed a discounted payback period, defined as the first year (within the 20-year rotation), with a positive discounted cumulative cash flow based on a 5% discount rate.
(3) Water supply	Score (0–10)	More is better	The degree to which land use can improve freshwater availability and quality.	Farmers ranked the six land-use types (Table 1) against these indicators. Their average and standard deviation were computed from the scores. Standard deviations were calculated from standard errors by multiplying with $\sqrt{n}$ and using $n = 32$.
(4) Soil protection			The degree to which the land use maintains soil fertility long-term.	

The standard deviations of these ecological indicators represent the uncertainty in the rankings due to variations in farmer responses. They were calculated from the standard errors reported in the original publication, multiplied by the square root of the number of farmers interviewed. For the economic indicators, the standard deviation was obtained by Monte-Carlo simulations in the original publication considering the variation in historical time series for yield and product prices of each land-use type; for details, see Gosling et al. (2021). Other sources of uncertainty that are interesting for future research are included in our discussion. The resulting indicator values we expect on average for the different land-use types and their standard deviations are reported in Table 4 (in the Results chapter). We conservatively treated

Table 3 Cash flows used to compute NPVs and payback periods (from Gosling et al. 2021, provided in their Supplementary Table S8); values do not include subsidies. Negative cash flows show that the investment (financial outflow) was higher than the financial inflow. We assumed no commercial products for the natural forest (called Forest in the Table) and thus zero cash flows.

	Cash flows (US$ ha^{-1})										
	Period (year)										
	0	1	2	3	4	5	6	7	8	9	
Cropland	444	531	531	531	531	531	531	531	531	531	
Pasture	-1435	456	393	393	393	393	393	393	393	393	
Alley cropping	-817	130	178	-242	-95	-209	-31	-95	-95	-95	
Silvopasture	-1970	177	114	183	248	244	240	236	278	272	
Plantation	-2185	-581	-485	-199	-423	-129	-129	-129	-129	-129	
Forest	0	0	0	0	0	0	0	0	0	0	
	Period, continued (year)										
	10	11	12	13	14	15	16	17	18	19	20
Cropland	531	531	531	531	531	531	531	531	531	531	531
Pasture	393	393	393	393	393	393	393	393	393	393	1168
Alley cropping	1393	-31	-95	-95	-95	-95	-95	-95	-95	-95	14132
Silvopasture	267	261	256	249	243	236	229	222	214	206	10234
Plantation	2336	-129	-129	-129	-129	-129	-129	-129	-129	-129	22710
Forest	0	0	0	0	0	0	0	0	0	0	0

expected indicator values as the best-case scenario and derived worst cases using multiples ($m = 2,3,4$) of the standard deviation. The best cases form an upper bound, and the worst cases form a lower bound of intervals, which we later integrate into the optimisations as the possible range of future indicator values.

3.3 Pareto optimisation

Constructing a Pareto-efficient set of landscape portfolios involves first solving for the portfolio that maximises economic performance without any regard to ecological effects, then introducing a constraint requiring a minimum provision of ecological benefits and solving again to obtain the following portfolio. By iteratively increasing the ecological requirement and calculating new solutions, we generate Pareto frontiers representing the maximum economic benefit that can be reliably obtained for all feasible levels of ecological benefits.

Our method also extends classical deterministic Pareto optimisation by integrating uncertainty. This is achieved by defining an interval of possible benefit levels for each land use and indicator, the magnitude of which is scaled by multiples of the standard deviation (Table 4). Wider intervals reflect a more uncertain future (or more uncertainty-averse decision-makers). We combinatorically aggregate the best and worst cases (i.e. the bounds of the intervals) across all land uses to create the surface of a multi-dimensional uncertainty space containing all possible combinations of future benefit levels for all land-use types. Each unique interval-bound combination constitutes a future uncertainty scenario, corresponding to a corner point of the uncertainty space, with $2^6 = 64$ corner points per indicator. By considering only the bounds of the benefit intervals—a representation known as 'box uncertainty' (Gorissen et al. 2015)—the resulting portfolios guarantee a performance floor for all benefits and land uses included in the uncertainty space (e.g. Bertsimas et al. 2011). For each uncertainty scenario, we compute the distances between portfolio performance and the best-case value for each indicator, where portfolio performance is an area-weighted mean of the benefits associated with its constituent land uses.

Mathematically, the objective function identifies the portfolio that minimises the maximum distance across the economic indicators β_r and their uncertainty scenarios without violating the maximum tolerable distance across the ecological indicators β_e:

$$\beta_r = \max_{(r,u)} D_{ru\%} \qquad \text{(Eq. 1)}$$

$$\beta_e = \max_{(e,u)} D_{eu\%} \qquad \text{(Eq. 2)}$$

$D_{ru\%}$ and $D_{eu\%}$ are relative distances between the desired and achieved indicator levels for the portfolio given uncertainty scenario u:

$$D_{ru\%} = \frac{Y_{ru}^{*} - Y_{ru}(a_l)}{Y_{ru}^{*} - Y_{ru*}} \cdot 100 \qquad \text{(Eq. 3)}$$

$$D_{eu\%} = \frac{Y_{eu}^{*} - Y_{eu}(a_l)}{Y_{eu}^{*} - Y_{eu*}} \cdot 100 \qquad \text{(Eq. 4)}$$

Distance $D_{ru\%}$ describes the degree of economic 'underperformance' and depends, *inter alia,* on the best (Y_{ru}^*) and worst (Y_{ru*}) economic indicator values for each land use and uncertainty scenario. y_{lru} represents the economic benefit of a single land-use type l in uncertainty scenario u.

$$Y_{ru}(a_l) = \sum_l a_l \cdot y_{lru} \qquad \text{(Eq. 5)}$$

with

$$y_{lru} = \begin{cases} E(y_{lr}) & \text{as the optimistic economic indicator level} \\ E(y_{lr}) \pm m \cdot sd_{lr} & \text{as the pessimistic economic indicator level} \end{cases} \qquad \text{(Eq. 6)}$$

$E(y_{lr})$ refers to the expected level of an indicator. Standard deviations sd_{lr} for each land use and indicator are reported in Table 4. The size of the uncertainty space is controlled by the factor m. The same description applies to the variables included in Eq. 4 for the ecological benefit indicators.

Note that the best-case indicator value Y_{ru}^* or Y_{eu}^* can be either the maximum or minimum values (Knoke et al. 2022b)--after all, managers prefer shorter payback periods but larger NPVs. Because the numerator and the denominator of $D_{ru\%}$ are both negative when the minimum represents the best case (zero is also possible in the case of the numerator), the distance to the reference point is always positive, and Eqs. 3,4 hold irrespective of whether the indicator should be minimized (payback period) or maximized (NPV).

To minimize the maximum distance $D_{ru\%}$, we allocate area proportions (a_l) across land-use types (l), thus controlling the area-weighted portfolio benefit $Y_{ru}(a_l)$, subject to stepwise reductions in the tolerated maximum distances Z_{et} for the ecological decision criteria e (Eq. 9) (see Knoke et al. 2024). We initialise the Pareto frontier by maximizing the economic benefit without any ecological requirement (tolerating $\beta_{et} = 100$), then iteratively reduce Z_{et} (i.e. increase the ecological requirement) in 5% steps until no feasible solution remains. Requiring Eq. 8 and 9 for all uncertainty scenarios ($\forall\ u$) entails a robust optimisation problem.

$$\min_{a_l} \beta_r \qquad \text{(Eq. 7)}$$

s.t.

$$\beta_r \geq D_{ru\%} \quad \forall\, u \qquad \text{(Eq. 8)}$$

$$Z_{et} \geq \beta_e \quad \forall\, u \qquad \text{(Eq. 9)}$$

Requiring Eq. 8 and 9 for all uncertainty scenarios ($\forall\, u$), we have selected a robust mathematical representation of the optimisation problem. The resulting landscape portfolios thus provide solutions that are deterministically immune to realisations of the uncertain land-use type benefits from uncertainty spaces (Bertsimas et al. 2011). We started without any specific required ecological benefit, thus tolerating $\beta_{et} = 100$, which means we maximised the economic benefit only. Subsequently, we reduced Z_{et} in Eq. 9 in steps of 5% to enhance the required ecological benefits as long the problem optimisation remained feasible.

To visualize the Pareto frontier, we translated the maximum distances into robust benefits p_r and p_e:

$$p_r = 100 - \beta_r \qquad \text{(Eq. 10)}$$

$$p_e = 100 - \beta_e \qquad \text{(Eq. 11)}$$

Because p_r and p_e are guaranteed for all possible values within the uncertainty interval, the portfolio solutions for each scenario are also deterministically immune to future variations in benefit levels, provided they do not exceed bounds of the uncertainty space (Bertsimas et al. 2011).

4 Results

4.1 Indicators

Best-case NPVs ranged from US \$0 ha^{-1} (unmanaged natural forest) to \$7061 ha^{-1} (croplands) (Table 4). Although croplands and teak plantations can achieve the highest NPVs, they comprise only a minor share of the actual study area. The real-world landscape predominates in pastureland, whose NPV ranks only above unmanaged natural forests. However, this apparent discrepancy is readily resolved by considering uncertainty aversion. The NPV for croplands and teak plantations is high but also highly variable, whereas pasture is remarkably consistent. As a result, pasture offers the highest reward-to-variability ratio (NPV/SD) of any land-use type (\$7.31 vs. \$2.67 for cropland).

Table 4 Expected indicator values used for the optimisations (mean ± SD). SD for NPV and payback period obtained from Table 4 in Gosling et al. (2021), and scores and SD for freshwater supply and soil protection adopted from Table 4 in Gosling et al. (2020b). These indicator levels are considered best cases, ranking in brackets.

Land-use	**Net present value**	**Payback period**	**Water supply**	**Soil protection**
	US\$ ha^{-1}	Years	Score (0-10)	
Cropland	7061 (±2643) *[1]*	1 (±1.6) *[2]*	4.0 (±2.4) *[6]*	5.5 (±2.60) *[5]*
Pasture	3815 (±522) *[5]*	5 (±1.1) *[3]*	4.7 (±2.3) *[5]*	5.0 (±1.81) *[6]*
Alley cropping	4605 (±1792) *[4]*	8 (±8.6) *[4]*	6.8 (±1.5) *[4]*	6.5 (±2.26) *[4]*
Silvopasture	4622 (±696) *[3]*	11 (±2.8) *[5]*	7.6 (±1.2) *[2]*	6.9 (±1.81) *[2]*
Plantation	5273 (±2019) *[2]*	20 (±0) *[6]*	7.2 (±2.5) *[3]*	6.6 (±2.60) *[3]*
Forest	0 *[6]*	0 *[1]*	9.9 (±0.5) *[1]*	9.1 (±2.15) *[1]*

Despite exhibiting similar, moderate best-case NPVs (i.e. superior to pasture but worse than teak plantations), the agroforestry systems can also be differentiated by benefit volatility: silvopasture offers a reward-to-variability ratio of \$6.64, versus \$2.56 for alley cropping.

Cropland exhibited short but variable payback periods, while those for pasture were both short and consistent. The agroforestry options were moderate performers; teak plantations feature the longest payback period, with the initial investment recovered with the final harvest in year 20.

Cashflow continuity is primarily a function of the prevalence of trees in each land-use type (Table 3). Cropland and pasture generate cash flows quickly and regularly. The agroforestry options produce early revenue but exhibit more significant fluctuations associated with timber harvests. In alley cropping, timber revenue dominates the cash flow distribution. Although the maize cultivated in the alleys generates net-positive cashflows as early as the second year, it is shaded out by year five. As a result, positive returns are expected in only four years of the 20-year-long production period.

Unmanaged natural forests' payback period and NPV are null (no initial investment is required, and no revenue is generated). Note that the opportunity costs of keeping the unmanaged natural forest were considered implicitly, as any area allocated to the unmanaged natural forest reduced the landscape-level NPV proportionally. However, natural forests offer the highest ecological benefits from the six land uses. Depending on the indicator, teak plantations or agroforestry offer the second-best ecological performance. Ecological benefits are lowest for pasture and cropland.

4.2 The economic contribution of agroforestry when ignoring uncertainty

In scenarios that ignore uncertainty and ecological benefits, the optimal landscape portfolio consists exclusively of intensive maize agriculture (Figure 1). Introducing ecological requirements stimulates the inclusion of silvopasture and natural forests, with the maximum ecological benefit being achieved by allocating roughly two-thirds of the total land area to silvopasture. Interestingly, however, the economic performance of portfolios including silvopasture was only marginally higher than those excluding agroforestry. Without agroforestry, the ecological constraint is satisfied mainly by increasing the share of tree

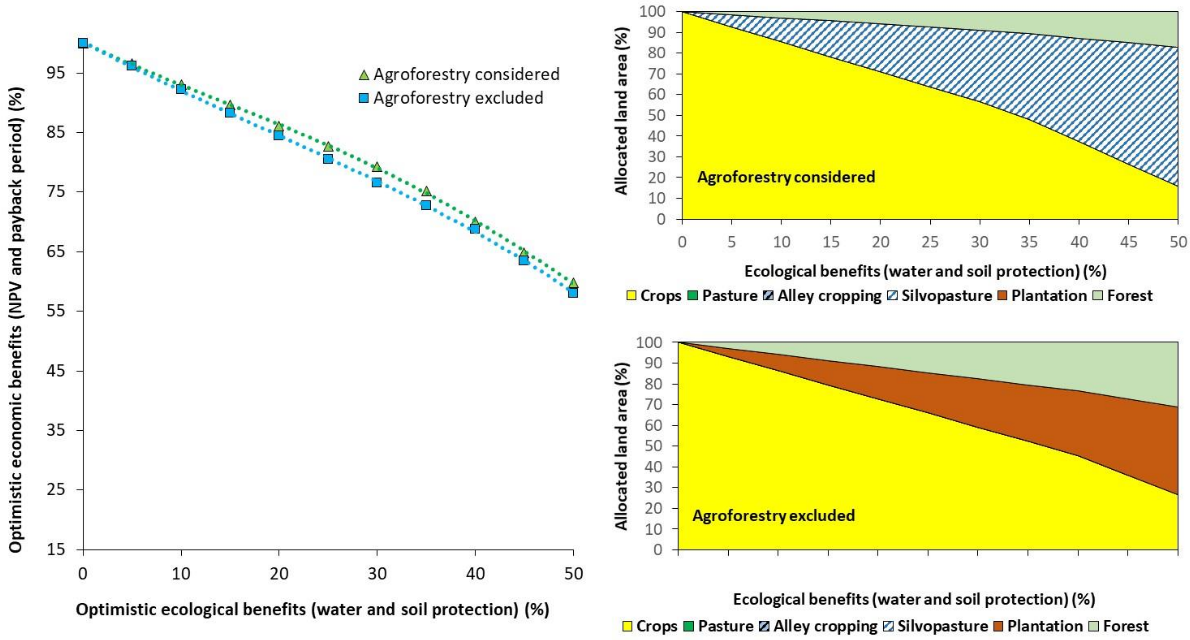

Figure 1 Left: Pareto frontiers (i.e. efficiency frontiers) and landscape portfolio compositions for maximum economic benefits under increasing levels of required ecological benefits when uncertainty was ignored. The frontiers show the maximum (optimistic) economic benefit achievable when requiring certain levels of ecological benefits, either allowing for agroforestry or not. Right: Changes in the landscape composition with increasing levels of required ecological benefits, the upper part allowing for agroforestry and the lower part excluding it

plantations and natural forests (Figure 1). No land was allocated to pasture or alley cropping without uncertainty, regardless of the ecological requirement.

4.3 The economic contribution of agroforestry in an uncertain world

Under moderate uncertainty ($m = 2$), agroforestry options are only included in the solution if there is also a demand for ecological benefits (Figure 2A). However, accounting for higher uncertainties ($m \geq 3$) results in incorporating both agroforestry land-use types even without ecological requirements (Figure 2B).[1]

As uncertainty grows, portfolios with agroforestry increasingly outperform those without it. At the highest uncertainty levels, 11.8% and 21.8% of the land area is allocated to alley cropping

[1] An uncertainty level of $m = 2$ means that the worst-case indicator value is two times the standard deviation worse than the best-case indicator value; $m = 3$ means three times the standard deviation; and so forth (Table 4).

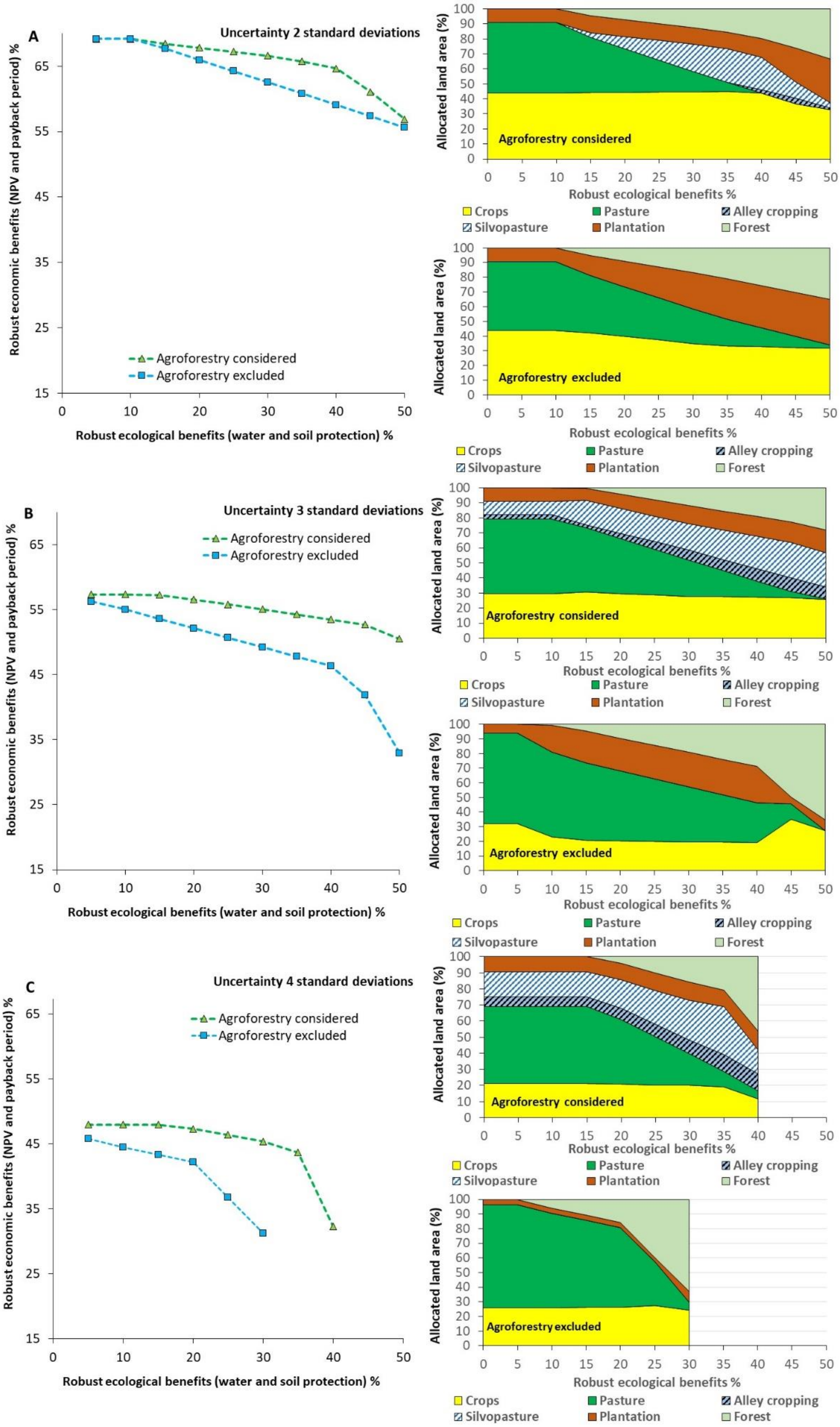

Figure 2 Pareto frontiers (i.e. efficiency frontiers) and landscape portfolio compositions for maximum economic benefits under increasing required ecological benefits for different levels of uncertainty. Panel A considers m=2 standard deviations to compute the worst-case benefits of the individual land-use types, while panels B and C account for 3 and 4 standard deviations, respectively, in finding the worst-case benefits.

and silvopasture, respectively (Figure 2, left corner). Agroforestry also mitigates trade-offs between ecological and economic performance in scenarios featuring a high demand for ecological benefits. Expanding the uncertainty space enhances the maximum proportion of agroforestry (silvopasture plus alley cropping) from 23.9% for $m = 2$ to 40.1% for $m = 4$. However, even these proportions are notably smaller than the 67.1% achieved in the no-uncertainty scenario with maximum ecological requirements.

In addition to modulating the share of agroforestry in the landscape, the size of the uncertainty space also alters the curvature of the Pareto frontiers. Large uncertainty spaces magnify the sensitivity of economic benefits to ecological demands, notably when agroforestry options are excluded. The no-agroforestry frontiers exhibit clear economic tipping points: beyond a certain threshold, ecological requirements force sharp increases in the land area allocated to natural forests (Figure 2). Including agroforestry options attenuates this effect when uncertainty is elevated by displacing part of the natural forest area: for uncertainty $m = 4$, for example, robust ecological benefits top out at 30% without agroforestry versus 40% with agroforestry. This ten-point increase also comes with economic benefits that exceed the best-performing non-agroforestry portfolio (Figure 2).

4.4 Testing for the robustness of the desirable landscape portfolios

Mathematically, the performance of our landscape portfolios should be robust as long as benefit variability remains within the uncertainty intervals. To test this empirically, we confronted the optimised portfolio sets with benefit levels randomly drawn from the uncertainty intervals (Figure 3). We also forced pessimistic benefit combinations as an additional robustness check but could not generate any empirical outcomes that underperformed the frontier (Figure 3).

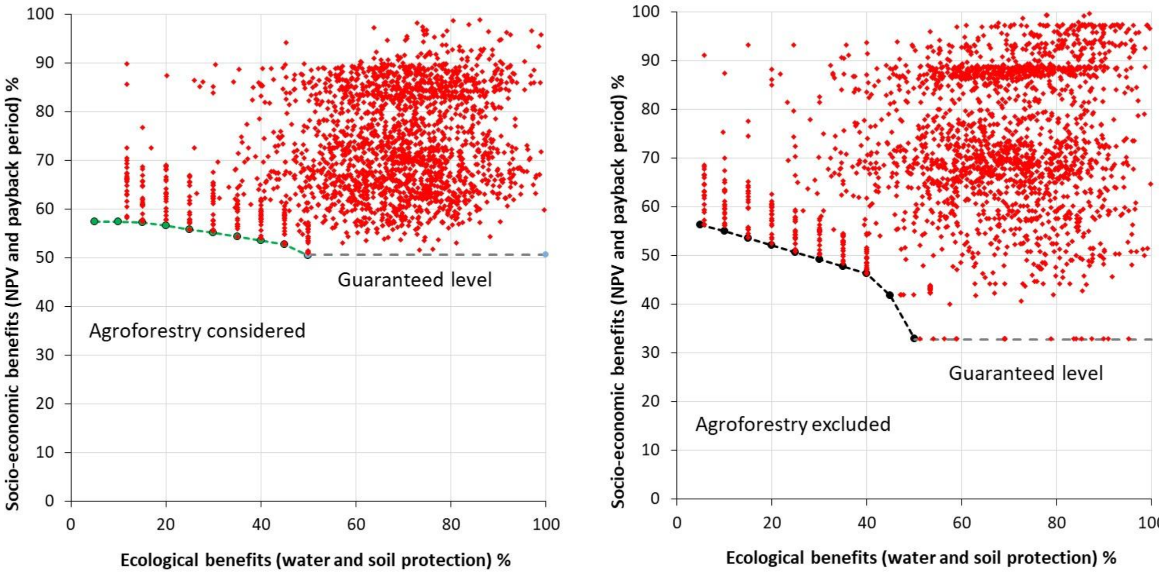

Figure 3 Simulated benefits of the efficient landscape portfolios when benefits of the single land-use types were drawn from the considered benefit intervals formed by worst and best cases. The Figure is built on $m = 3$, meaning the worst case is three times the standard deviation of the considered benefit smaller than the best case.

Thus, the frontiers visualise a guaranteed floor below which portfolio performance will not fall for a given uncertainty scenario (dashed grey lines in Figure 3). Landscape portfolios containing agroforestry maintained robust economic benefits of at least 51% over the full range of ecological constraints (Figure 3, left). When agroforestry was excluded, economic performance fell to 33% under elevated ecological constraints (Figure 3, right side).

5 Discussion

This study builds on earlier efforts to consider risk and uncertainty in agroforestry economics. In particular, Paul et al. (2017) set the stage by providing a framework to economically assess land-use combinations using Markowitz portfolio optimisation. While it offers a helpful reference, their approach encounters several limitations. For instance, it is probabilistic and does not situate allocation decisions within the conventional agricultural landscapes where agroforestry transitions would presumably occur.

In contrast, our non-stochastic approach embeds agroforestry in portfolios encompassing *status-quo* agricultural alternatives. Unlike the Markowitz model, our approach does not require outcome probabilities to be assigned *a priori*. Instead, it captures benefits guaranteed across entire uncertainty spaces (see Figure 3) defined by land managers according to their degree of caution (e.g. Knoke et al. 2022a). As far as we know, ours is the first study to adopt this broader Pareto perspective, at least in the context of agroforestry research.

We are also indebted to a handful of previous studies that applied robust multi-criteria portfolio optimisation to study the potential role of agroforestry in the study area where we obtained our example data (Gosling et al. 2020b; Gosling et al. 2020a; Reith et al. 2020; Gosling 2021; Reith et al. 2022). These studies have struggled to reproduce the real-world landscape composition based on economic indicators alone, tending to overestimate cropland and underestimate pasture, the predominant land use in the area, despite its seemingly uncompetitive NPV (Gosling et al. 2021).

Our model successfully approximates this counterintuitive result, which occurs in scenarios that account for uncertainty but ignore ecological performance. Thus, we also suggest a lens for understanding existing landscape dynamics. If land managers favour pasture because it generates modest but reliable returns, they are likely sensitive to future costs and benefits volatility. Consequently, their land allocation decisions are unlikely to be captured by simple NPV comparisons, arguably the default approach in agroforestry economics today (Do et al. 2020).

Methodologically, these earlier studies also assume equal weights for all decision criteria. In contrast, we generate Pareto-efficient sets of portfolios representing all possible weighting schemes (Figs. 2,3). This feature makes our method easier to generalise to other settings. For instance, it could be deployed to support stakeholder consultations, participatory decision-making (Marques et al. 2020), or co-creation heuristics like the Nature Futures Framework (e.g. Pereira et al. 2020), which seeks to identify interventions that are responsive to diverse perspectives and worldviews (Kim et al. 2023).

6 A research agenda for agroforestry ecological economics

This article presents an argument for broadening the ecological economics of agroforestry beyond the narrow view offered by deterministic cost-benefit analysis to explore how adoption decisions are shaped by the landscapes they are embedded in and how they shape, in turn, the capacity of those landscapes to provide ecological and economic benefits in an increasingly uncertain world.

To that end, this section sketches the contours of a new research agenda for agroforestry ecological economics. We highlight eight points: (1) making uncertainty explicit; (2) accounting for temporal discontinuities in cost-benefit flows; (3) focusing on the pivotal establishment phase for agroforestry transitions; (4) quantifying the economic implications of biophysical interactions and feedbacks; (5) using new monitoring technologies and simulating models and accounting for their uncertainties; (6) taking a proactive approach to market-based instruments; (7) exploring trade-offs in context; and (8) embedding agroforestry transitions in landscapes.

Making uncertainty explicit

Our findings suggest a potential new economic argument for agroforestry adoption: incorporating agroforestry into land-use portfolios could enhance their ability to provide ecological and economic benefits robust to various possible futures. This advantage is not captured by NPV alone but instead results from moderate reward-to-uncertainty ratios and partially discontinuous cashflows. This hypothesis warrants further empirical testing in other contexts, such as productive landscapes in the Global North.

Incorporating uncertainty into descriptive studies can complement the normative decision-theoretical approach described here. For example, previous work has successfully applied microeconomic stochastic frontier analysis to obtain efficiency information from uncertain agricultural outputs (Stetter and Sauer 2022). This method can help to explore the production frontier of uncertain agricultural output and input to obtain efficiency information related to the joint provision of agroforestry solutions. Similarly, recent simulation experiments suggest German farmers may consider agroforestry practices as a risk-hedging strategy in response to increasing extreme weather events (Stetter and Sauer 2024), highlighting the importance of uncertainty for future decision-making. Given the proliferating uncertainties associated with land management planning (e.g. Molina Bacca et al. 2023; Verburg et al. 2013), we encourage an explicit consideration of uncertainty in future work.

Accounting for temporal discontinuities in cost-benefit flows

Our study builds on dynamic economic data covering a timeline of 20 years for each benefit and land use. Future work should take advantage of temporally disaggregated information, particularly concerning the 'early life' of land-use practices that exhibit cashflow discontinuities and significant discrepancies in the duration of production cycles. The economic attractiveness of agroforestry could be plausibly enhanced by identifying strategies for obtaining earlier and more continuous economic returns from the tree components. For example, multi-purpose trees could enable land managers to earn income earlier from non-timber products like fruits, nuts, or fodder. An alternative might involve incorporating components with shorter production times into the tree lines themselves, as suggested by syntropical (Andrade et al. 2020) and other successional agroforestry systems. This would diversify the product portfolio and provide earlier and more frequent financial returns, although potentially at the cost of additional labour input.

Focusing on the pivotal establishment phase for agroforestry transitions

Improving the design of agroforestry systems requires long-term information, beginning with the pivotal "early life" phase. Establishing agroforestry involves navigating an array of variables, many of which have yet to be researched systematically: ungulates browsing shoots or damaging bark, spring drought, suboptimal planting conditions, and inadequate soil or fungal symbionts can all contribute to tree mortality and increase material costs (Cossel et al. 2020). Soil water, carbon, nutrient dynamics and the structure and function of biota living in soil and acting as architects for soil health may gradually change when agroforestry systems are established until a new stable equilibrium is reached; thus, managers might leverage supporting factors (e.g., diverse vegetation) in early phases. While trees are growing, dynamic soil niche spaces between crops and trees are created. Initially, resource competition in the same soil space could be prevalent (Ludwig et al. 2004), while effective niche partitioning and more efficient resource use between trees and crops may develop with tree growth (Bouttier et al. 2014; Goisser et al. 2016). How these dynamics unfold presumably depends on interactions between management decisions and environmental dynamics, but the nature of these relationships is still poorly understood.

In short, there is considerable potential for statistically well-designed, long-term experimental platforms to drive significant advances in our understanding of agroforestry transitions. Only a handful of such platforms exist worldwide (Veldkamp et al. 2023; Fedrigo et al. 2024). While expensive experimental approaches will always represent only a narrow ecological and socio-economic context, they can serve as hubs for knowledge exchange through international and interdisciplinary research initiatives.

Quantifying the economic implications of biophysical interactions and feedbacks

Generally, combining forestry and agriculture is believed to increase ecosystem services provisioning (Torralba et al. 2016) and product diversification (Neupane and Thapa 2001) while also supporting resistance, soil health, yield, and economic stability (Pumariño et al. 2015; Isbell et al. 2017; Fahad et al. 2022). Ecosystem services associated with trees, such as water or nutrient redistribution (Sun et al. 2014; Alagele et al. 2021), may reduce irrigation and fertilization costs for neighbouring crops—a largely unquantified benefit. The diversification of the agricultural ecosystems may also increase biodiversity, although current evidence is mixed, see Mupepele et al. (2021), and more work is needed.

Using new monitoring technologies and simulating models and assessing their uncertainties

Remote sensing and artificial intelligence can play a crucial role in mitigating uncertainties in agroforestry by providing real-time monitoring and predictive insights (Thapa et al. 2023). Integrating the Internet of Things (a network that connects and controls sensors and devices, exchanges data and communicates with users) and sensing technologies, such as strap-cameras, multispectral drone imagery, and real-time monitoring devices (e.g. Valentini et al. 2019) can enable early identification of stresses and diseases so that managers can react quickly to reduce yield losses. Additionally, digital platforms can integrate weather forecasts and market trend data to support a proactive approach to managing meteorological variability, market fluctuations, and resource allocations. However, integrative research leveraging such technologies in the context of agroforestry is still needed.

Frequent tree, crop and tree-crop-interaction measurements during the establishment phase will be crucial for developing and testing dynamic agroforestry simulation models across their lifespan. Some dynamic agroforestry models and modelling approaches exist (van Noordwijk and Lusiana 1998; Riofrío et al. 2015; Morhart et al. 2016; Dupraz et al. 2019; Bohn Reckziegel et al. 2021; Bohn Reckziegel et al. 2022; Rahman et al. 2023; Žalac et al. 2023), mainly focusing on biomass and yield (Kraft et al. 2021), which can be translated to economic benefits using price time series. However, these models still often ignore the impact of agroforestry on ecological benefits related to water and nutrient dynamics, micro-climate, and soil biota, for which detailed field data are a prerequisite for further model enhancements. In addition, comprehensive assessments of the uncertainty associated with the model predictions are largely missing. Dynamic agroforestry simulation models will be needed for evaluating agroforestry practices for different soils, climatic conditions and future climate scenarios and for scaling up agroforestry field experiments across regions, similarly as recently shown for simple crop-disease system interactions (Pequeno et al. 2024). To quantify agroforestry model uncertainty and understand uncertainty propagation in a system will eventually require a multi-model approach combined with field experiments as proposed by the Agricultural Model Intercomparison and Improvement Project, AgMIP (Wang et al. 2024).

Taking a proactive approach to market-based instruments

The idea of leveraging agroforestry as a buffer against uncertainty in sustainable landscape portfolios raises the possibility of further mitigating ecological-economic trade-offs by seeking to monetize their ecosystem services. To support this, market-based solutions, such as Pigouvian subsidies or certification of agricultural products grown in ecologically favourable agroforestry systems, warrant exploration. Certification schemes could differentiate products in the marketplace, allowing farmers to charge premium prices based on consumer preferences for sustainable goods, similar to organic, Fairtrade, or Forest Stewardship Council certifications (Altmann and Berger Filho 2020; Ota et al. 2022). However, the costs of establishing and acquiring such certifications are significant and may hinder farmers' entry.

An alternative approach could involve the creation of "ecological certificates," similar to the trading forest certificates discussed by Soares-Filho et al. (2016). Under this system, farmers who adopt land-use practices delivering measurable ecological benefits—such as improved soil health or enhanced water retention—could sell their "ecological certificates" to companies seeking to offset their environmental impacts. These certificates could be traded on markets driven by consumer expectations or regulatory requirements for ecological sustainability, such as non-financial reporting standards. Both approaches provide direct financial incentives for farmers that could facilitate agroforestry transitions.

Exploring trade-offs in context

The inclusion of agroforestry into landscape portfolios may compromise alternative land-use types with high conservation value. For example, under higher uncertainty levels, agroforestry replaced part of the area that would have otherwise been allocated to natural forests with a high conservation value (Fig. 3 and Reith et al. 2022, showing similar effects). While this is a sensitive issue at the tropical forest frontier, it may not be a significant problem in other contexts, such as Central Europe, where primary forests cover only 0.7% of the forest area (Sabatini et al. 2018). However, agroforestry in Europe may compromise open-space demanding species, such as skylarks or lapwings (Gayer et al. 2019). Also, while agroforestry systems may harbour more animal (e.g. insect) species as mono-cropping systems, their insect communities are still less diverse than those of natural forests (Perry et al. 2016; Mupepele et al. 2021). Future land-use studies must address such trade-offs and possible legal implications.

While we have focused on small-scale uncertainties like fluctuations in productivity and prices or expert uncertainty about ecological benefits, exploring risks and trade-offs associated with agroforestry adoption in other settings will likely require incorporating assessments of the policy landscape. For example, the EU's Common Agricultural Policy (CAP) focuses on sustainable land use and incorporating environmental aspects into agricultural practices. Our results confirm that agroforestry may align with these policy objectives while potentially minimising trade-offs with economic objectives. Given the diverse agroecological zones across Europe, from Mediterranean to temperate regions, it is crucial to adapt evidence-based agroforestry practices to specific regional environmental and economic conditions.

Embedding agroforestry transitions in landscapes

Rather than examining the economics of an agroforestry system in isolation, this study sought to capture partial adoption decisions by considering portfolios of land-use alternatives that agroforestry systems may displace or be displaced by. This might include competition from non-agricultural land uses. Solar farms, for example, represent an increasingly important land-use alternative in many countries (Dias et al. 2019). Their deployment on potential agricultural lands suggests the need for additional economic comparisons. Portfolio-based approaches like the one we describe here (see also Paul et al. 2017) can be re-tooled to address how subsidising financial risk in emerging land-use types could influence the competitiveness of agroforestry-based land uses in different environmental settings.

7 Outlook

The extent to which agroforestry systems can compete economically with standard agricultural practices *ceteris paribus* remains unclear. Indeed, substantial evidence suggests they might not compete (e.g. Thiesmeier and Zander 2023). We argue that by failing to explicitly consider the role of uncertainty and landscape context in agroforestry adoption decisions, the available economic evidence—favourable or not—has overlooked a crucial consideration.

In our study area, allowing the partial adoption of agroforestry options into landscape portfolios mitigated environmental-economic trade-offs and increased portfolio performance under uncertainty. Beyond our study area, we hypothesise that uncertainty considerations can also provide convincing arguments in support of agroforestry in the Global North, where adoption remains slow despite growing scientific interest. Understanding how variations in uncertainty and temporal discontinuities in benefit flows influence economic assessments of agroforestry relative to conventional land uses is crucial for stimulating uptake. By offering a lens through which the economics of agroforestry adoption can be assessed alongside *status quo* systems in the face of growing uncertainty about future benefit flows, we aim to broaden the scope of such assessments.

At the same time, we identify substantial knowledge gaps, beginning with the pivotal 'early life' phase of agroforestry transitions. Developing rigorous, realistic, and helpful agroforestry ecological economics will require ongoing cooperation between economists, natural scientists and land managers.

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