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When considering uncertainty, agroforestry can reduce trade-offs between economic and ecological benefits

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Abstract Persistent uncertainty about the economic implications of agroforestry presents a significant 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 explored 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

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options. Drawing on published data from smallholders in Panama, we used robust optimisation of multiple objectives to allocate fractions of land area across six agroforestry and non-agroforestry land uses under a range of possible futures. We visualised trade-offs between uncertain ecological and economic benefits using robust Pareto frontiers. We found that neglecting uncertainty reduces the attractiveness of agroforestry. Instead, agroforestry became increasingly competitive as uncertainty grew, and incorporating it into landscape portfolios could mitigate trade-offs between ecological and economic objectives when the future is uncertain. At the same time, we argue that agroforestry-uncertainty relationships are multilayered. Early-life information is largely missing, and discontinuous cash flows, deficiencies in modelling, and a lack of financial incentives contribute to the uncertainty of agroforestry land uses and their barriers to broader adoption under global change.

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

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 potential 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 different 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. 2020a; Gosling et al. 2020b; Gosling and Reith 2020; Reith et al. 2020; Gosling 2021; Reith et al. 2022; Reith 2024). Building on previous Panamanian research is an excellent

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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.

State of knowledge

Existing stochastic land-use allocation approaches build on random variables and associated probabilities (Knoke et al. 2011; Castro et al. 2013, 2015; Neuner et al. 2013; Hauk et al. 2017; Friedrich et al. 2019; Matthies et al. 2019; Fuchs et al. 2022, 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 means that the set of potential outcomes is known but not their probabilities of occurring (e.g. Walker et al. 2010; Knoke et al. 2022a, 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). Increasing uncertainty could also influence the farmers' future land-use decisions. 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. 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 subsidised non-ecosystem-based land-use alternatives. Policies insuring landowners against financial losses likely boost the expansion of the subsidised options, 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 cashflows 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 cashflows while waiting for deferred income from trees (Knoke et al. 2020a). 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) found 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 cashflows 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, 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 used 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. 2022b; 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.

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).

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).

The six land-use types constitute the decision alternatives for the Pareto optimisation, which allocates fractions of the total land area ranging from 0 to 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 cashflows have recovered the initial investment. We selected a 5% discount rate to reflect Panamanian farmers' relatively high time preference. In a detailed study on landowner's choices to participate in an agroforestry program, Lloyd-Smith et al. (2021) estimated a time preference corresponding to a constant exponential discount rate of 5.6% for Panamanian farmers, which we used as an orientation. Roughly coinciding with the empirical estimations, Pearce et al. (2003) suggest a discount rate of 5% for assessing tropical forestry projects.

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)

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 maize (*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

Names for the land-use types were not changed from the original publication, although 'alley cropping' could have also been named 'Taungya system'

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 cashflows (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	

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 cashflows shown in Table 3.

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.

We conservatively treated 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.

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

Table 3 Cashflows used to compute NPVs and payback periods (from Gosling et al. 2021, provided in their Supplementary Table S8); values do not include subsidies

	Cashflows (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	14,132
Silvopasture	267	261	256	249	243	236	229	222	214	206	10,234
Plantation	2336	− 129	− 129	− 129	− 129	− 129	− 129	− 129	− 129	− 129	22,710
Forest	0	0	0	0	0	0	0	0	0	0	0

Negative cashflows 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

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 multidimensional 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

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)

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]

These indicator levels are considered best cases, ranking in brackets

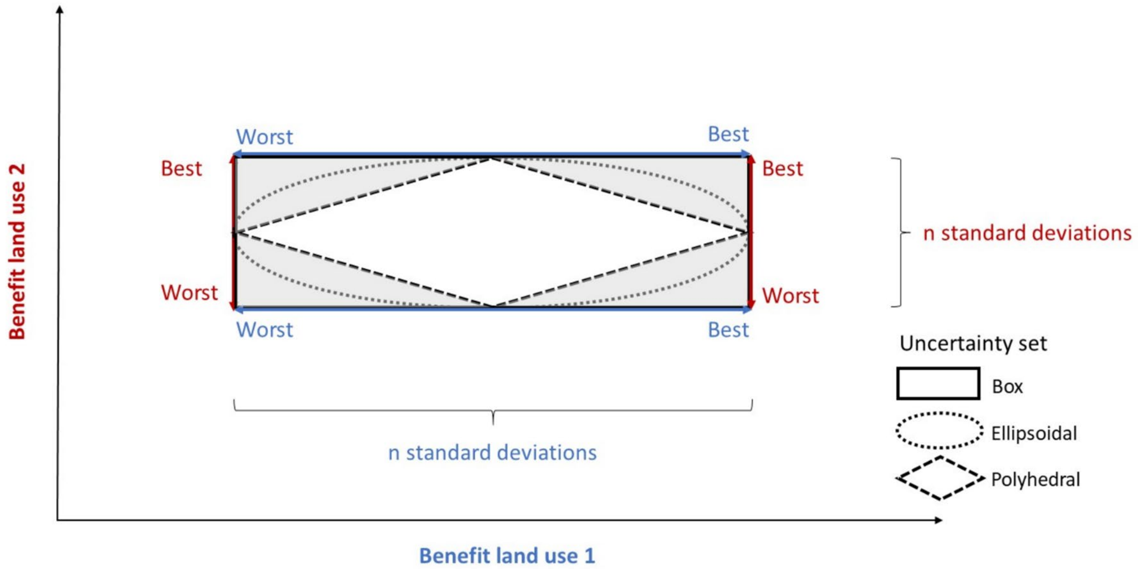


Fig. 1 Different uncertainty sets to represent possible benefit combinations of two land uses. The box, ellipsoidal or polyhedral sets include the combined benefits from land use 1 and 2, which the robust optimisation accounts for. The performance identified for the optimal land allocation is guaranteed for all included benefit combinations. Guaranteed performance means that this performance may be higher for many benefit combinations, but it will never be lower

for all benefits across the land uses included in the uncertainty space (e.g. Bertsimas et al. 2011). A box uncertainty set is shown for a two-dimensional example in Fig. 1. 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.

There are several opportunities to decide which combinations of benefits are accounted for in robust optimisations, which differ in the geometry of the uncertainty set. The most common geometries of uncertainty sets are box-shaped, ellipsoidal, or polyhedral (Gorissen et al. 2015; Jalilvand-Nejad et al. 2016). We illustrate the three standard uncertainty sets with a simplified example of possible best–worst benefit combinations between two land uses (Fig. 1).

Box uncertainty sets are generous, including stochastically unlikely combinations of outcomes, such as multiple land uses simultaneously generating best-case or worst-case results. Ellipsoidal and polyhedral uncertainty sets rule out such a coincidence: when one land use generates an extreme result, the alternative land use is assumed to yield a moderate benefit level (e.g. the average of the best and worst cases): in Fig. 1, for example, the polyhedral uncertainty set ignores the benefit combinations represented by the grey-shaded areas. For some problems, pruning away the corners of the box set provides a more realistic representation of the uncertainty space. At the landscape scale, however, extreme results can plausibly be obtained from all land uses at once: for instance, a severe drought could cause all elements of a land-use portfolio to simultaneously produce their worst-case benefit levels. Thus, by adopting box uncertainty sets here, we neither assume that benefit levels are correlated nor rule out scenarios where land uses converge simultaneously to extreme outcomes.

Mathematically, we use an objective function to identify 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:

$$\beta_r = \max_{(r,u)} D_{ru\%} \quad (1)$$

$$\beta_e = \max_{(e,u)} D_{eu\%} \quad (2)$$

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

$$D_{ru\%} = \frac{Y^*_{ru} - Y_{ru}\left(a_l\right)}{Y^*_{ru} - Y_{ru*}} \cdot 100 \tag{3}$$

$$D_{eu\%} = \frac{Y^*_{eu} - Y_{eu}\left(a_l\right)}{Y^*_{eu} - Y_{eu*}} \cdot 100 \tag{4}$$

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.

$$Y_{ru}\left(a_l\right) = \sum_l a_l \cdot y_{lru} \tag{5}$$

with

$$y_{lru} = \begin{cases} E(y_{lr}) & \text{as the best economic indicator level} \\ E(y_{lr}) \pm m \cdot sd_{lr} & \text{as the worst economic indicator level} \end{cases} \tag{6}$$

$E\left(y_{lr}\right)$ 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 indicator value 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 minimised (payback period) or maximised (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$Y_{ru}\left(a_l\right)$, subject to stepwise reductions in the tolerated maximum distances Z_{et} for the ecological decision criteria e (9). We initialise the Pareto frontier by maximising the economic benefit without any ecological requirement (tolerating $Z_{et} = 100$), then iteratively reduce Z_{et} (i.e. increase the ecological requirement) in 5% steps until no feasible solution remains. Requiring Eqs. 8 and 9 for all uncertainty scenarios ($\forall u$) entails a robust optimisation problem.

$$\min_{a_l} \beta_r \tag{7}$$

s.t.

$$\beta_r \geq D_{ru\%} \forall u \tag{8}$$

$$Z_{et} \geq \beta_e \forall u \tag{9}$$

Requiring (8) and (9) for all uncertainty scenarios ($\forall u$), we have selected a robust mathematical representation of the optimisation problem. The constraints formulated in (8) and (9) ensure that the performance identified by the objective function will not be violated, regardless of which of the 64 uncertainty scenarios per decision criterion is considered. 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 (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:

$$p_r = 100 - \beta_r \tag{10}$$

$$p_e = 100 - \beta_e \tag{11}$$

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).

Results

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).

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, vs. \$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 cashflows 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.

The payback period and NPV of unmanaged natural forests 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

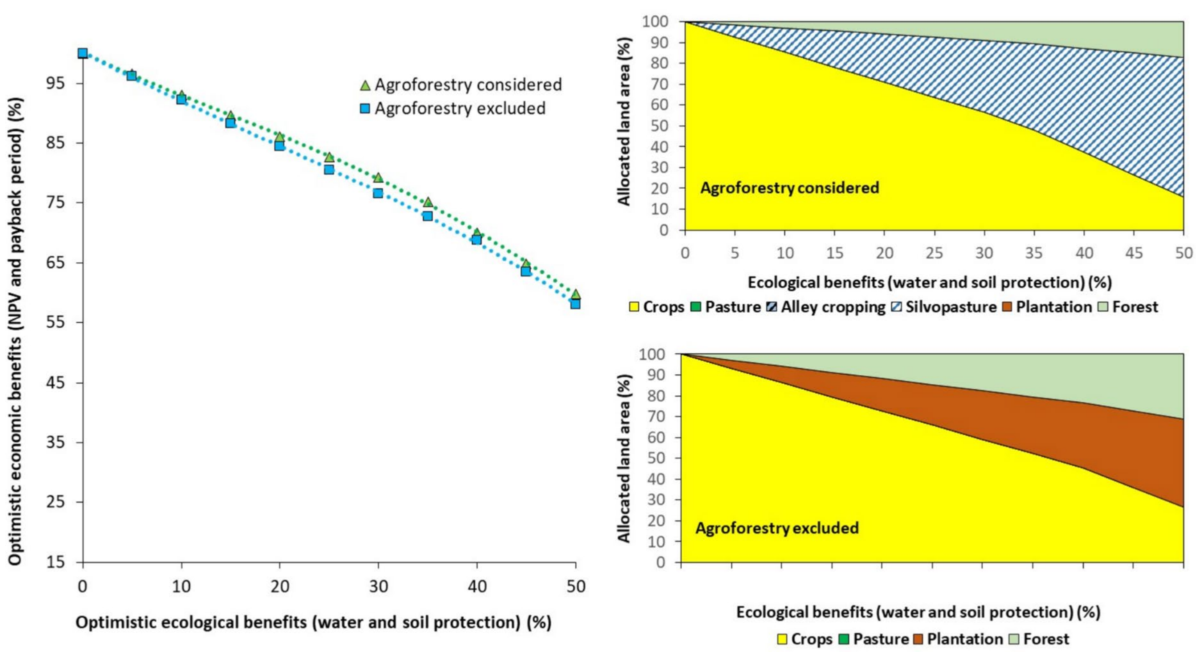


Fig. 2 Left: Pareto frontiers (i.e. efficiency frontiers) and landscape portfolio compositions for maximum economic benefits under increasing levels of required ecological benefits when uncertainty was ignored. The frontiers show the maximum (optimistic) economic benefit achievable when requiring certain 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

uses. Depending on the indicator, teak plantations or agroforestry offer the second-best ecological performance. Ecological benefits are lowest for pasture and cropland.

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 (Fig. 2). 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 plantations and natural forests (Fig. 2). No land was allocated to pasture or alley cropping without uncertainty, regardless of the ecological requirement.

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 (Fig. 3A). However, accounting for higher uncertainties ($m \geq 3$) results in incorporating both agroforestry land-use types even without ecological requirements (Fig. 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 and silvopasture, respectively (Fig. 3, 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.

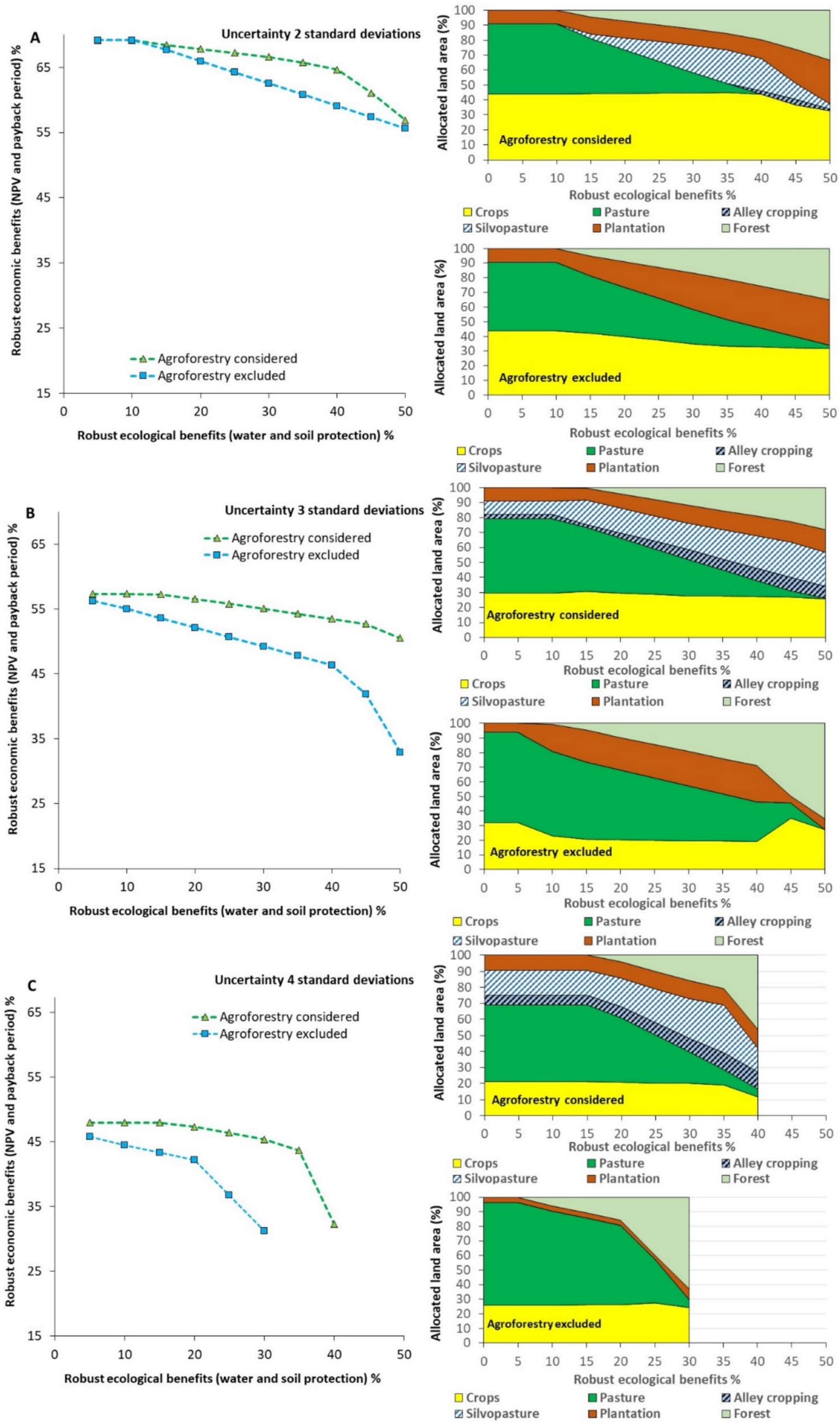
In addition to modulating the share of agroforestry in the landscape, the size of the uncertainty space also alters the curvature of the Pareto frontiers. Large uncertainty spaces magnify the sensitivity of economic benefits to ecological demands, notably when agroforestry options are excluded. The no-agroforestry frontiers exhibit clear economic tipping points: beyond a certain threshold, ecological requirements force sharp increases in the land area allocated to natural forests (Fig. 3). 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 vs. 40% with agroforestry. This ten-point increase also comes with economic benefits that exceed the best-performing non-agroforestry portfolio (Fig. 3).

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 (Fig. 4). We also forced pessimistic benefit combinations as an additional robustness check but could not generate any empirical outcomes that underperformed the frontier (Fig. 4).

Thus, the frontiers visualise a guaranteed floor below which portfolio performance will not fall for a given uncertainty scenario (dashed grey lines in Fig. 4). Landscape portfolios containing agroforestry maintained robust economic benefits of at least 51% overall ecological constraints (Fig. 4, left). When agroforestry was excluded, economic performance fell to 33% under elevated ecological constraints (Fig. 4, right side).

[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).


A
Uncertainty 2 standard deviations
Robust economic benefits (NPV and payback period) %
Robust ecological benefits (water and soil protection) %
Agroforestry considered
Agroforestry excluded
Allocated land area (%)
Robust ecological benefits %
Crops
Pasture
Alley cropping
Silvopasture
Plantation
Forest
B
Uncertainty 3 standard deviations
C
Uncertainty 4 standard deviations

◂**Fig. 3** 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

Discussion

This article presents a method and 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.

Main contribution

Our primary contribution is a method for systematically exploring the uncertainty impact on ecological-economic benefit trade-offs and the inclusion of agroforestry into land-use portfolios. The suggested optimisation approach 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. Beyond agroforestry applications, Markowitz portfolio theory has been used and further developed for conservation planning by Ando and Mallory (2012) (conservation planning under climate change uncertainty), Shah and Ando (2015) (non-symmetric, so-called downside risk integration), as well as Mallory and Ando (2014) (efficient conservation portfolio design). Matthies et al. (2019) provide an overview of Markowitz-Portfolio applications in environmental studies. While Paul's portfolio optimisation offers a helpful reference (Paul et al. 2017), this approach encounters several limitations. For instance, it is probabilistic and does not yet 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 Fig. 4) 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. 2020a, 2020b; Reith et al. 2020, 2022; Gosling 2021). 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. 3, 4). This feature makes it easier to generalise our method 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).

Limitations

Our study builds on conservative assumptions concerning uncertainty, which might compromise the expected performance. Other studies adopted less conservative ellipsoidal uncertainty

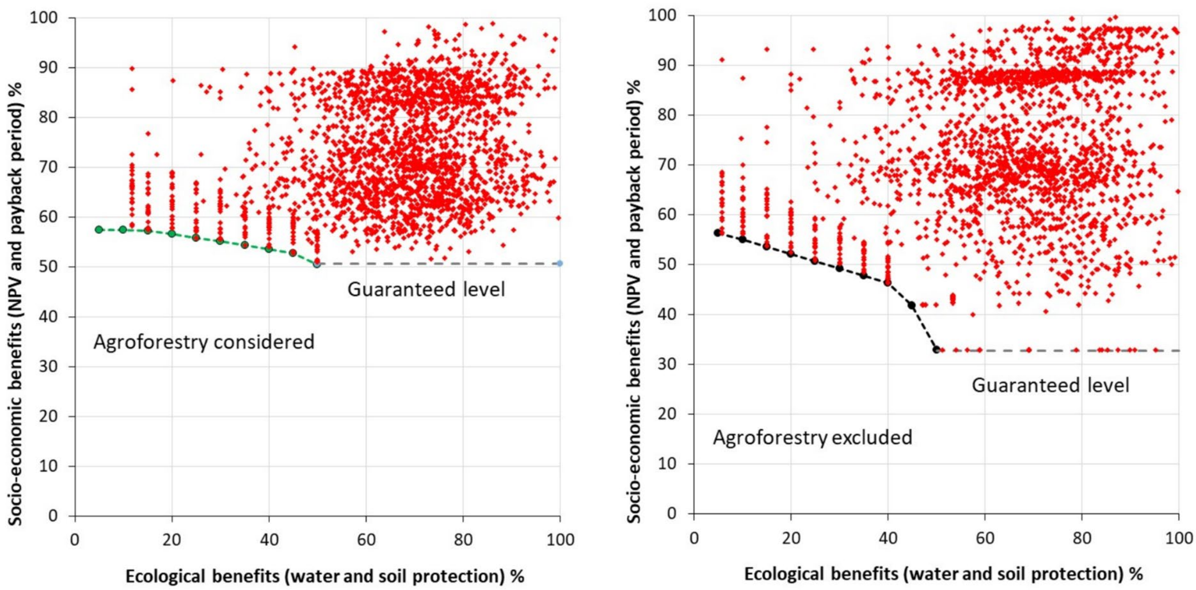


Fig. 4 Simulated benefits of the efficient landscape portfolios when benefits of the single land-use types were drawn from the considered benefit intervals formed by worst and best cases. The figure is built on $m = 3$, meaning the worst case is three times the standard deviation of the considered benefit smaller than the best case

sets for optimising forest management or land use (Augustynczik et al. 2020; Knoke et al. 2020a; b). However, favouring ellipsoidal or polyhedral uncertainty sets implies a random behaviour of the considered benefits and excludes those worst-case benefits which occur simultaneously for various land uses. This is a somewhat optimistic perspective, possibly overrating the diversification potential. If we had applied ellipsoidal or polyhedral uncertainty sets, the guaranteed performances would have been greater, as would the benefits of diversification.

We consider it unlikely that our solutions are too conservative. Instead of using absolute benefit values, we used min–max normalised relative benefits to avoid overly conservative solutions (see Averbakh 2005; Groetzner and Werner 2022; or Knoke et al. 2025). Using such relative benefits in robust optimisation may perform only slightly worse than Markowitz's portfolio approaches, as Messerer et al. (2017) show for a forestry example. Kouvelis and Yu (1997) classify robust optimisation with relative values as less conservative than seeking absolute robustness using non-normalised values. These authors argue that relative values account for the magnitude of missed opportunities by benchmarking the achieved performance with the maximum performance of the ex-post optimal decision.

An alternative to avoid overly conservative solutions is to adopt a hybrid objective function consisting of a conservative optimisation part similar to the one in our study and another part optimising the stochastically expected benefits. Both parts can be aggregated using a weighting factor (Diaz-Balteiro et al. 2018). Gregor et al. (2022) have used such an objective function to optimise European-level forest management, which should be further explored in future agroforestry studies.

Our study has primarily excluded the indirect impact of agroforestry on economic outcomes. For example, agroforestry is expected to support resistance, soil health and yield (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 fertilisation costs for neighbouring crops—a largely unquantified economic 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.

Multi-layered relationships between agroforestry, uncertainty and adoption

Uncertainty can influence the likelihood of agroforestry adoption in various directions. In this study, we tested silvopasture, which showed a desirable reward-to-variability ratio, qualifying this agroforestry land use as a valuable element for economically diversifying agricultural land-use portfolios. However, tree-dominated land uses are less likely to achieve attractive reward-to-variability ratios. For example, in Rössert et al. (2022), short-rotation-coppices with attractive expected economic benefits were excluded from farm portfolios because the uncertainty of their economic benefits was too high. Detailed information on the site dependency of the economic success of agroforestry is lacking. Pasture use dominated the poor sites in our Panamanian case study region, with 26% of cropland. Our results may not be generalisable to areas with better site qualities. For example, on more productive sites in Germany, agroforestry alley cropping could only compete in NPV with conventional farming when short tree rotations were simulated and high prices for woodchips or subsidies (Thiesmeier 2024). Do et al. (2020) confirm significant agroforestry adoption risks for resource-poor farmers. Unfamiliarity with agroforestry practices, agronomic knowledge gaps (Tranchina et al. 2024) and the risk of losing economic flexibility add to the uncertainties concerning a successful agroforestry adoption (Abdul-Salam et al. 2022). The degree of uncertainty aversion of farmers is also a crucial factor (Gosling et al. 2021), while one can generally assume the consideration of uncertainty in farmer decisions (Findlater et al. 2019). Reducing uncertainties will be pivotal to obtaining a clearer picture of the economic attractiveness of agroforestry (Do et al. 2020) and enhancing the adoption of agroforestry practices. In what follows, we will briefly discuss future research lines to mitigate the ecological economic uncertainty surrounding agroforestry adoption.

Fostering earlier agroforestry cashflows will lower economic uncertainty

The economic attractiveness of agroforestry could be plausibly enhanced by identifying strategies for obtaining earlier and more continuous economic returns from the tree components, reducing the variability of the aggregated discounted cashflows. 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 (Young 2017). This would diversify the product portfolio and provide earlier and more frequent financial returns, although potentially at the cost of additional labour input.

Provide ‘early-life’ information to reduce uncertainty

Establishing agroforestry involves navigating an array of variables, many of which are yet associated with high uncertainty: 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 which has long-term economic relevance; thus, managers might leverage supporting factors (e.g., diverse vegetation) in early phases.

‘Early-life’ information is essential for precise agroforestry models as well. Frequent tree, crop and tree-crop-interaction measurements during the establishment phase will be crucial for developing and testing credible and precise 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, 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 cost and 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 understanding 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).

Financial incentives may help reduce uncertainty and bridge adoption barriers

If agroforestry can buffer uncertainty in sustainable landscape portfolios, further mitigating ecological-economic trade-offs may be possible by seeking to monetise ecosystem services. In turn, this could encourage agroforestry adoption by providing income at more regular intervals than temporally discontinuous income from timber; for example, if the reward-to-variability ratio plays a decisive role in adoption decisions, as our results suggest, then financial incentives that reduce upfront costs, diversify revenue streams, and smooth out income discontinuities could plausibly reduce barriers to adoption. Efforts are already underway to connect growing literature on market-based instruments (MBIs) and payments for ecosystem services (PES) to support agroforestry adoption (Benjamin and Sauer 2018; Nath et al. 2023; Tavernier et al. 2024). We expect such work to play an important role in shaping the development of agroforestry economics moving forward.

Without attempting to sum up the literature on PES and MBIs here, it may be helpful to gesture toward a few particularly relevant themes. First, while some scholars argue that sophisticated PES schemes should seek to maximize cost-effectiveness using techniques like spatial targeting, conditionality, and payment differentiation (Wunder et al. 2018, 2020), others have advocated for program designs that are less technically demanding for administrators and participants (Wells et al. 2020). Competitive market mechanisms like reverse auctions, for example, can be designed to improve budgetary efficiency or to induce landowners to reveal private opportunity cost information (Kindu et al. 2022a; Bingham et al. 2024). However, these features may not be attractive for experimental agroforestry systems where the profile of costs, risks, and benefits is poorly understood. Rather than offloading these risks onto participants, programs seeking to build practical knowledge while encouraging the adoption of novel production systems might prefer relatively low-friction flat-rate open-enrollment mechanisms in the early stages. These sites selected for experimental agroforestry may be favourable for biodiversity conservation but less for economic benefits. However, it is not guaranteed that the broader adoption of agroforestry will automatically contribute to the objectives of the agencies or governments in charge of such programs. For example, a growing tree cover does not necessarily imply optimal biodiversity protection (Chen et al. 2020). To enhance the willingness to participate in experimental agroforestry programs, action-based standards may be preferred to outcome-based standards for assessing compliance with PES contracts or certification schemes (Schilizzi and Latacz-Lohmann 2016; Andeltová et al. 2019), as conditioning on ES provisioning or environmental performance could reduce the attractiveness of the incentive when the production system is unfamiliar to potential enrollees.

In places where agroforestry is already practised, new incentive programs might consider being lenient concerning additionality, particularly in light of conflicting results regarding motivational crowding in PES (Huang et al. 2024). At the community level, for instance, providing payments only to providers whose baseline practices are less sustainable while excluding those who have maintained more sustainable ones, even in the absence of external incentives, might risk undermining intrinsic motivations for environmental stewardship (Chan et al. 2017; Blanco et al. 2023; Frings et al. 2023). As our understanding of agroforestry economics continues to develop—integrating information about production systems, their environmental-economic trade-offs, and risk profiles, for example—the process of upscaling incentive programs might enable transitions to more sophisticated designs that leverage things like competition and spatial targeting to increase their environmental or budgetary cost-effectiveness.

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.

Negative impacts of agroforestry

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. 4 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.

Outlook

The extent to which agroforestry systems can compete economically with standard agricultural practices *ceteris paribus* remains unclear. Indeed, some 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.

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 integrating 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.

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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AM, JS, MS, KY, MZ, LK, MvL; Data curation-CP, EG, ER, TK; Writing (original draft)-TK, CP, MvL; Writing (review & editing)-TK, CP, EG, ER, PA, SA, LB, LC, FF, BH, SDL, LM, AM, JS, MS, KY, MZ, LK, MvL; Project administration-CP, TK; Funding acquisition-CP, JK, TK.

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Data availability Data is provided within the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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