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Posted Date: November 26th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11537787/v1

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Additional Declarations: No competing interests reported.

Long-Term Investment Risk and Policy Dependence of Walnut-Based Tree Systems on Small Farms in Slovenia

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Abstract

Whether long-lived tree–crop systems are adopted depends on private returns under market, climate and policy uncertainty. We developed a 40-year bioeconomic model for northeastern Slovenia comparing organic arable cropping, walnut alley cropping (56 trees ha^{-1} and 0.80 ha of crops), and a pure walnut orchard (100 trees ha^{-1}). The model links canopy-related crop responses, tree maturation, mortality and replanting to conditional payments and stochastic uncertainty. We examine an exploratory low-drought scenario based on a locally calculated 18.60% bioclimatic indicator; this indicator is not a field-calibrated probability of damaging agricultural drought. The corresponding assumed annual event probability rises from 15% in year 1 to 18.60% in year 40. Frost exposure for late-budburst Franquette is estimated at 8/46 years (17.39%). At a 4% real discount rate and with conditional modelled payments, net present value was EUR 10 244, EUR 8 508 and EUR 23 579 ha^{-1}, respectively. Across 10,000 Monte Carlo iterations, the probabilities of positive NPV were 99.70%, 64.20% and 88.00%. Alley cropping had the highest NPV in 0.71% of runs. Findings are conditional on the low-drought proxy and modelling assumptions, and should not be interpreted as observationally validated climate-risk predictions. The pure orchard has the highest central-case NPV, whereas alley cropping is not uniformly superior to arable cropping. Results support site-specific investment appraisal and transparent treatment of policy support.

Keywords: Agroforestry adoption; Silvoarable land use; Financial appraisal; Stochastic simulation; Spring frost; Public payments

1. Introduction

Silvoarable agroforestry places perennial woody vegetation and arable crops on the same parcel. It can supply food, timber and ecosystem services together, but that ecological promise does not by itself make a farm investment attractive. Delayed tree revenue, long payback periods, market

volatility and institutional rules all enter the land manager's decision (Torralba et al. 2016; Tsonkova et al. 2012; Thiesmeier and Zander 2023).

Adoption is better understood as a farm-system decision than as a response to one technology. Biophysical suitability, available capital, market access, knowledge, tenure, policy and perceived risk operate together (Amare and Darr 2020, 2024). Evidence from several European regions also shows that reasons for maintaining or adopting agroforestry differ with local socioeconomic conditions, which argues for targeted rather than uniform support (Raimondo et al. 2026).

European bioeconomic studies find that results are sensitive to tree density, site quality, crop-yield interactions, product prices, discounting and support schemes (Thiesmeier and Zander 2023; Žalac et al. 2023; Thiesmeier 2024). Yield-SAFE and Farm-SAFE provide a basis for linking tree–crop resource use with plot- and farm-scale economics (van der Werf et al. 2007; Graves et al. 2010, 2011). A Croatian study that compared arable cropping, pure walnut and intercropped walnut is particularly close to the land-use choice examined here (Žalac et al. 2023). We extend that line of work by combining multi-decade cash flows with joint market and climate uncertainty, break-even thresholds and an explicit separation of private returns from policy-dependent benefits.

Climate exposure is material for perennial investments in Slovenia. A longer growing season may advance phenological development and increase exposure to late spring frost, while agricultural drought has become more frequent and severe (Slovenian Environment Agency 2025a, 2025b). For walnut, damage depends not only on whether a cold event occurs but also on phenological stage, genotype, tissue hardiness, and event intensity (Charrier et al. 2018; Charrier et al. 2013; Khadivi et al. 2019; Črepinšek et al. 2009). This makes it important to separate event probability from conditional yield loss rather than equating meteorological exposure with damage.

The analysis builds on the financial simulation developed in Kos's master's thesis (Kos 2022), which examined a 1-ha walnut alley-cropping system with 56 trees and a 40-year appraisal horizon. That deterministic study explored alternative price and yield assumptions but did not model the canopy-related crop response and joint climate and market uncertainty evaluated here. The present study updates the economic inputs and develops the original framework into a comparative, risk-adjusted assessment.

The analysis updates Slovenian economic and policy inputs, allows crop performance to change with walnut canopy development, and evaluates the three land uses in both deterministic and 10 000-run stochastic settings. Private profitability, conditional public payments and an illustrative monetized climate benefit remain separate throughout. The resulting model is a conditional bioeconomic assessment, not an econometric forecast.

Our objective is to assess the risk-adjusted financial viability of organic arable cropping, walnut alley cropping and a pure walnut orchard in Slovenia. We examine how discounting and conditional payments alter comparative NPV, which inputs dominate alley-cropping risk, how the systems rank under joint economic and climate uncertainty, and whether break-even prices or a monetized carbon-benefit scenario change the investment interpretation.

Investment appraisals of smallholder tree systems commonly report both net present value (NPV) and internal rate of return (IRR), while emphasizing risks associated with delayed revenues, capital constraints and discounting. For example, Ota et al. (2022) applied NPV and IRR to sandalwood production on small holdings and demonstrated how timing of harvest, labour opportunity costs and financing arrangements affect profitability. Our comparison similarly evaluates capital-intensive woody perennial systems, but adds crop–tree interactions and a joint stochastic appraisal of climate and market risks in a European land-use context.

2. Materials and methods

2.1. Analytical design, land-use alternatives and regional context

The assessment was conducted on a 1-ha basis over 40 years with annual time steps. All cash flows are expressed in 2025 euros. Real discount rates of 2%, 4%, 6%, and 8% were evaluated. Land purchase value was excluded because land is common to all alternatives. The analysis includes product revenues, conditional modelled public payments, establishment and management costs, replanting, walnut harvesting, terminal timber revenue, and removal costs. Taxes, financing structure, and the opportunity cost of owned land are excluded. The framework is comparative and scenario-based; it is not an optimization, econometric, or forecasting model.

Three land-use alternatives were compared: (i) 1.00 ha of organic arable cropping; (ii) walnut alley cropping with 56 trees ha^{-1} and 0.80 ha of crops; and (iii) a pure walnut orchard with 100 trees ha^{-1}. A Python implementation links annual cash flows, logistic canopy development, a

transparent crop-yield metamodel, age-cohort tree survival and replanting, weather events, investment criteria, deterministic sensitivity analysis, and 10 000 Monte Carlo iterations. An equivalent spreadsheet implementation is available in Microsoft Excel format. A fixed pseudorandom seed (20260806) makes the Monte Carlo calculations reproducible.

Maribor and the wider Podravska NUTS 3 region provide the regional and meteorological context. Podravska accounted for 80 648 ha of utilized agricultural area in 2020, or 17.0% of Slovenia's total, the largest share among statistical regions (Statistical Office of the Republic of Slovenia 2022b). In 2023, the region contained 1 164 ha of intensive orchards across 1 359 holdings, while walnut occupied 597.0 ha of intensive orchards nationally, up from 339.3 ha in 2017 (Statistical Office of the Republic of Slovenia 2024). A complementary analysis of the national crop-registration spatial dataset for 2020–2025 shows that registered walnut-related area increased in both Podravska and Slovenia (Table 1).

The spatial evidence is used to establish regional relevance rather than to claim that modern silvoarable walnut systems are common in Podravska. Published regional orchard tables do not cross-tabulate statistical region and fruit species, and the public GERK/KRZ land-use layer does not include fruit species (Statistical Office of the Republic of Slovenia 2025; Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026c). Registered walnut and walnut-chestnut areas for 2020–2025 were analysed in ArcGIS Pro 3.7, and kernel-density mapping was used to characterize their spatial concentration (Esri 2026). The 2025 map shows the strongest concentration of registered walnut-related parcels in northeastern Slovenia, especially Podravska and Pomurska (Figure 2). European LUCAS-based estimates likewise suggest that Slovenian agroforestry is dominated by silvopastoral and tree-garden categories; silvoarable systems were not detected in the relevant 2018 sample (Rubio-Delgado et al. 2023). The modelled 56-tree alley system should therefore be interpreted as an alternative land-use scenario, not a representative existing regional practice.

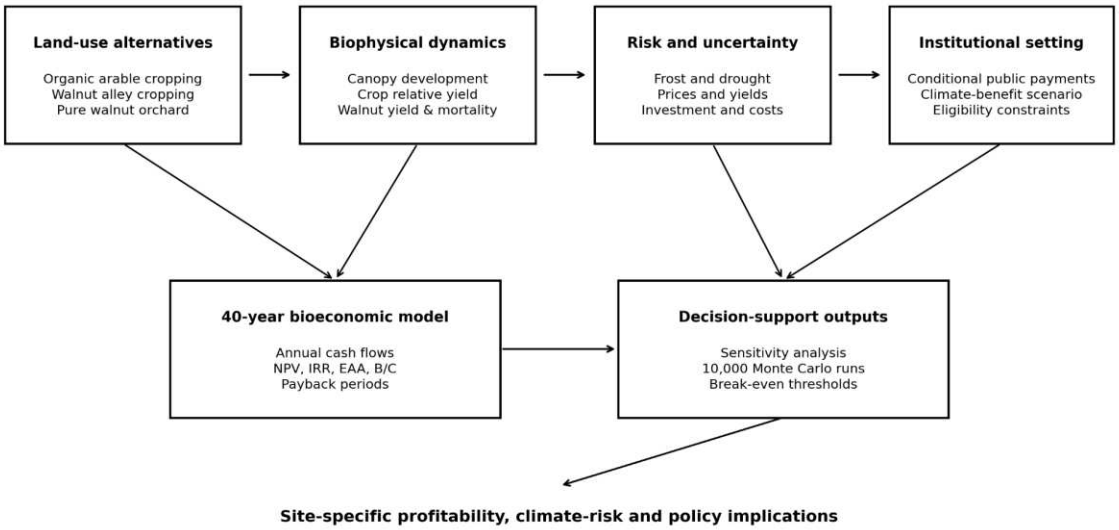

Fig. 1. Analytical structure of the bioeconomic and stochastic framework.

The analytical framework shown in Figure 1 is applied within a regional context in which walnut cultivation has expanded in recent years. Table 1 summarizes the 2020–2025 development of registered walnut and walnut-chestnut areas in Podravska and Slovenia.

Table 1. Registered walnut areas in Podravska and Slovenia, 2020–2025.

Year	Podravska walnut	Podravska walnut + chestnut	Podravska total	Slovenia walnut	Slovenia walnut + chestnut	Slovenia total
2020	217.72	9.67	227.39	552.59	17.19	569.78
2021	237.31	10.31	247.62	589.41	18.95	608.36
2022	241.28	13.29	254.57	621.07	26.86	647.93
2023	256.88	16.96	273.84	654.00	32.55	686.55
2024	276.37	14.11	290.48	684.17	28.29	712.46
2025	285.31	18.26	303.57	713.11	35.55	748.66

Areas are in hectares. The crop-registration categories are used as spatial context and do not identify modern silvoarable systems.

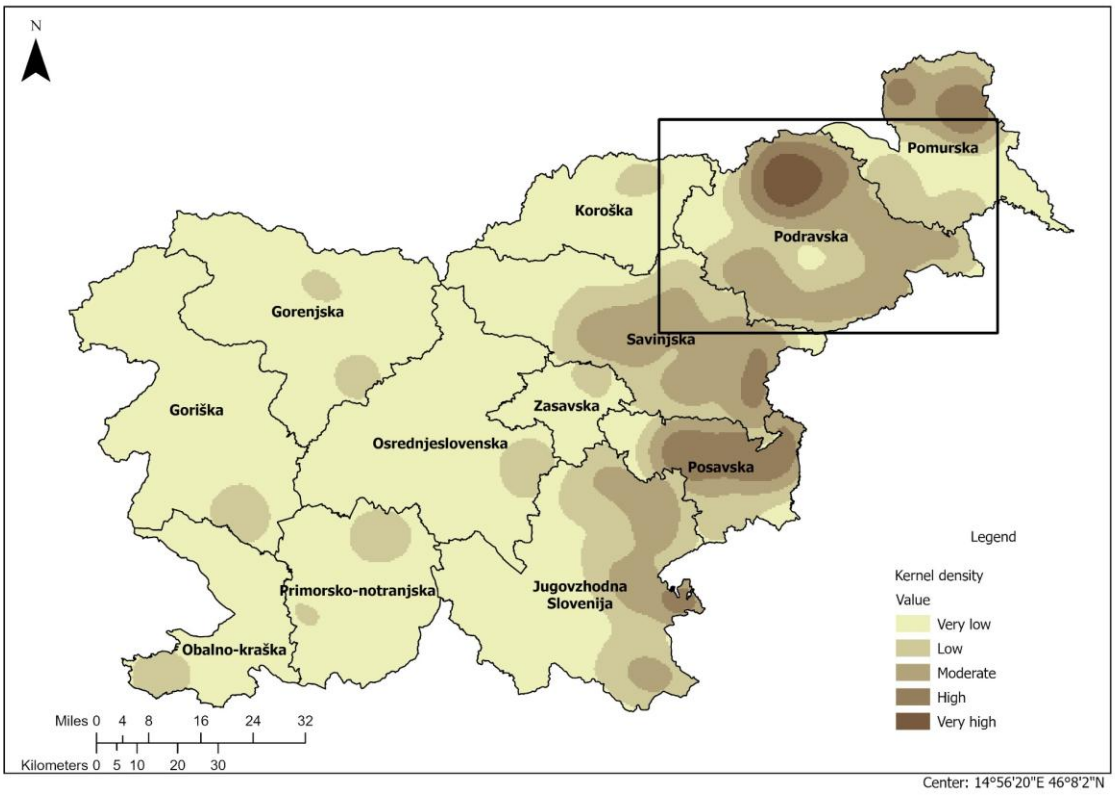

Fig. 2. Kernel density of registered walnut-related areas in Slovenia, 2025.

The spatial concentration shown in Figure 2 establishes northeastern Slovenia as a relevant setting for the case study, but it does not imply that walnut alley-cropping systems are already widespread. The three land-use alternatives evaluated in the bioeconomic model are therefore specified explicitly in Table 2.

Table 2. Land-use alternatives in the 40-year model.

System	Spatial design	Description
Organic arable	1.00 ha crops	Five crop states in the rotation: maize, spelt, oilseed rape, crimson clover, and oil pumpkin; no initial tree investment.
Walnut alley cropping	56 walnuts ha^{-1} + 0.80 ha crops	Five tree rows; about 20% of area in tree strips; terminal timber value in year 40.
Pure walnut orchard	100 walnuts ha^{-1}	Intensive walnut orchard without market crops; higher establishment and annual costs; terminal timber value.

2.2. Economic inputs, biophysical dynamics, and conditional public payments

Input updating combined the crop enterprise budgets underlying Kos (2022) with official price and input indices and public market offers. In 2025, Slovenian agricultural producer prices were

on average 7.2% above 2024 levels, while agricultural input prices increased by about 2.0%; gross wage data were used as an additional cost reference (Statistical Office of the Republic of Slovenia 2026b; Statistical Office of the Republic of Slovenia 2026a; Statistical Office of the Republic of Slovenia 2026c). These statistics served as control points rather than as one automatic deflator.

Because no single public national panel covers all modelled crop costs and farm-gate prices, revenues in the underlying budgets were revalued with crop-specific factors of 1.50–1.60 and costs with an aggregate factor of 1.45. As seen in Table 3 the base in-shell walnut price is EUR 6.00 kg^{-1}, with a Monte Carlo interval of EUR 4.50–7.50 kg^{-1}. Public nursery offers in August 2026 provided market anchors for planting material (Sadika na dom 2026; Mirosan 2026). The base walnut timber price is EUR 650 m^{-3}, with a deliberately wide EUR 300–1 500 m^{-3} range; the highest 2025 price reported for walnut at a Slovenian high-value timber auction was EUR 1 489 m^{-3} (Tiama 2025). These values are market anchors rather than estimates of representative average prices.

The crop-price multiplier is a dimensionless aggregate parameter applied proportionally to baseline market revenues of the crop rotation: 1.00 represents the revalued base level, 0.80 a 20% reduction, and 1.20 a 20% increase. It does not alter physical crop yield, crop costs, walnut price, or public payments. The crop-cost multiplier is defined analogously, with values from 0.85 to 1.20 applied to aggregate crop costs. Because the source budgets are not disaggregated into every cost item in the manuscript, this parameter should be interpreted as an aggregate cost-level uncertainty.

Conditional public payments (Table 3) were parameterized at EUR 607 ha^{-1} yr^{-1} for arable crops and EUR 885 ha^{-1} yr^{-1} for orchards meeting the relevant density rule under the Slovenian regulation used at the study cut-off (Government of the Republic of Slovenia 2026). For alley cropping, only 0.80 × EUR 607 was included for the cropped component. These values are modelling assumptions conditional on legal eligibility; they are not a determination that a specific parcel qualifies for payment. Eligibility depends on land registration, organic-control status, intervention conditions, and rules governing combined land uses.

The national CAP framework also distinguishes practice-based agri-environmental payments from outcome-based carbon revenue. IRP19 supports organic farming, while other interventions encourage practices such as conservation tillage (Government of the Republic of Slovenia 2026;

Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026d; Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026g). Therefore, the base private NPV includes no direct carbon-credit revenue. The framework distinguishes (i) farm NPV, (ii) an extended NPV with an illustrative monetized climate benefit, and (iii) any future certified carbon-revenue scenario, which would require additionality, monitoring, verification, and a buyer.

Table 3. Key bioeconomic model assumptions.

Parameter	Base value	Rationale
Horizon	40 years	Long-term comparison
Real discount rate	2%, 4%, 6%, 8%	Opportunity-cost scenarios
In-shell walnut price	EUR 6.00 kg^{-1}; MC 4.50–7.50	Market-anchored scenario
Mature yield – alley	20 kg $tree^{-1}$; MC 15–25	Source-model yield curve
Mature yield – orchard	18 kg $tree^{-1}$; MC 13.5–22.5	Higher-density correction
Timber price	EUR 650 m^{-3}; MC 300–1,500	Walnut timber market-price scenario
Initial investment	EUR 11,500 / 18,000 ha^{-1}	Initial establishment cost: alley / orchard
Early annual mortality	2.5%	Trees up to age 3
Later annual mortality	0.4%	Older trees
Frost	Franquette P = 17.39%; base loss 60%	23 Apr–15 May; Tmin ≤ −1 °C; MC P 9.09–17.39–30.72%; 34.78% broad-window stress
Drought	P 15% → 18.60%	Exploratory proxy-based economic sensitivity case
Conditional payment – arable/orchard	EUR 607 / 885 ha^{-1} yr^{-1}	Modelled only under assumed eligibility

MC = Monte Carlo. Climate-event probability and conditional severity are modelled separately. Values are scenario inputs, not universal estimates.

Canopy expansion in alley cropping is represented by a logistic function of the modelled canopy-share index Ct:

$$C_t = Cmax/[1 + \exp(-k(t - m))], \quad Cmax = 0.60, k = 0.22, m = 22. \quad (1)$$

The relative crop yield RY_t is represented by a transparent metamodel informed by the logic of Yield-SAFE and European alley-cropping evidence (van der Werf et al. 2007; Žalac et al. 2023; Ivezić et al. 2021):

$$RY_t = \max[0.55, 1.02 - \beta C_t], \quad \beta = 0.62. \quad (2)$$

The resulting relative yield begins close to 1 and declines to approximately 0.66 by year 40. This function is not locally calibrated to a full Yield-SAFE implementation because daily weather data, soil profiles, variety parameters, and field measurements were not available for all required processes. Its advantage is transparency and direct replaceability by locally calibrated process-model output. Assuming unchanged crop yield across the full 40-year horizon would be less consistent with European evidence (Žalac et al. 2023; Ivezić et al. 2021; Reuse and Langhof 2025; Majaura et al. 2025).

The walnut yield trajectory follows the earlier walnut system examined by Kos (2022): no marketable yield in years 1–9, 5 kg tree^{-1} in year 10, a gradual increase to 20 kg tree^{-1} by year 23, and stabilization from year 24 onward. The pure orchard uses a base mature yield of 18 kg tree^{-1} with a density correction. The cohort module calculates age-specific mortality, surviving trees, and replanting through year 8; losses after year 8 are not replanted. Replanting costs EUR 55 tree^{-1}.

Tree mortality and replanting are represented by:

$$D_{a,t} = \mu_a N_{a,t}; \quad N_{a+1,t+1} = N_{a,t} - D_{a,t}; \quad R_t = \Sigma_a D_{a,t} \text{ for } t \leq 8, \text{ otherwise } R_t = 0. \quad (3)$$

where N_a,t is the number of living trees of age a in year t, mu_a is the age-specific annual mortality rate (2.5% for trees up to age 3 and 0.4% thereafter), D_a,t is tree mortality, and R_t is the number replanted. Figure 3 shows the crop relative-yield trajectory and walnut yield per tree.

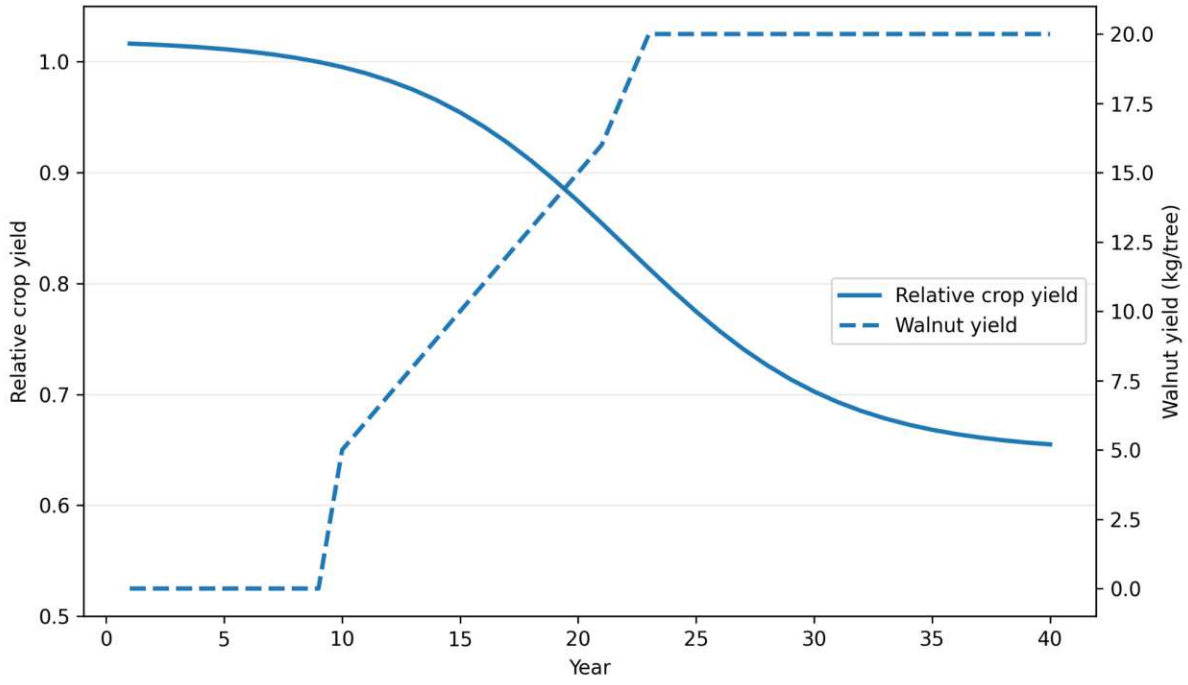

Fig. 3. Modelled crop and walnut yield trajectories. Crop yield is relative to the open-field comparator; walnut yield is per tree.

2.3. Climate risk, financial criteria and stochastic uncertainty

Weather-risk calibration used Slovenian Environment Agency indicators, official records of agricultural natural disasters, and national walnut production statistics. For 2010–2025, six years were identified with nationally important frost events and five with nationally important drought events, implying contextual frequencies of 37.5% and 31.25%, respectively (Slovenian Environment Agency 2025a; Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026h; Slovenian Environment Agency 2025b; Statistical Office of the Republic of Slovenia 2018; Statistical Office of the Republic of Slovenia 2022a). These national frequencies refer to events that reached an official disaster threshold somewhere in Slovenia and are not interpreted as local plot-level probabilities.

The local frost input was derived from daily Maribor meteorological records for 1980–2025. A frost-exposure year contains at least one day with minimum temperature ≤ −1 °C during the cultivar-adjusted window from 23 April through 15 May, with both endpoints included. Franquette was selected because its late budbreak lowers overlap with early spring frosts. The start date is five days before the 28 April mean budbreak reported for Franquette in Slovenia in

2000–2006 and is therefore deliberately conservative (Črepinšek et al. 2009). Quality control removed duplicate calendar dates. Eight of 46 years met the rule, giving $p^f = 8/46 = 17.39\%$. This is a phenology-adjusted meteorological exposure estimate, not an observed probability of crop damage.

The 95% Wilson interval for 8 events in 46 years is 9.09%–30.72%. The central deterministic scenario uses $p^f = 17.39\%$, while the lower- and upper-statistical scenarios use 9.09% and 30.72%; Monte Carlo analysis samples p^f from Tri(0.0909, 0.1739, 0.3072). A broad 15 April–15 May screen gives 16/46 = 34.78% and is retained only as a stress test because it includes frost before the assumed Franquette susceptibility window. Walnut injury nevertheless depends on temperature, duration, phenology, tissue hardiness and genotype (Charrier et al. 2013, 2018; Khadivi et al. 2019; Črepinšek et al. 2009). Event occurrence and conditional yield-loss severity are therefore modelled separately.

For an independent local check on the drought range, monthly mean temperature and precipitation at Maribor Airport were analysed for 1980–2023. An arid month was screened with the Walter-Lieth/Walter-Gaussen criterion $P < 2T$ (Walter and Lieth 1960). The criterion is transparent and reproducible but is not a direct measure of agricultural drought or yield loss because operational drought assessment also uses evapotranspiration and water balance (Slovenian Environment Agency 2025a; Slovenian Environment Agency 2026). A modified $P < 4T$ threshold is retained only as an additional sensitivity check. Recent walnut irrigation experiments confirm that sustained water deficit can reduce yield, supporting the biological relevance of separately modelled drought severity (Durán Zuazo et al. 2025).

In the exploratory low-drought scenario, the assumed annual drought-event probability increases linearly from 0.15 in year 1 to 0.186 in year 40. The 18.60% value originates from the supplied Maribor workbook using a modified $P < 4T$ screening criterion requiring at least two consecutive arid summer months. This is an operational bioclimatic proxy, not a directly observed probability of crop-damaging drought. The uncertainty interval 0.150–0.199 used below is a scenario range, not a statistical confidence interval.

$$p^s_t = 0.15 + [(t - 1)/39] \cdot (p^s_{40} - 0.15). \quad (4)$$

Expected weather multipliers for crop revenue and walnut yield are:

$$F^P_t = 1 - p^s_t l^{Ps}. \quad (5)$$

$$F^{O}_{t} = (1 - p^{f} l^{f})(1 - p^{s}_{t} l^{Os}). \quad (6)$$

For frost, 9.09% and 30.72% are Wilson bounds from the 46-year Maribor frost screen; the central estimate is 17.39%. In contrast, drought probabilities of 15.0%, 18.6% and 19.9% define exploratory low-risk scenarios, not inferential intervals. A broad frost-screen period (15 April–15 May) is retained only as an independent stress test.

For each land-use system, we calculated NPV, internal rate of return (IRR), equivalent annual annuity (EAA), simple and discounted payback periods, and the benefit-cost ratio (B/C). B/C is the present value of discounted gross benefits (market revenues and conditional modelled public payments) divided by the present value of gross costs including initial investment. B/C > 1 indicates discounted benefits exceed discounted costs.

The annual net cash flow of system s in year t is:

$$CF_{s,t} = B_{s,t} + P_{s,t} - S_{s,t}. \quad (7)$$

NPV over the 40-year horizon is:

$$NPV = -I_0 + \Sigma_{t=1}^{T} (B_t + P_t - S_t)/(1 + r)^t, \quad T = 40. \quad (8)$$

IRR is the discount rate that sets NPV to zero:

$$0 = -I_0 + \Sigma_{t=1}^{T} (B_t + P_t - S_t)/(1 + IRR)^t. \quad (9)$$

For the arable comparator, which has no initial negative investment flow, IRR and payback time are not economically interpreted. EAA, B/C, discounted payback (DPP), and simple payback (SPP) are calculated as:

$$EAA = NPV \cdot r/[1 - (1 + r)^{-T}]. \quad (10)$$

$$B/C = [\Sigma_{t=1}^{T}(B_t + P_t)/(1 + r)^t]/[I_0 + \Sigma_{t=1}^{T} S_t/(1 + r)^t]. \quad (11)$$

$$DPP = \min\{\tau: \Sigma_{t=0}^{t} CF_t/(1 + r)^t \geq 0\}; \quad SPP = \min\{\tau: \Sigma_{t=0}^{t} CF_t \geq 0\}. \quad (12)$$

One-factor sensitivity analysis was conducted for alley cropping at a 4% discount rate with conditional public payments. Model robustness was evaluated in three deliberately specified low-drought scenarios using 15.0%, 18.60%, and 19.9% as the year-40 event probabilities and local frost exposure bounds. The 10,000-run Monte Carlo analysis samples year-40 drought probability from Tri(0.150, 0.186, 0.199), a scenario range that is not an empirical confidence interval.

Long-run uncertain variables X_j were sampled as X_j ~ Tri(a_j, m_j, b_j), while annual weather occurrence Z_e,t ~ Bernoulli(p_e,t). Within an iteration, sampled frost probability is constant over time, whereas drought probability rises linearly from 0.15 to the sampled year-40 endpoint.

Table 4. Triangular distributions for Monte Carlo parameters.

Variable	Minimum	Mode	Maximum
Real discount rate	2%	4%	8%
In-shell walnut price (EUR kg^{-1})	4.50	6.00	7.50
Mature alley yield (kg $tree^{-1}$)	15	20	25
Mature orchard yield (kg $tree^{-1}$)	13.5	18	22.5
Timber price (EUR m^{-3})	300	650	1 500
Investment multiplier	0.80	1.00	1.25
Crop price multiplier	0.80	1.00	1.20
Crop cost multiplier	0.85	1.00	1.20
Tree mortality multiplier	0.50	1.00	2.00
Canopy competition β	0.45	0.62	0.80
Frost probability	0.0909	0.1739	0.3072
Drought probability, year 40	0.150	0.186	0.199

2.4. Carbon-benefit scenario, validation and reproducibility

Carbon is excluded from base NPV because a farmer is not automatically paid for every tonne of CO_2 removed (Government of the Republic of Slovenia 2026; Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026d, 2026g). For alley cropping, the reference sequestration rate comes from the temperate-agroforestry meta-analysis of Mayer et al. (2022): 0.26 t C ha^{-1} yr^{-1} in the 0–20 cm layer plus 0.23 t C ha^{-1} yr^{-1} at 20–40 cm, or about 1.8 t CO_2 ha^{-1} yr^{-1} after conversion by 44/12. This is a scenario reference rather than a Slovenian field measurement; realized mitigation also depends on system design and site context (Dmuchowski et al. 2024).

For the pure walnut orchard, 2.2 t CO_2 ha^{-1} yr^{-1} is an explicit scenario assumption rather than a local measurement. The illustrative carbon value is EUR 75 t^{-1} CO_2 with a realization/safety factor f = 0.85. The EUR 75 value is anchored to 2026 CBAM certificate prices only as a

transparent reference; CBAM is not an agricultural carbon-credit market and the value is not an official social cost of carbon (European Commission 2026c).

At r = 4% and T = 40, the annual monetized climate benefit is EUR 114.75 ha^{-1} for alley cropping and EUR 140.25 ha^{-1} for the orchard; corresponding present values are EUR 2 271.22 and EUR 2 775.94 ha^{-1}. These are illustrative extended-scenario values, not guaranteed farm revenues.

EU Regulation 2024/3012 establishes the voluntary Carbon Removals and Carbon Farming (CRCF) certification framework (European Parliament and Council 2024b). The European Commission adopted methodologies covering carbon farming and agroforestry on mineral soils in July 2026 (European Commission 2026b). At the study cut-off, this did not create an automatic payment: a recognized certification scheme, additionality and net-benefit demonstration, monitoring/reporting/verification (MRV), a buyer, and treatment of reversal risk remain necessary (European Commission 2026a). MRV may entail sampling, laboratory analysis, data management, reporting, and independent verification costs, which are excluded from the base financial model because reliable local quotations were unavailable.

Validation was documentary rather than field-based. We cross-checked the source model, official indices, payment levels, public market offers and the internal consistency of the spreadsheet and Python outputs. Grower and expert interviews were not undertaken, so the estimates should not be read as field-validated values for all Slovenian farms. The fixed seed 20260806, equations and parameter ranges make the calculations reproducible; the calculation workbooks are retained in the study records.

$$q^{A} = (0.26 + 0.23)\cdot 44/12 = 1.80 \text{ t } CO_2 \text{ ha}^{-1} \text{ yr}^{-1}. \quad (13)$$

$$A^{c}_{s} = q_s p^{c} f; \quad PV^{c}_{s} = A^{c}_{s}[1 - (1 + r)^{-T}]/r; \quad NPV^{M}_{s} = NPV_s + PV^{c}_{s}. \quad (14)$$

2.5. ArborShadow shade simulation

Shade generated by walnut rows was assessed with ArborShadow R4 (Skellern 2011) to provide a complementary spatial interpretation of the canopy-competition assumption. A standardized hypothetical layout contained two parallel rows of 11 walnut trees (22 trees total). Tree spacing, inter-row distance, target area, date, and time were held constant within the archived scenario sets.

Three development stages were evaluated: young trees (about 10 years, 5 m height, 50% canopy density), medium-developed trees (20–25 years, 10 m, 60%), and mature trees (about 40 years, 15 m, 75%). The height scenarios are consistent with the use of representative, management-dependent walnut growth states rather than fixed biological age-height relationships (Schindler et al. 2023). Each stage was simulated with north-south (N-S) and east-west (E-W) rows, giving six scenarios (Table 5). Inspection of the archived ArborShadow outputs shows latitude 46°30′ N for all panels, but longitude 13°40′ E for the N-S scenarios and 15°40′ E for the E-W scenarios. Consequently, development-stage comparisons within a given orientation are spatially consistent, whereas differences between N-S and E-W scenarios are treated as descriptive supporting evidence rather than a strictly controlled causal test of row orientation. Figure 4 presents the standardized layout.

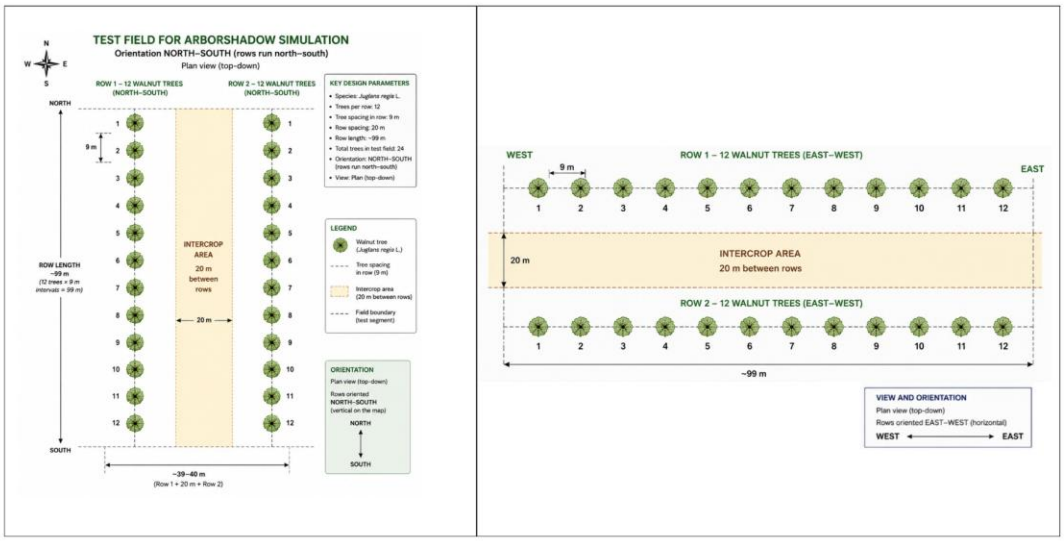

Fig. 4. Standardized ArborShadow layout for walnut-row shade scenarios.

Figure 4 illustrates the common geometric logic used for the shade scenarios. The corresponding assumptions on tree age, height, canopy density, and row orientation are summarized in Table 5.

Table 5. ArborShadow tree stages and row orientations.

Scenario	Tree age (yr)	Height (m)	Canopy density (%)	Orientation
1a – Young	10	5	50	N-S
1b – Young	10	5	50	E-W

Scenario	Tree age (yr)	Height (m)	Canopy density (%)	Orientation
2a – Medium	20–25	10	60	N-S
2b – Medium	20–25	10	60	E-W
3a – Mature	40	15	75	N-S
3b – Mature	40	15	75	E-W

3. Results and discussion

3.1. Discount rate and climate robustness

Discount rate materially changes economic ranking (Table 6 and Figure 5). At 4% in the exploratory 18.60% drought scenario, NPV is EUR 10 244 ha^{-1} for arable cropping, EUR 8 508 ha^{-1} for walnut alley cropping and EUR 23 579 ha^{-1} for the pure walnut orchard. At 8%, only the arable alternative retains a positive NPV; the long-delayed revenues of the tree-based systems produce stronger discount-rate sensitivity.

Table 6. NPV by real discount rate.

System	2%	4%	6%	8%
Arable field	13 980	10 244	7 886	6 329
Walnut alley	26 344	8 508	-1 091	-6 378
Walnut orchard	56 027	23 579	5 726	-4 388

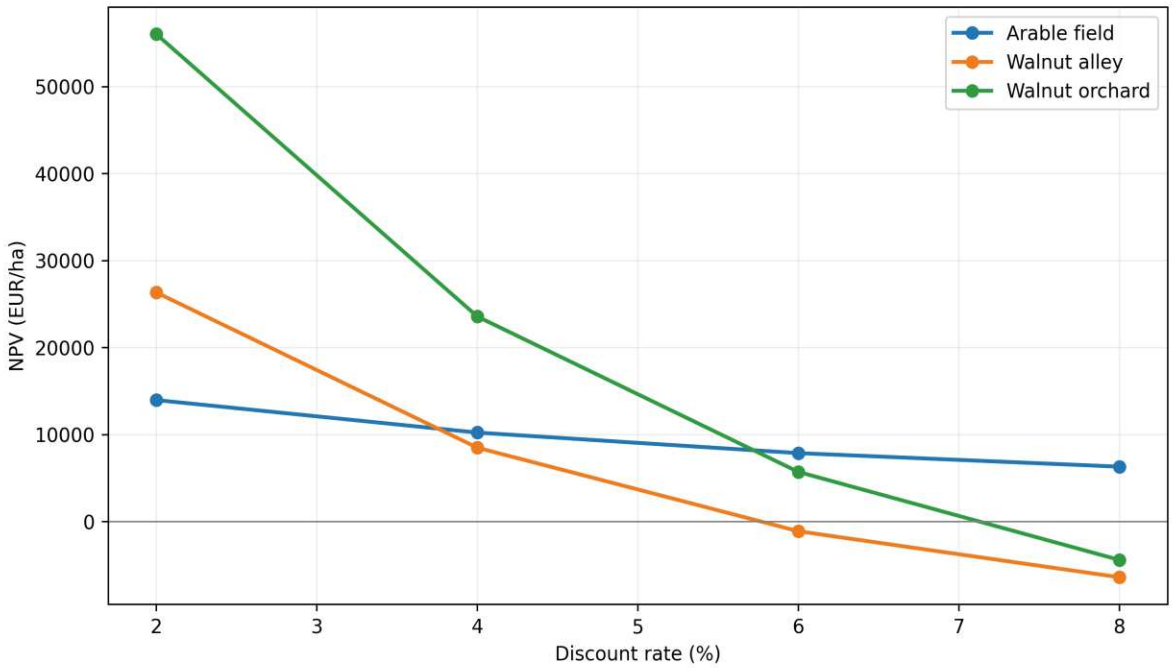

Fig. 5. Net present value by real discount rate.

The assumed climate scenarios strongly affect returns (Table 7). The lower-risk scenario combines a 9.09% frost exposure and 15.0% year-40 drought event probability; the central low-drought case uses 17.39% and 18.60%; and the upper within-20% drought case uses 30.72% and 19.9%, respectively. These are conditional tests of model sensitivity, not forecasts of climate hazard frequencies.

The supplementary local drought checks are not interchangeable: the standard $P < 2T$ screen shows a different frequency of years with at least one dry summer month, while the modified $P < 4T$ screen with a consecutive-month requirement gives the selected 18.60% indicator. Neither screening definition directly identifies agricultural drought damage. Accordingly, the 18.60% case is an exploratory scenario to test economic sensitivity, not a statistical estimate of on-farm loss probability.

Table 7. Climate-scenario NPV at 4% with payments.

Scenario	P(frost)	P(drought), yr 40	Arable NPV	Alley NPV	Orchard NPV	Alley − arable
Lower-risk	9.09%	15.00%	10 273	11 442	28 030	1 170
Central 18.6%	17.39%	18.60%	10 244	8 508	23 579	-1 736

Scenario	P(frost)	P(drought), yr 40	Arable NPV	Alley NPV	Orchard NPV	Alley − arable
Upper within <20%	30.72%	19.90%	10 234	4 119	16 889	-6 114
Broad-window stress	34.78%	30.0%	10 153	2 212	14 057	−7 941

3.2. Financial performance and the role of public payments

With conditional modelled payments at 4%, the pure walnut orchard has the highest deterministic NPV (EUR 23 579 ha^{-1}), followed by arable cropping (EUR 10 244 ha^{-1}) and alley cropping (EUR 8 508 ha^{-1}). Profitability measures for the three systems are summarized in Table 8. The alley system remains below the arable comparator, despite a positive NPV under the assumed public payments.

Table 8. Financial indicators at a 4% real discount rate.

System	NPV	IRR	EAA	DPP	SPP	B/C
Arable field	10 244	n.a.	518	n.a.	n.a.	1.30
Walnut alley	8 508	5.70%	430	32.0	23.0	1.11
Walnut orchard	23 579	6.99%	1 191	26.0	21.0	1.33

NPV and EAA are in EUR ha^{-1} (EAA per year); payback periods are in years. IRR and payback are not interpreted for the arable comparator.

Removing the conditional public payments changes the financial viability of the three systems (Table 9). These payments are modelling assumptions subject to actual eligibility; they must not be interpreted as guaranteed entitlements for any particular parcel.

Table 9. Public-payment effects on NPV at 4%.

System	NPV with payments	NPV without payments	Payment effect	B/C without payments
Arable field	10 244	-1 770	12 014	0.95
Walnut alley	8 508	-1 104	9 611	0.99
Walnut orchard	23 579	6 062	17 517	1.08

3.3. Monetized climate benefit and sensitivity

The illustrative monetized climate-benefit scenario adds a non-market benefit to the private financial appraisal (Table 10). It does not create an automatic carbon-credit revenue or evidence

of market transaction. Values in the extended analysis should be read separately from financial NPV.

Table 10. Monetized climate-benefit scenario at 4%.

System	Base NPV	NPV incl. climate benefit	Increase	B/C incl. benefit
Arable field	10 244	10 244	0	1.30
Walnut alley	8 508	10 779	2 271	1.14
Walnut orchard	23 579	26 355	2 776	1.37

The deterministic one-factor sensitivity analysis identifies the key variables affecting the alley-system NPV in the selected low-drought case (Figure 6 and Table 11). Larger changes in the discount rate, walnut price and mature yield generally dominate the effect of modest variations in the assumed year-40 drought probability.

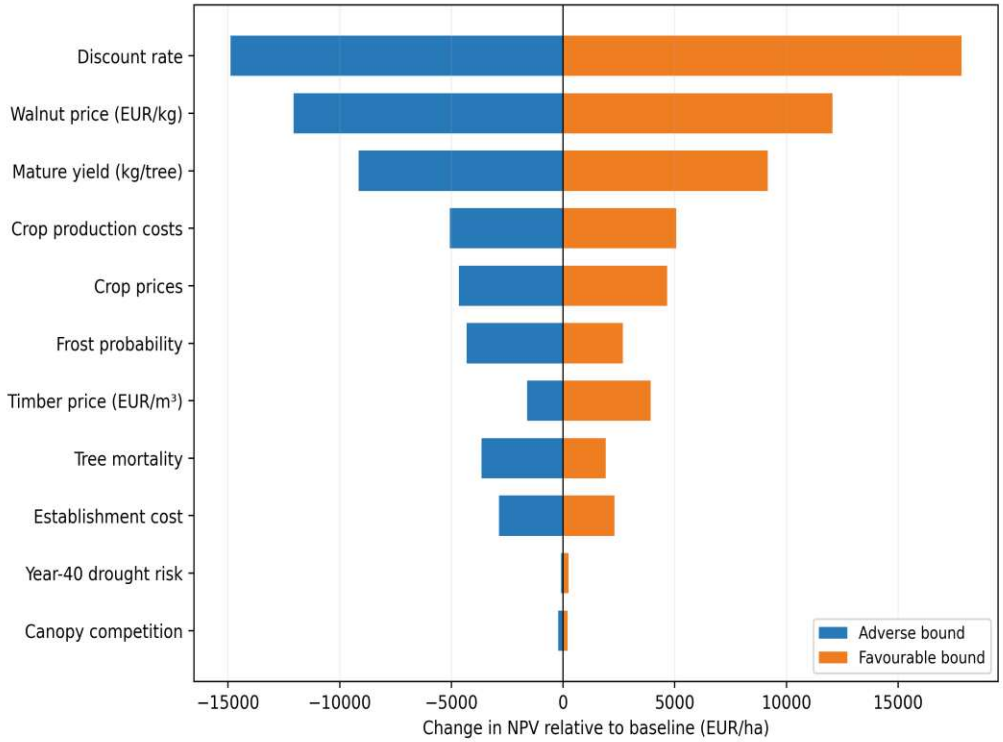

Fig. 6. One-factor sensitivity of walnut alley-cropping NPV.

Figure 6 provides a visual ranking of one-factor sensitivity around the central case. Table 11 reports the same information numerically, allowing the magnitude and direction of the adverse and favourable deviations to be compared across parameters.

Table 11. One-factor sensitivity of alley-cropping NPV.

Parameter	Adverse bound	Favourable bound	Maximum absolute effect
Discount rate	-14 886	17 836	17 836
Walnut price (EUR/kg)	-12 067	12 067	12 067
Mature yield (kg/tree)	-9 160	9 160	9 160
Crop production costs	-5 066	5 066	5 066
Crop prices	-4 660	4 660	4 660
Frost probability	-4 310	2 684	4 310
Timber price (EUR/m³)	-1 615	3 922	3 922
Tree mortality	-3 650	1 910	3 650
Establishment cost	-2 875	2 300	2 875
Drought risk in year 40	-86	238	238
Canopy competition	-219	207	219

The policy implication follows from the interaction of those drivers. Establishment support may help, but it does not remove price, yield or site risk. Raimondo et al. (2026) likewise report that European agroforestry motivations and adoption conditions vary across contexts. For walnut alley systems, a package that combines site screening, technical advice and risk-reducing investment is therefore more credible than a uniform payment for planting trees.

3.4. Stochastic uncertainty and profitability thresholds

Stochastic analysis shows the central-case ranking is not guaranteed (Table 12). Across 10,000 conditional Monte Carlo simulations, positive-NPV probabilities are 99.70% for arable cropping, 64.20% for alley cropping and 88.00% for the orchard. These are model-based probabilities under the stipulated low-drought scenario.

Table 12. Monte Carlo results.

System	Mean	Median	P5	P95	P(NPV > 0)	P(highest NPV)
Arable field	8 994	8 765	3 175	15 691	99.70%	32.90%
Walnut alley	4 614	3 221	-8 607	22 700	64.20%	0.71%
Walnut orchard	17 346	15 192	-4 377	46 771	88.00%	66.39%

Table 12 summarizes the central distributional statistics and decision probabilities from the Monte Carlo analysis. Figure 7 complements these summary measures by showing the full

conditional NPV distributions, including the extent of downside and upside dispersion across the three land-use systems.

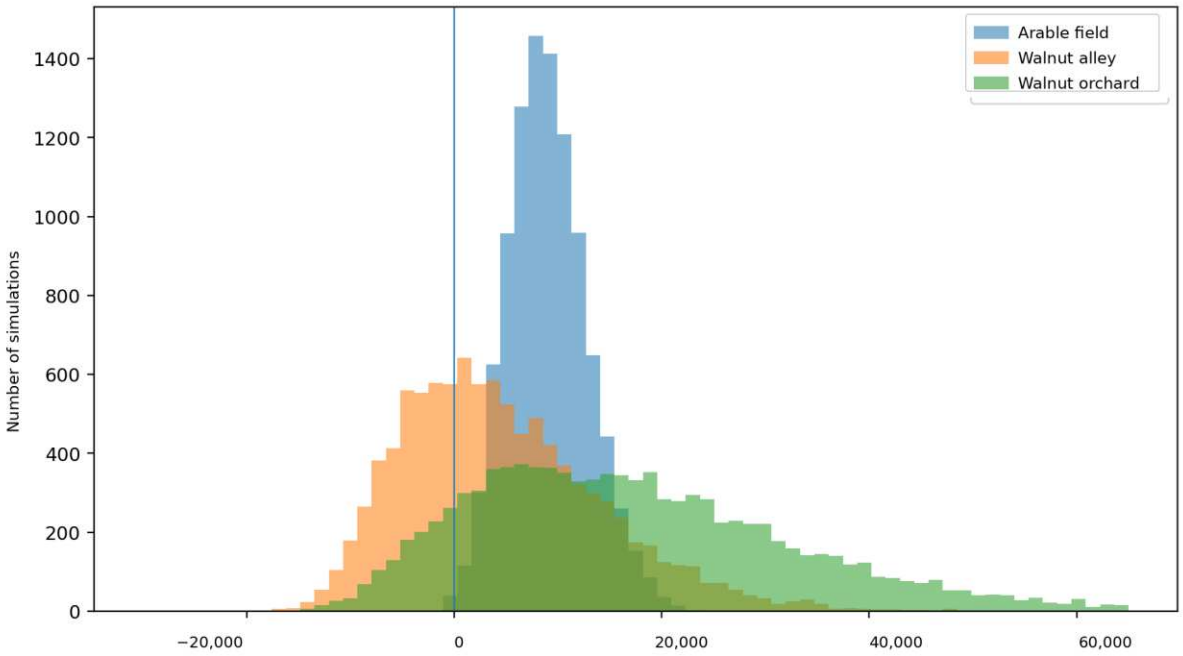

Fig. 7. Conditional NPV distributions across Monte Carlo simulations.

Alley cropping produces the highest NPV in only 0.71% of runs, despite a 64.20% probability of positive NPV. Financial viability and preference over alternative land uses are distinct criteria (Figure 8).

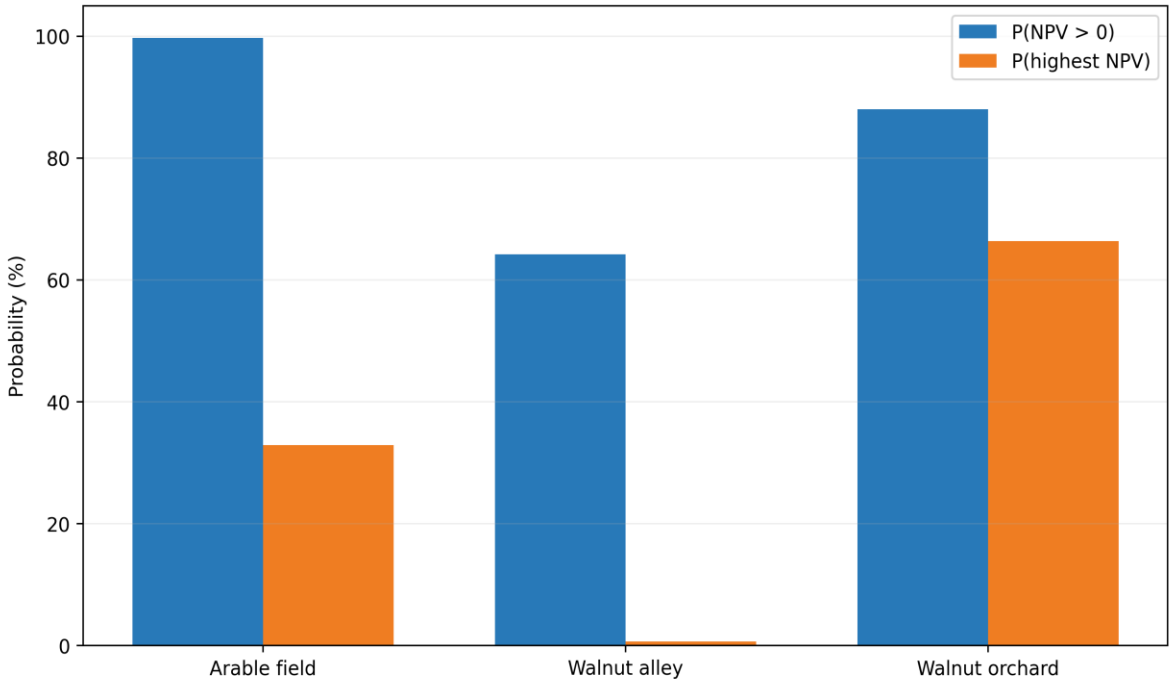

Fig. 8. Financial viability and highest-NPV probabilities.

Figure 8 contrasts the probability of financial viability with the probability of being the best-performing land-use option, highlighting that these are distinct decision criteria. To identify which uncertain inputs are most closely associated with alley-cropping outcomes, Table 13 reports the corresponding descriptive Spearman rank correlations.

Table 13. Spearman correlations with alley-cropping NPV.

Input variable	**Spearman ρ**
Discount rate	-0.662
Walnut price EUR/kg	0.433
Mature yield alley kg/tree	0.329
Crop price multiplier	0.202
Crop cost multiplier	-0.178
Frost probability	-0.125
Establishment multiplier	-0.114
Mortality multiplier	-0.110
Timber price EUR/m3	0.107
Drought probability year 40	0.009
Canopy competition beta	0.002

Spearman rank correlations for the updated 10,000 simulations appear in Table 13. They measure association within the sampled parameter distributions, not causal effects or independent empirical estimation.

Field evidence reinforces the uncertainty surrounding the crop-interaction parameter. Crop responses vary with distance from tree rows, tree height, crop species, and weather year (Reuse and Langhof 2025; Majaura et al. 2025). The β coefficient and time path of relative crop yield should therefore be replaced by locally calibrated process-model output when suitable data become available.

At 4% in the selected scenario, alley cropping reaches NPV = 0 at an in-shell walnut price of EUR 4.94 kg^{-1} and matches the arable NPV at EUR 6.22 kg^{-1}. The corresponding orchard thresholds are EUR 4.08 and EUR 4.91 kg^{-1} (Table 14).

Table 14. Conditional in-shell walnut price thresholds.

System	Price for NPV = 0 (EUR kg^{-1})	Price for NPV = arable NPV (EUR kg^{-1})
Walnut alley	4.94	6.22
Walnut orchard	4.08	4.91

3.5. Policy implications, limitations and transferability

For an individual land manager, the relevant comparison is $\Delta NPV_s = NPV_s - NPV_arable$, rather than NPV_s alone. Under the central exploratory low-drought case, alley cropping trails arable cropping by EUR 1 736 ha^{-1}, while the orchard exceeds it by EUR 13 335 ha^{-1}. The risk scenarios in Table 15 illustrate that the economic attractiveness of alley cropping depends on site-specific conditions and assumptions.

New plantings should be based on micro-site exposure rather than regional averages. Slovenian walnut phenology varies by cultivar and can shift earlier under warmer winters and springs, potentially increasing late-frost exposure (Črepinšek et al. 2009). Together with dynamic hardiness research, this supports later-budding or locally tested material and local monitoring of phenology and minimum temperatures (Charrier et al. 2018; Charrier et al. 2013; Khadivi et al. 2019). Because water deficit can reduce walnut yield, long-run water availability and irrigation feasibility should be assessed before investment (Durán Zuazo et al. 2025). Alley layout and

intercrop choice should remain adaptive because tree effects vary by crop, distance, and year (Reuse and Langhof 2025; Majaura et al. 2025).

At national level, this logic is compatible with the Slovenian CAP Strategic Plan 2023–2027 and its 2026 revision, which emphasizes organic farming and climate-adaptation investments (Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026a). Intervention IRP16 supports adaptation in permanent crops, including tolerant varieties and irrigation or protective infrastructure; the source used in this study reports a 50% base support rate with higher support under specified conditions (Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026f). Slovenia also co-finances agricultural insurance premiums, including frost risks (Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026e). For the modelled alley system, administrative feasibility matters: current direct-payment rules recognize agroforestry and tree rows, but the treatment of trees on arable land and eligible area must be verified for the actual parcel (Ministry of Agriculture, Forestry and Food of the Republic of Slovenia 2026b). The model's 56 trees ha^{-1} and separate 0.80-ha cropped component therefore cannot be interpreted as automatic payment eligibility.

At EU level, policy is moving beyond planting subsidies alone. The 2025 Vision for Agriculture and Food emphasizes risk management, adaptation, water resilience, innovation and rewards for verified carbon removals (European Commission 2025b). The proposed post-2027 CAP points toward more targeted support for environmental outcomes, although it remained a proposal at the study cut-off (European Commission 2025a). This direction is consistent with the business-model perspective of Mehrabi and Giagnocavo (2024): positive externalities require a credible mechanism for internalization, not an assumption that private product revenue will pay for them automatically.

The broader policy literature reaches a similar conclusion. FAO treats agroforestry as one element of resilient agrifood systems but stresses site suitability, knowledge, institutions and value chains (FAO n.d.). The Kunming–Montreal Global Biodiversity Framework promotes biodiversity-friendly production approaches (Convention on Biological Diversity 2022), while FAO and IFAD (2026) call for coordinated policy packages rather than isolated instruments. The financial results here add a practical condition: public support should be tied to risks or benefits that the instrument can actually address.

Several limitations qualify the results. Regional statistics do not identify all walnut-based agroforestry parcels. Crop-yield interaction is a metamodel rather than a locally calibrated Yield-SAFE execution. Shade comparisons use differing archived longitudes and therefore do not isolate row-orientation effects. Most importantly, the selected 18.60% local screening value is based on a modified bioclimatic criterion and must not be regarded as a directly observed probability of economically damaging agricultural drought. Modelled payments require legal eligibility, and walnut yields and prices are scenario assumptions. Generalization beyond the case-study region requires external validation.

Future work should combine orchard-level hourly temperatures, cultivar-specific phenology, dynamic hardiness, and observed damage and yield data, allowing P(frost) to be separated formally from P(damage | frost). Drought calibration should incorporate daily rainfall, reference evapotranspiration, soil water balance, soil properties, irrigation, and observed yield. Including frost-protection technologies, microrelief, insurance, and locally calibrated Yield-SAFE or a comparable process model would reduce the main biological and spatial uncertainties.

Table 15. Site-specific interpretation by climate scenario.

Scenario	Investment interpretation	Risk-management and policy implication
Lower-risk	The orchard has the highest NPV (EUR 28,030 ha^{-1}). Alley cropping (EUR 11,442 ha^{-1}) slightly exceeds arable cropping (EUR 10,273 ha^{-1}).	Use later-budding/local material, phenology and Tmin monitoring, water-balance assessment, feasible protection, insurance and payments for verified benefits.
Central 18.6%	The orchard has the highest deterministic NPV (EUR 23,579 ha^{-1}). Alley cropping remains positive (EUR 8,508 ha^{-1}), but is below arable cropping (EUR 10,244 ha^{-1}).	Tie support to demonstrable adaptation, market planning, monitoring and parcel-specific eligibility checks; consider phased investment.
Upper within <20%	The orchard ranks first (EUR 16,889 ha^{-1}). Alley cropping remains positive (EUR 4,119 ha^{-1}), but is below arable cropping (EUR 10,234 ha^{-1}).	Prioritize water security, insurance, advice and demonstration before broad planting incentives; pay for measurable environmental outcomes.
Broad-window stress	The orchard ranks first (EUR 14,057 ha^{-1}). Alley cropping remains positive (EUR 2,212 ha^{-1}), but is below arable cropping (EUR 10,153 ha^{-1}).	Treat this as a conservative robustness check, not the central Franquette probability; retain phenology monitoring and parcel-level protection planning.

3.6. Effects of tree development and row orientation on shade

ArborShadow simulations show that shade overlap increases strongly with tree development (Figure 9). In the young scenarios, periods with more than 50% overlap account for only about 0.5% in the archived N-S run and 2.3% in the archived E-W run. In medium-developed rows, the

share rises to 47.7% and 43.4%, respectively; in mature rows it reaches 63.0% and 61.3%. Across the archived simulations, development stage is associated with substantially larger changes in shade intensity than the observed differences between orientation sets. Because the N-S and E-W output files use different longitudes, however, those between-orientation differences cannot be attributed to row direction alone.

The shade simulations are complementary rather than a direct calibration of the crop-yield function. They support the decision to allow crop performance to decline as trees develop, but the financial model still uses the transparent canopy-yield metamodel described above. The longitude inconsistency between orientation sets and the absence of field calibration mean that the shade outputs should not be interpreted as parcel-specific yield losses or as a causal estimate of the effect of row orientation. Accordingly, no policy recommendation is based on the orientation comparison itself.

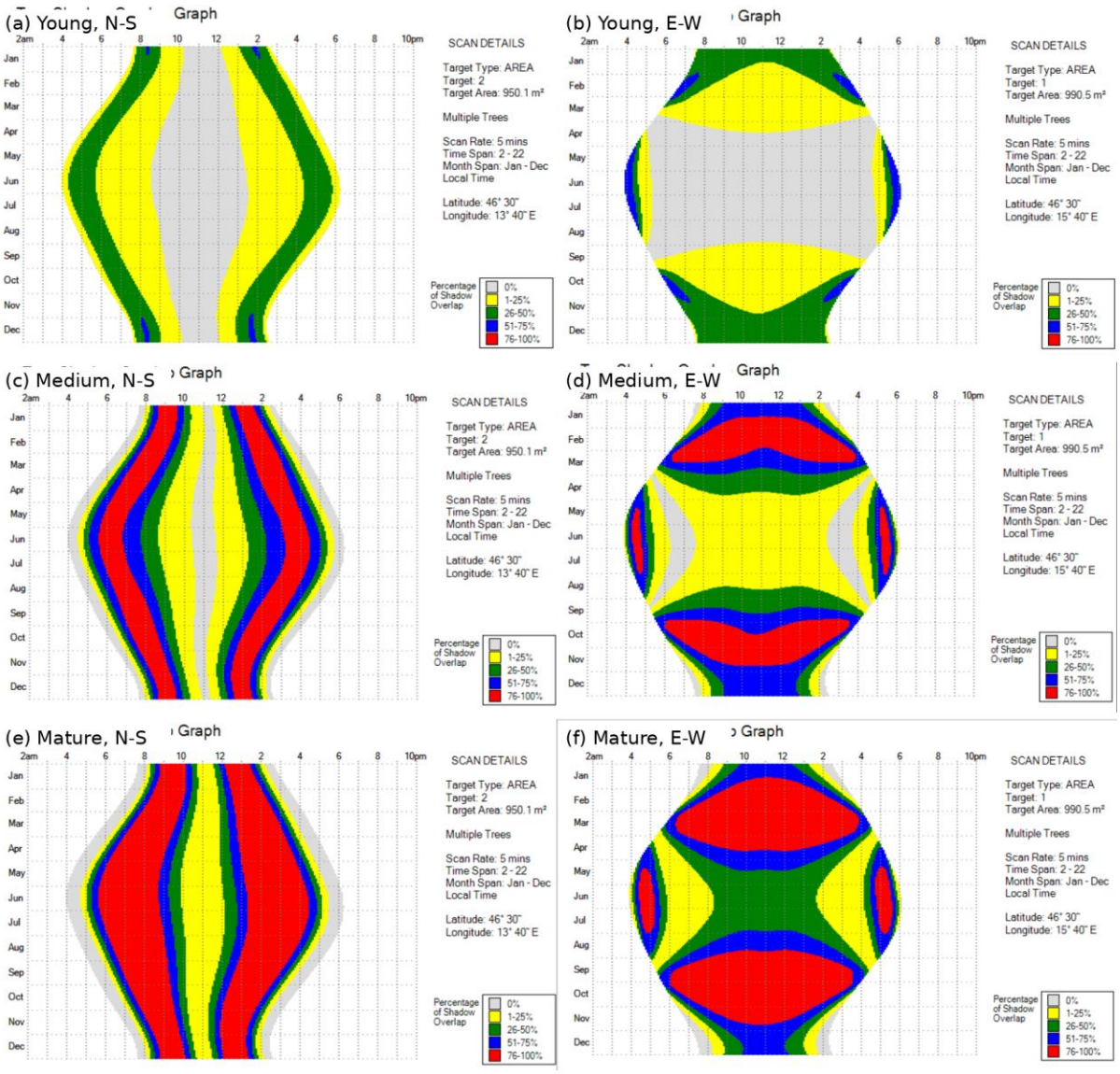

Fig. 9. Annual shade overlap by tree stage and row orientation. Archived N–S outputs use 46°30′ N, 13°40′ E; E–W outputs use 46°30′ N, 15°40′ E.

The interpretation of investment profitability also parallels Ota et al. (2022): NPV and IRR describe distinct aspects of long-term tree-system returns, but neither alone resolves financing, late-income and exposure risks. In the present case, comparisons across discount rates and stochastic scenarios reinforce the importance of considering timing and uncertainty together rather than treating a positive IRR as sufficient evidence of adoption feasibility.

4. Conclusions

The results distinguish the environmental rationale for agroforestry from its conditional private investment performance. In the exploratory 18.60% drought scenario at 4% with modelled payments, the pure walnut orchard returns an NPV of EUR 23 579 ha^{-1}, versus EUR 10 244 ha^{-1} for arable cropping and EUR 8 508 ha^{-1} for alley cropping. These are model-derived values rather than observed farm returns.

Across the revised 10,000-run analysis, probabilities of positive NPV are 99.70%, 64.20% and 88.00% for arable cropping, alley cropping and orchard, respectively. Because the drought input is a proxy-based scenario and not an independently validated damaging-drought probability, quantitative risk results must be interpreted conditionally.

Walnut alley cropping should therefore be neither dismissed nor promoted as uniformly profitable. Its case is strongest on suitable sites where diversification or ecosystem services have demonstrable value. Support is better directed toward site screening, adaptation investment, insurance, technical advice and verified public benefits than toward undifferentiated planting incentives.

Because the biophysical module, economic inputs, climate distributions and policy parameters can be replaced independently, the framework can be adapted to other temperate tree–crop systems. Its practical contribution is to show when land-use rankings change once private cash flow, climate uncertainty, public payments and non-market benefits are kept analytically distinct.

Declaration of generative AI use

OpenAI ChatGPT was used for language and structural editing, literature-search assistance, and support in preparing computational and graphical materials. All authors remain responsible for validating the data, code, references, figures and interpretations before submission. The tool is not listed as an author and was not treated as a primary scientific source.

Availability of data and materials

The datasets and calculation workbooks supporting the findings of this study are available from the corresponding author on reasonable request.

List of abbreviations

ARSO, Slovenian Environment Agency; B/C, benefit–cost ratio; CAP, Common Agricultural Policy; CRCF, Carbon Removals and Carbon Farming; DPP, discounted payback period; EAA, equivalent annual annuity; IRR, internal rate of return; MC, Monte Carlo; MRV, monitoring, reporting and verification; NPV, net present value; SPP, simple payback period.

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