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Agroforestry adoption in Germany: using decision analysis to explore the impact of funding mechanisms on system profitability

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Abstract Since 2023, Agroforestry (AF) is recognised as eligible for direct payments in Germany under the Common Agricultural Policy in the form of annual financial support (Eco Schemes) and regionally variable investment support. However, AF adoption remains low, indicating that Germany is not reaching its AF targets. We investigate whether current and proposed funding schemes sufficiently increase the comparative advantage of AF over arable cropping to improve its financial attractiveness for German farmers. Using Decision Analysis (DA) and probabilistic modelling, we assess the plot-scale economic performance of a silvoarable system integrating apple trees with arable crops. We use Monte Carlo simulations to compute the Net Present Value of the decision to implement the AF system across 10 funding scenarios, including region-specific schemes and one proposed by the German AF Association (DeFAF). Using Value of Information (VoI) analysis, we identify key uncertainties and assess the informative value of our model across various simulation lengths. Our results show a minimal effect of all current funding schemes across simulation lengths. Only the DeFAF-suggested scheme makes AF the preferable option in intermediate time frames (10 years), while the baseline scenario remains preferable in all other scenarios. Over longer periods (15–20 years), AF becomes economically viable in all scenarios, although outcome uncertainty increases. VoI analysis identifies expected apple yield and market prices as decision-relevant uncertainties. Our findings highlight the importance of time-sensitive, outcome-driven support measures that account for farmers' economic constraints. We show that DA can support funding evaluation, by informing effective targeted support schemes for land-use transitions.

Keywords Agroforestry · Institutional support · Decision analysis · Probabilistic analysis

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Introduction

Only since the 2023 reform of Europe's Common Agricultural Policy (CAP) has Germany implemented a legal definition of agroforestry (AF) in its national agricultural funding legislation (BMEL 2023a). AF is now recognized as a form of agricultural land use that is eligible for basic payments under the CAP. Additionally, the maintenance of such systems can be funded under the Eco Scheme (ES) programme if certain requirements are met. The ES programme, which is part of the new CAP's first pillar, allows farmers to supplement their income from annual basic payments through additional ecology-oriented efforts.

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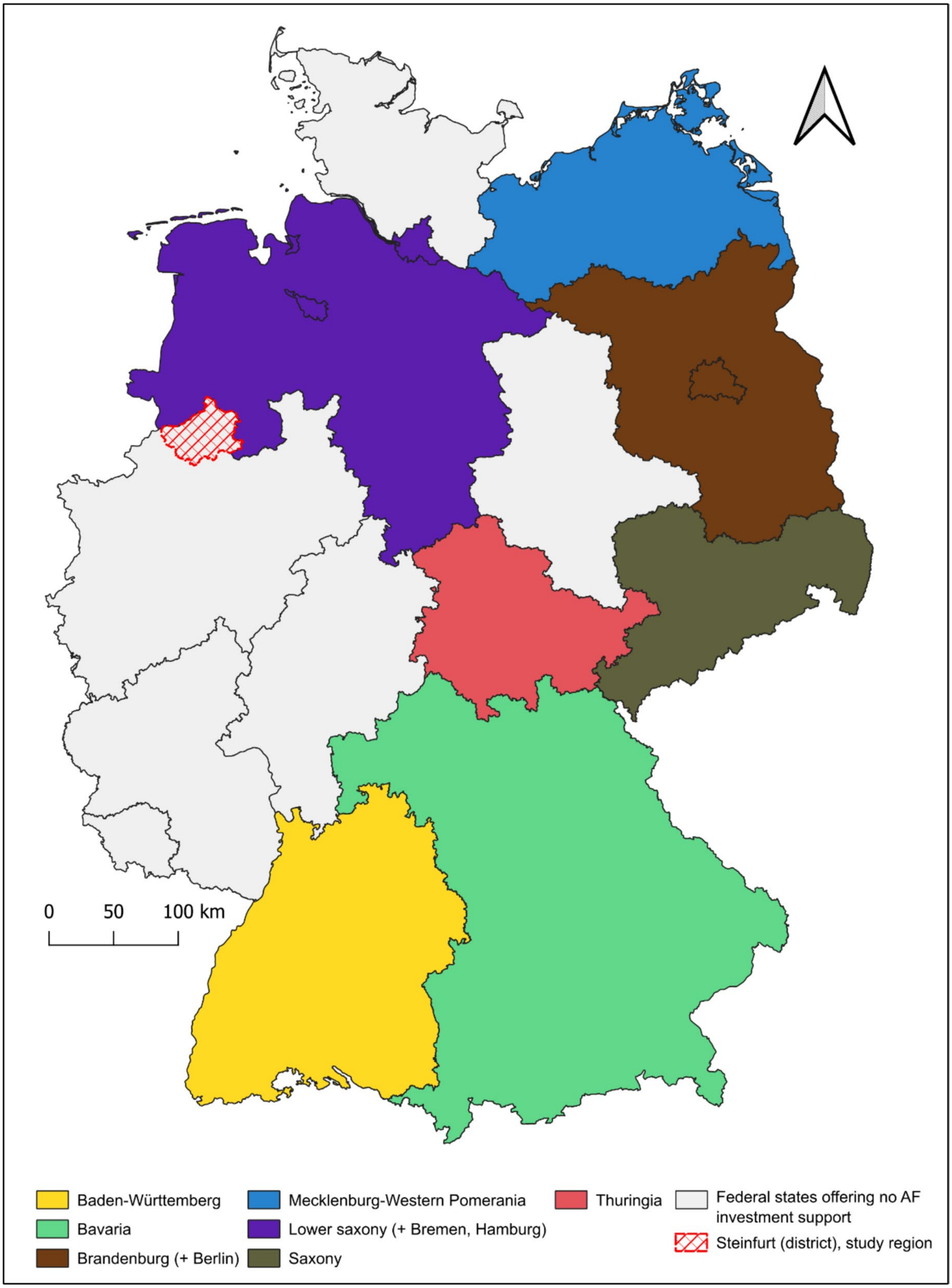

0 50 100 km
Baden-Württemberg
Bavaria
Brandenburg (+ Berlin)
Mecklenburg-Western Pomerania
Lower saxony (+ Bremen, Hamburg)
Saxony
Thuringia
Federal states offering no AF investment support
Steinfurt (district), study region

◂**Fig. 1** Map of Germany, highlighting federal states that offer AF funding in addition to annual Eco Scheme payments

Despite providing farmers with a framework intended to create legal security for managing and harvesting woody vegetation on agricultural land, the number of new officially registered AF plots is low. The Federal Ministry of Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft, BMEL[1]) aimed to support the maintenance of 25,000 ha of AF in 2023, yet farmers only registered 51 ha of AF in that year (BMEL 2023b), while no numbers on actually implemented AF systems can be found. This strongly suggests that Germany may fail to meet its goal of supporting the maintenance of 65,000 ha of AF through the ES programme by 2027 (BMEL 2023a). In response to the low demand for the respective ES funding, in 2024, the annual payment was increased from 60 to 200 € per hectare of area covered with trees or shrubs (hereafter referred to as 'wooded area'). Possibly as a response to this increase, the number of applications for AF support through the ES programme increased to 173 ha in 2024 (BMEL 2024a). This equates to 2.3% of the revised goal of funding 7,500 ha of AF maintenance in 2024, which itself is significantly lower than the original target of 50,000 ha set in 2022 (BMEL 2022). The increase in annual support is considered insufficient by AF stakeholders such as the German AF association (Deutscher Fachverband für Agroforstwirtschaft, DeFAF). Since payment increases were also applied to various other ES options, some of which produce lower environmental benefits but incur less management effort, adopting AF may still be less attractive to farmers than alternative options (Böhm 2023). This implies that these adjustments may still not be sufficient for encouraging the adoption of AF in Germany.

The societal and environmental benefits AF provides are highlighted multiple times in the German CAP strategic plan (SP). Carbon sequestration, climate change adaptation, reduction of nitrogen leaching and enhancement of agricultural biodiversity are seen as key reasons for the promotion of AF in Germany (BMEL 2024b). This indicates acknowledgement of current scientific opinion on AF and ecosystem services (e.g. Veldkamp et al. 2023), and the intention of German policymakers to foster AF to enhance agricultural sustainability. Furthermore, the German CAP SP suggests implementing a targeted investment support measure to help farmers establish new AF systems (BMEL 2024b). This support is intended to complement the annual payment farmers can receive through the ES programme (BMEL 2023c). Such investment support schemes are classified as rural development measures under the CAP's second pillar. Since in Germany, all second-pillar measures are administered by the federal states, there is no nationally standardised AF investment support measure. While this approach allows funding to be tailored to region-specific needs, it has resulted in only some federal states introducing AF investment support measures. In 2023 and 2024, 10 out of 16 federal states offered such support (Fig. 1). Across these 10 states, these measures vary significantly in three key aspects: the total funding available to farmers, the requirements for obtaining support, and the types of costs considered eligible for funding. For instance, Lower Saxony explicitly excludes planning and consulting costs from funding (ML Nds. 2023) whereas Baden-Württemberg and Thuringia offer only subsidised AF consulting services (TLVwA 2023; LEL 2023).

It remains uncertain whether the introduced funding measures will effectively promote AF in Germany and help achieve national AF targets. We argue that policymakers must consider a farmers' decision-making process when designing targeted subsidy measures to ensure the intended outcomes are realized. This can be done by ex-ante evaluations, which compare the profitability of AF to, e.g., standard arable farming. The scope of the evaluation must be set to what is considered immediately decision-relevant in the context of implementing alternative farming practices. Findings on the adoption of agri-environmental measures suggest that the hurdle of changing well-adjusted farming routines can only be overcome by guaranteeing at least stable economic performance if not additional financial benefit (Wittstock et al. 2022). Current approaches used to determine payment levels for AF support seem to not yet systematically integrate such decision-focused analysis. For instance, the

[1] The German Federal Ministry for Food and Agriculture (Bundesministerium für Ernährung und Landwirtschaft, BMEL) changed its name to Federal Ministry of Agriculture, Food and Regional Identity (Bundesministerium für Landwirtschaft, Ernährung und Heimat, BMLEH) in 2025).

introduction of the first German AF funding scheme provided 60 €/ha of wooded area in 2023, which was based on calculations by the Thünen-Institut (Röder et al. 2021). These calculations have been criticised for assuming unrealistically high woodchip revenues and yield increments, and for the exclusion of establishment and re-cultivation costs (Zehlius-Eckert and Böhm 2022). Subsequent increases in funding to 200 and then to 600 €/ha of wooded area (planned to come into effect from 2026 provided that approval by the European Commission is granted (BMLEH 2025)), appear reactive to stakeholder pressure rather than informed by systematic ex-ante evaluation. Our study demonstrates a workflow that may complement such approaches by modelling whether proposed funding is likely to positively affect adoption decisions while quantitatively expressing the uncertainty surrounding all input metrics and model outputs.

We analyse the impact of targeted support payments on the plot-scale profitability of a German AF system using probabilistic modelling following a Decision Analysis (DA) approach (Luedeling and Shepherd 2016). While previous studies have examined AF adoption in Europe through economic or policy perspectives (e.g., Lehmann et al. 2020; Sollen-Norrlin et al. 2020; Smith et al. 2022; Thiesmeier and Zander 2023; Rezgui et al. 2024; Thiesmeier 2024) few studies explicitly evaluate how alternative funding designs might influence AF adoption decisions relative to existing land-use systems under uncertainty. We here demonstrate how probabilistic modelling following DA logic can be used to assess how alternative funding schemes affect the relative profitability of AF systems compared to a baseline system at the plot level. The presented approach allows the systematic comparison of different support scenarios and provides insights into their possible influence on farmers' adoption decisions, providing policymakers with a tool for designing targeted, outcome-driven support schemes.

We demonstrate the approach through a case study evaluating the impact of all agroforestry support payments available in Germany under the 2023–2027 CAP on a silvoarable alley cropping system integrating rows of apple trees with arable crops. In addition, we incorporate a funding scheme proposed by the largest AF stakeholder group in Germany to explore policy options beyond the current regulatory framework. We collated all information that we considered decision-relevant for the introduction of apple trees into an arable farming operation, using the current state of knowledge derived from the literature as well as from expert knowledge. In the context of AF adoption in Germany, this means focusing initially on the plot-level economic performance, since national policy aims to incentivize AF through financial support, while farmers remain constrained by the need to maintain a viable business (Wittstock et al. 2022; Bartkowski et al. 2023). After first conceptually modelling the decision, we quantified all model variables in terms of value ranges and probability distributions. Using Monte Carlo (MC) simulations, we performed a probabilistic cost–benefit analysis, computing the Net Present Value (NPV) of the adoption decision for different simulation periods. The basic decision model was then modified to include 10 different payment scenarios to examine their impacts on the NPV of the AF system. Subsequently, we computed the payback period of the decision across funding scenarios to examine the time required for the AF system to compensate for forgone net benefits from the baseline system. We then evaluated the expected value of perfect information (EVPI) to estimate how much a rational decision maker should be willing to pay for perfect information to derive clear guidance for action from the MC simulation output.

Methods

Case study

The case study site is a silvoarable AF system in the district of Steinfurt, in the north-western part of North Rhine-Westphalia (NRW), Germany. Steinfurt is situated at an average elevation of 60 m above sea level. From 1990 to 2020, the area experienced a mild oceanic climate with a mean temperature of 10.2 °C and mean annual precipitation of 783 mm (LANUV 2024). The landscape is defined by agricultural production, with 63% of the total area being agricultural land and 79% of this area being arable agriculture (IT. NRW 2022).

The AF system was established in 2022 on 10.14 ha of arable land, with loamy-sandy soil and no noticeable slope. 5.6% of the plot (0.57 ha) have been converted into 3 m-wide tree rows, spaced 30 m apart. Due to the asymmetrical shape of the plot, the rows vary between 60 and 180 m in length, adding up to a length of 1,890 m. A total of 473 apple trees of 9 different cultivars were planted. The varieties were chosen to be suited for the intended low-input cultivation method, with minimal use of fungicides, herbicides or insecticides. Plant protection measures are to be limited to using pheromone dispensers for codling moth (*Cydia pomonella* L.) control. The system is expected to reach maturity after around 9 to 12 years and will contain nearly closed rows of apple trees with wide, low canopies, giving the tree rows a hedge-like appearance. A drip irrigation system has been installed in all tree rows to optimize apple production as well as minimize competition for water between arable crops and fruit trees. The arable area of the AF system is conventionally managed with a crop rotation consisting of maize, winter wheat, winter barley and rape seed. Soil cultivation is minimized strategically, and where possible, no-till methods with the application of a total herbicide are used to prepare the field for sowing (Jan Große-Kleimann, personal communication, 23. January 2024). The analysed silvoarable apple AF system represents a typical temperate alley cropping approach combining annual arable crops with perennial fruit production. In temperate Europe, AF systems commonly take the form of alley cropping systems integrating fruit or nut trees, high-value timber trees or short-rotation coppice species with arable cropping or pasture (Hübner and Günzel 2026). The selected system, therefore, represents one of the main conceptual AF types currently considered in German policy.

Germany's AF funding framework

In 2023, Germany implemented a legal definition of AF in its national policy, which distinguishes AF from other tree-based agricultural systems, such as orchards, short-rotation coppice plantations or even landscape elements protected by nature conservation law (BMEL 2023a). This allows the integration of trees into agriculture while maintaining eligibility for CAP basic payments. If farmers choose to apply for a premium payment for the maintenance or establishment of AF systems, certain requirements have to be met that go beyond those for the basic payment.

The national ES programme under the CAP's first pillar provides an annual payment of 200 € per hectare of wooded area for the maintenance of AF systems, with specific requirements (BMEL 2024c):

- Trees must not be scattered across the plot but arranged in at least 2 rows, spanning up to 25 m in width,
- Tree rows may cover 2 to 40% of the agricultural plot,
- The distance between two tree rows must be 20–100 m.
- Whenever the field borders a forest or specific landscape element, the distance between an AF tree row and the field edge must exceed 20 m.
- Harvesting biomass from the woody vegetation is permitted only in January, February and December.
- Specific tree species are prohibited from being planted in an AF system (negative list).

The implementation of new AF systems is supported at rates that differ between the federal states. As of 2024, 10 out of 16 German federal states (7 out of 13 funding regions) had implemented AF investment support schemes (Fig. 1). These schemes can be divided into three categories:

1. subsidised AF consultancy,
2. investment support based on the Joint Task for the Improvement of Agricultural Structures and Coastal Protection (Gemeinschaftsaufgabe Agrarstruktur und Küstenschutz, GAK),
3. investment support designed independently of the GAK.

The GAK is a national funding instrument that coordinates subsidy programs between federal states. It contains, among other things, a list of agroecological interventions–explicitly incorporating AF–along with suggested funding scheme designs emphasizing the national importance of these measures. By aligning funding schemes with the designs suggested in the GAK, second-pillar funding can be nationally co-financed (BMEL 2023d).

In this study, we compared the impact of available payments across different funding regions in Germany for the abovementioned AF system, assuming its implementation in these regions. This allows us to identify which funding scheme is most conducive to encouraging the adoption of AF. We also compared the existing funding schemes with an alternative scheme proposed by DeFAF. To improve understanding of how impacts of financial support unfold over time, we analysed the effect of the funding schemes on the system NPV for different simulation lengths.

Two funding regions, Bavaria and Mecklenburg-Western Pomerania, offer investment support based on the GAK. In both regions, the maximum total funding depends on the type of AF system. Farmers can receive up to 1,566 € per ha of wooded area when planting species intended for short rotation cycles. Shrub planting is supported with up to 4,138 € per ha of wooded area, while planting trees to produce food or high-value timber can qualify for up to 5,271 € per ha of wooded area. In both regions, the AF investment support is a pro-rata payment funding, covering 65% of eligible investment cost. The maximum support per farm is limited to 50,000 € in Bavaria (StMELF and StMUV 2022) and 300,000 € in Mecklenburg-Western Pomerania (MKLUM MV 2023).

Saxony and Lower Saxony both introduced AF investment support that is independent of the GAK. Saxony's scheme is implemented within a directive on the promotion of general agricultural investments. It covers agricultural investments ranging from planting material for silvoarable AF systems to agricultural buildings, which all are supported with up to 40% of the total cost. For these payments to be granted, farmers must present proof that the eligible investment costs exceed 20,000 €. The directive does not differentiate between tree planting or investment in agricultural buildings, which is why a theoretical maximum subsidy of 5,000,000 € can be assumed. Agroforestry consultancy is not eligible for funding (SMUL 2023). The Lower Saxony funding region (which includes the city-states of Bremen and Hamburg) introduced its AF investment support in a directive dedicated to this cause (ML Nds. 2023). According to this directive, 40% of eligible investment expenses are supported with a maximum of 20,000 € per AF project. Similar to Saxony, expenses related to planning and consulting – although regarded as crucial parts of the AF establishment process by many experts – are explicitly excluded from eligibility for funding (ML Nds. 2023).

Three German funding regions support the establishment of AF systems by providing subsidised AF consultancy services. While Brandenburg (including Berlin) and Thuringia offer fixed amounts — up to 1,530 € per AF project (MLUK, personal communication, 2. April 2024) and 6,000 € per AF project (TLVwA, personal communication, 28. March 2024), respectively — Baden-Württemberg covers 80% of consultancy costs, with a maximum subsidy of 1,500 € per AF project (LEL 2023).

In addition to the previously mentioned existing AF funding options, we also evaluated an alternative AF funding scheme based on the suggestions of the German AF association, DeFAF. Böhm et al. (2023) suggest, in an open letter to German agricultural and environmental policy-makers, to significantly increase annual payments as well as the introduction of a national investment support scheme for farmers intending to establish AF systems. The authors suggest an increase of the available annual funding from 200 € to at least 600 € per ha of wooded area. They further suggest offering complementary investment support for establishing AF systems, to cover 100% of the costs of the first 10 ha of wooded area, 80% for the next 10 ha, and 50% for all wooded area exceeding 20 ha. This recommendation does not distinguish between different cost categories, suggesting that all direct investment costs are to be regarded as eligible for funding. Böhm et al. (2023) argue that such a scheme would create a significant incentive to implement AF systems that may be sufficient for reaching the national targets.

In this study, we compared the NPV of the decision to integrate apple trees into an arable field across the following ten scenarios:

- No funding: No payment for AF systems is available, i.e. no investment support and no annual funding other than the basic area payment.
- Only ES: AF systems are funded solely via the ES programme, which provides 200 € per hectare of wooded area.
- Brandenburg (+Berlin, BB): AF systems are funded annually via the ES programme and AF consultancy is subsidised with up to 1,530 €.
- Thuringia (TH): AF systems are funded annually via the ES programme and AF consultancy is subsidised with up to 6,000 €.
- Baden-Württemberg (BW): AF systems are funded annually via the ES programme and AF consultancy is subsidised with up to 1,500 €, or 80% of consulting costs, depending on which is lower.

- Bavaria (BY): AF systems are funded annually via the ES programme and eligible investment costs are subsidised in the following way:
  - Tree rows containing fruit trees are subsidised with up to 5,271 €/ha.
  - • 65% of eligible cost is covered.
  - The maximum funding is 50,000 €.
- Mecklenburg-Western Pomerania (MV): AF systems are funded annually via the ES programme and eligible investment costs are subsidised in the same way as in Bavaria, with total funding capped at 300,000 €.
- Saxony (SN): AF systems are funded annually via the ES programme and eligible investment costs are subsidised up to 40%, if a minimum amount of eligible investment cost of 20,000 € can be proven. The maximum funding is 5,000,000 €.
- Lower Saxony (NI): AF systems are funded annually via the ES programme and eligible investment costs are subsidised up to 40%, explicitly excluding consultancy fees. The maximum funding is 20,000 €.
- DeFAF-suggestion: AF systems are funded annually with 600 € per ha of wooded area. Additionally, investment costs are to be funded at
  - 100% for first 10 ha of wooded area
  - • 80% for the next 10 ha
  - 50% for additional area.

Decision analysis model

DA offers a methodological framework intended for the ex-ante examination of interventions made to complex systems (Luedeling and Shepherd 2016). The approach explicitly acknowledges that real-life decisions are usually taken under uncertainty. By recognizing this, DA seeks to offer practical decision support rather than predicting precise future outcomes based on unrealistically precise assumptions. By prioritising decision-relevant factors, the analysis of the intervention problem is streamlined, allowing the strategic selection of the analytical focus. In an economically driven scenario, this may mean the exclusion of ecological or social impacts of the decision. Conversely, it may involve expanding the scope or shifting it to include indirect, abstract effects of an intervention such as the enhancement of landscape aesthetics or cultural heritage implications (Luedeling and Shepherd 2016). By employing modelling approaches fit to handle uncertainty, DA enables informed decision-making in complex systems where quantitative understanding on system components and interactions is limited (Eidsvik et al. 2015). DA reduces the uncertainty of a decision-making process by providing insights into the comparative benefits and drawbacks of available options. Providing an objective informative basis reduces the impact of cognitive biases or "wishful thinking", leading to a rational and evidence-based choice (Whitney et al. 2018). The DA approach used in this study has proven successful in many application cases, including the examination of disease control strategies in ornamental heather production in Germany (Ruett et al. 2022), adaptation to extreme weather in cherry orchards in Chile (Rojas et al. 2021) and evaluating the economic prospects of various AF systems in north-western Vietnam (Do et al. 2020).

Conceptual model

A key step of the DA approach is the clear identification of the decision-maker and the decision problem, followed by development of a conceptual model for the decision problem. The conceptual decision model is used to gather and display all variables considered relevant for the decision at hand. It provides a crucial overview of all relevant variables and the interactions between them. This conceptual model is then translated into a mathematical model, which provides quantitative information on the decision outcome.

We focused on the binary decision of whether to establish the above-described silvoarable AF system for table apple production. Here, the farmer is considered the primary decision-maker. As the main aim of this study is to examine the plot-scale economic effects of different AF funding schemes, we considered only economic variables that can be expressed in monetary units (€) as decision-relevant variables for our model. We, therefore, deliberately simplified the complex decision-making process inherent in agroecological interventions. We argue that maintaining the farms' economic viability is what drives farmers' decision-making and is therefore to be considered by policymakers when designing schemes to promote the implementation of specific agricultural practices.

In the model, we differentiated between one-time investment costs, recurring running costs, and irregular costs that may arise in particular situations. Benefits were categorised into yield from the arable component of the AF system and yield generated through the tree rows, i.e., apple yield and AF-specific support payments. Furthermore, the risk of reduction in yield due to the impact of extreme events is also included in the model. To identify the decision-relevant variables, we considered all available relevant information, prioritising official statistics and peer-reviewed literature where available but also explicitly including expert knowledge in the analysis process. We considered literature on AF, apple production in intensive orchards and extensive traditional meadow orchards, and arable farming (specified in the supplementary materials). To minimise omission of decision-relevant variables, we collated expert knowledge through a semi-structured process, where we consulted experts with long-standing knowledge on arable crop management, extensive apple production, fruit tree pruning, agricultural investment economics, irrigation systems and AF. Most importantly, we interviewed the farmer who implemented the AF system modelled in this study, making sure to capture what he considered decision-relevant. Prior to elicitation, all contributors received information about the farm, the AF system and the context. The collated information was assessed and then captured in a conceptual model.

Mathematical modelling

On the basis of the conceptual model, a mathematical model was formulated using the R programming language (R Core Team 2024), and the *decisionSupport* package (Luedeling et al. 2023). Most variables that describe the behaviour of complex systems inherently carry uncertainty regarding their precise values. We distinguish between uncertainty about parameter values and their variability over time. Uncertainty about parameter values reflects incomplete knowledge regarding, e.g., expected yields and prices. This type of epistemic uncertainty is represented through value ranges (90% Confidence Intervals (CI)) assigned to each input variable, with wider value ranges reflecting a greater level of epistemic uncertainty. In addition, many variables were assumed to vary between years due to stochastic influences such as weather conditions or market fluctuations. To introduce this aleatory uncertainty, coefficients of variation were assigned to all reoccurring input parameters.

We considered all available information on the AF system and its components when quantifying the input parameters. As in the conceptual part of the modelling process, we included data from literature and educated estimations from interviewees that consisted of practitioners, consultants, and researchers. Whenever information found in literature and estimations received from interviewees did not match, we chose to combine and broaden the value ranges to capture uncertainty. This approach is particularly valuable when examining complex systems for which observational data are scarce. For instance, for the apple component of the AF system, yields, prices and labour requirements were parameterised with wide ranges to reflect uncertainty across management intensities and marketing channels (e.g., processing vs. table fruit). Using probability distributions to quantify model parameters allows running initial simulations, without conducting extensive research, which might unnecessarily prolong the decision-making process. However, probability distributions used in the model should be interpreted as representations of decision-relevant uncertainty based on current knowledge rather than precise statistical descriptions of future outcome frequencies (Hardaker et al. 2015; Luedeling and Shepherd 2016).

Most relationships between the models' variables are simple algebraic expressions, e.g., sums of cost components or products of unit prices and quantities. The total investment cost, for example, consists of the sums of all material, labour and service costs with its 90% CI ranging from 24,984 to 33,012 €, which captures the true communicated investment cost of 25,000 € (Große-Kleimann 2023). For transparency, we provide the full, executable R code, as well as the input table in the supplemental GitHub repository. To express some of the modelled processes, we used dedicated functions from the *decisionSupport* package. For instance, the development of apple yields over time was expressed by a Gompertz function (Luedeling et al. 2023). This function expresses slow growth at the beginning, followed by a period of rapid growth, which then levels off as the maturing trees reach their peak production level (Fig. 2).

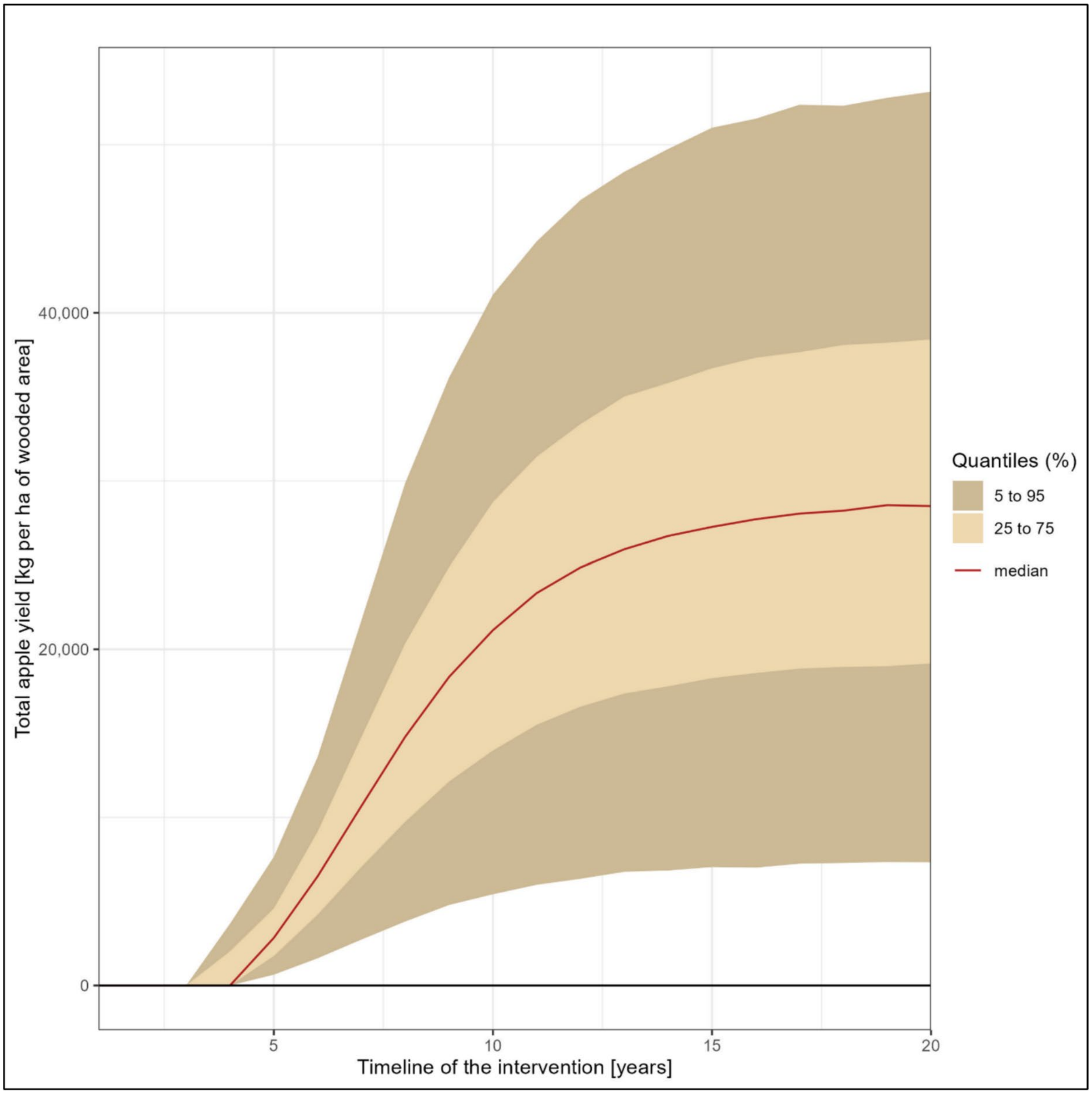


Fig. 2 Simulated total apple yield generated by the AF system [kg per ha of wooded area]. The curve, generated with the gompertz_yield ()-function from the decisionSupport package, shows the sigmoidal shape of the Gompertz function used to model the yield development of the apple trees. The dark shade, light shade and red line show the 90% CI, 50% CI and median, respectively, highlighting the increasing uncertainty regarding plausible apple yield over time

Yields of the arable crops were assumed to not express any trend over the length of the simulation and only vary in response to stochastic (e.g., weather-related) factors, which cause random variation around a specified mean. We made this choice for two reasons: first, yields in Central Europe have been broadly stable since the 1990s, as agronomic improvements and climate- or weather-related reductions have largely balanced each other out (e.g., Lopes 2022); second, our model explicitly accounts for annual variability and occasional non-specific yield-damaging weather events, which influence the baseline and AF systems to different extents, thereby reflecting short- to medium-term weather risks relevant for farm cash flow.

The specified mean as well as the lower and upper boundaries of the value ranges assigned to the variables were calculated based on observational data available for the district the study site is located in as well as data from neighbouring districts (IT.NRW 2024a, 2024b). These data, which include yields recorded between 1999 and 2023 (Fig. 3), were assumed to capture variability sufficiently to make realistic yield assumptions for the time period relevant in this study. The yield data also reflect severe drought years such as 2003 and 2018, accounting for the possibility of future yield reductions due to drought. To reflect the possibility that more severe weather events could occur and reduce yields beyond what the historical record shows, we included a yield-reduction risk factor with a likelihood of occurrence and severity taking into consideration the uncertainty.

We used our model to calculate and compare the overall economic performance of the baseline system (i.e. the arable system) and the AF system, expressed as the NPV (Gaspars-Wieloch 2019). The NPV is calculated by summing up the discounted net cash flow of each year of the simulation. Discounting is used to account for the influence of time, or opportunity cost, on perceived benefits and costs. This highlights the time value of money, i.e., that possession of money in the present is usually associated with greater worth than receiving the same amount of money in the future (Thompson and George 2009). We determined the discount rate by assuming it to be the price for the provision of liquidity. We used market interest rates provided by the German federal bank (Deutsche Bundesbank 2024) to generate its value range, while also considering other AF-investment-related studies (Thiesmeier and Zander 2023). This approach reflects typical financing conditions faced by farmers when evaluating investment decisions. While individual time preferences may vary significantly between decision-makers, modelling such behavioural heterogeneity lies beyond the scope of this study.

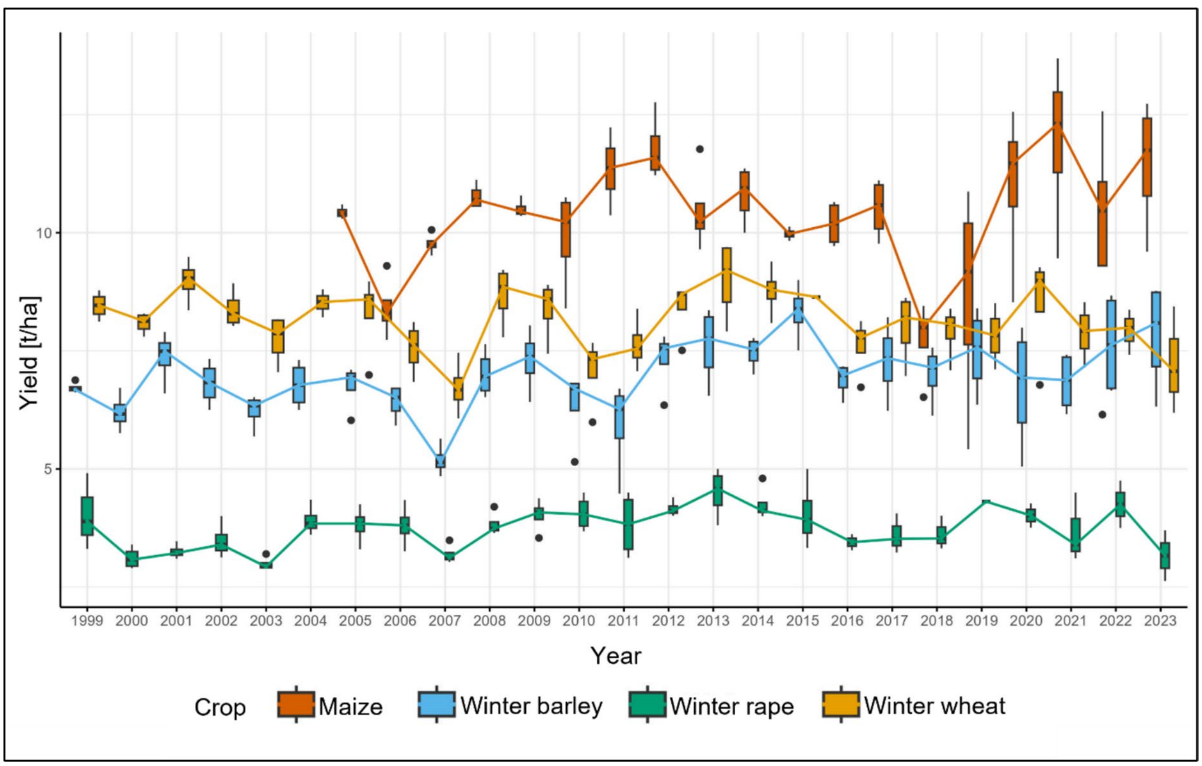


Fig. 3 Barley, rapeseed and wheat yields [t/ha] from 1999 to 2023; Maize yields [t/ha] from 2005 to 2022. Each boxplot represents 4 data points, 1 point each from the districts of Steinfurt, Coesfeld, Borken and Münster (IT.NRW 2024a, 2024b). Each line connects the median crop yield values to visually highlight the course of the data

$$NPV = -C_0 + \sum_{i=1}^{t} \frac{C_i}{(1+r)^i}$$

C_0 establishment cost [€].
C_i cash flow in year i [€].
r discount rate [%].
t duration of simulation [a].

The NPV provides information on the present value of a future cash flow, whether positive or negative. Considering this metric is important for farmers deciding whether to implement AF systems, as such systems only generate returns in the long term, after initial investments and many years of management.

We used 100,000 runs within an MC simulation to probabilistically compute the NPV of the baseline arable system and the AF system for simulation lengths of 5, 10, 15 and 20 years. Before generating the NPV, the difference in net benefit (total benefit−total cost) between the baseline system and the AF system is calculated. The *NPV of the decision*, isolated through this method, is the main metric for comparing funding scenarios. To ensure comparability across funding scenarios, simulations were conducted using common random numbers by setting a fixed random seed (*set.seed()*). This ensures that differences in model outputs can be attributed to differences in funding design rather than to variation in random draws.

In addition to the NPV, we calculated the payback period for all 10 funding options over a 20-year simulation period based on the cumulative cash flow (CCF) of the decision, i.e., the cumulated discounted incremental net benefit of adopting AF. The payback period is defined by the first year in which the CCF becomes non-negative. It therefore represents the time required to recover the initial economic disadvantage of adopting AF relative to the baseline. This incremental definition reflects the real-world decision context faced by farmers, who typically choose between maintaining an existing production system and adopting an alternative. Consequently, the payback period should not be interpreted as the time required for the tree rows to amortise, but as the time required for the AF system as a whole to compensate for forgone net benefits from the baseline system. Given the probabilistic nature of the approach, which generates 100,000 outputs per year, each decision scenario results in multiple years with negative and positive CCF values. We present the payback period in probabilistic terms, providing value ranges (90% CI, 50% CI and median) that highlight the uncertainty associated with the true length of time it takes to recover said initial economic disadvantage.

Value of information analysis

Decreasing the uncertainty of the output variable, thereby increasing its informative value, is possible by narrowing the value ranges of the input variables. Given that resources such as time, finances and labour are usually constrained, efforts to reduce uncertainty must be strategically allocated. It is, therefore, important to identify the variables where reducing uncertainty yields the greatest value. Using Value of Information (VoI) analysis, we calculate the expected value of perfect information (EVPI, Szaniawski 1967). For a particular input variable, the EVPI is defined as the difference between the expected value (EV) of the outcome variable given perfect information (PI) on that variable and the expected maximum value (EMV) of the outcome variable given the current imperfect knowledge on the variable (Ruett et al. 2022).

$$EVPI = EV|PI - EMV$$

The EVPI assesses quantitatively the expected benefit gained from acquiring knowledge about the values of uncertain parameters within a decision model (Strong et al. 2014). To compute the EVPI for all input variables across the funding scenarios and simulation lengths, we used the function binary_multi_evppi() from the *R*-package *evpi* (Kopton 2024).

Model limitations and assumptions

The DA procedure outlined by Hubbard (2014), on which the approach used in this study is based, includes the step of expert calibration. This procedure is used to familiarise the consulted experts with concepts such as cognitive biases that may affect estimations and to hone the experts' skills in quantifying their own uncertainty. Because of low willingness to invest significant time into the expert calibration process, only one expert underwent the calibration training. Therefore, some of the value ranges used in the model may be affected by biases.

Furthermore, we assumed all tested investment support schemes to be an upfront provision of liquidity, rather than a reimbursement of purchases. However, several investment funds require a written request for reimbursement, which farmers, e.g. in Bavaria, can submit even 2 years after the initial funding approval (StMELF and StMUV 2022). We, therefore, emphasize that the simulation output is not to be taken as clear evidence of one of the two systems (AF system or baseline system) outperforming the other over the considered time frames. We aim to present probabilistic modelling following a DA procedure as one possible method for aiding in the design of targeted agricultural support payments. Therefore, the following results are not to be interpreted as precise predictions of absolute profitability for the specific case study farm, but rather as evidence of how the tested funding options influence the relative NPV and thereby the farmer's decision-making process. Our focus is thus on the comparison of scenarios, not on absolute numbers.

Results

Conceptual cost–benefit model

The core decision of this study, whether to establish the proposed silvoarable AF system, is conceptualized in Fig. 4. Information on economic variables affected by the integration of apple trees into an arable system was gathered through a literature assessment as well as through expert consultations. The model depicts costs, benefits, risks, and modulating factors. The investment costs include exclusively AF-related costs since the decision is assumed not to introduce new

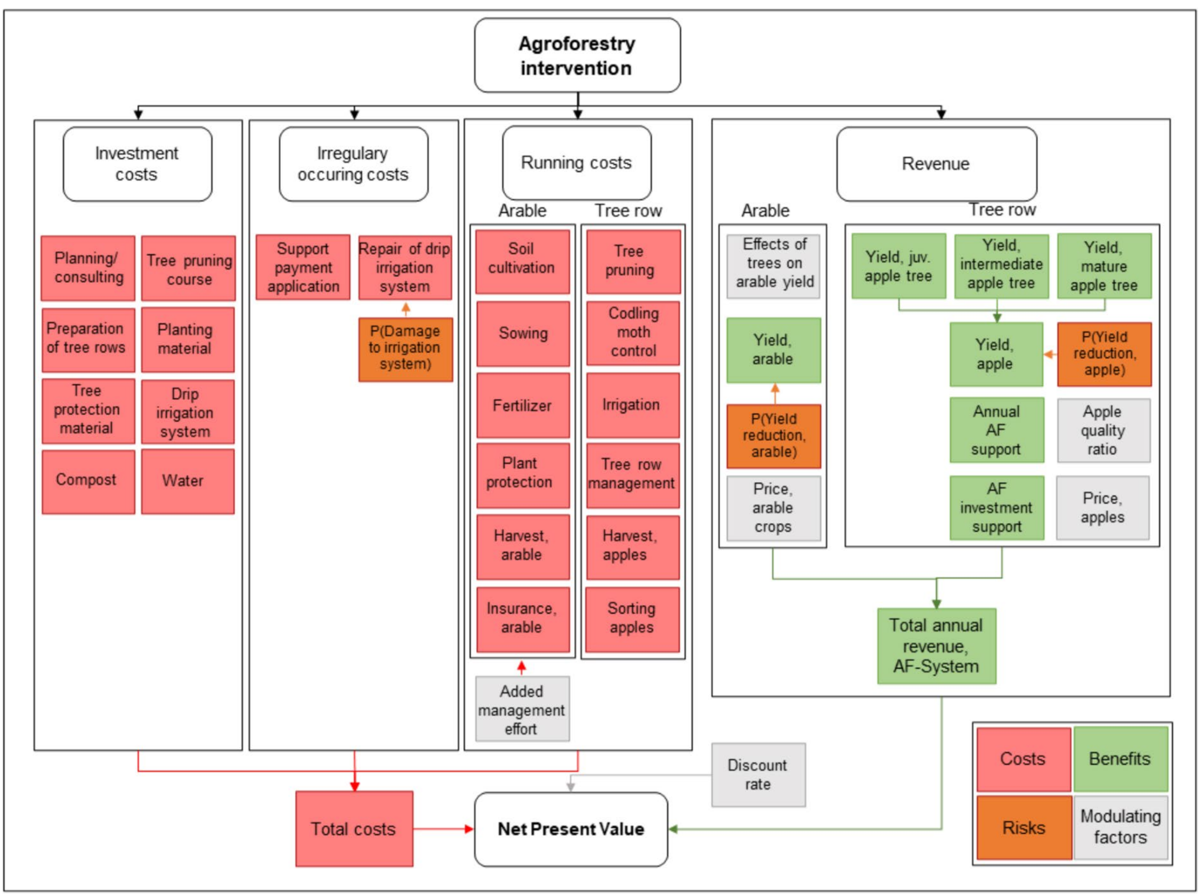


Fig. 4 Conceptual model of silvoarable apple agroforestry depicting decision-relevant variables, their interactions and their impacts on the NPV

investments into the arable component of the system. Changes in costs associated with the arable operation are expressed as differences in the running costs, as indicated by the modulating factor "added management effort". The integration of trees into the arable system introduces new running costs. Especially manual labour associated with, e.g., pruning of the apple trees and harvesting of the apples, is considered decision-relevant. Potential costs occurring due to unexpected events, indicated by 'P(variable name)' in Fig. 4, make up the third category of costs. The '*P*' in these expressions indicates that the event's probability of occurrence is considered in the model.

The benefits assumed in this model are limited to direct monetary metrics, thus including the revenue generated by the sale of the crops (field crops and apples) as well as support payments that arise in 9 out of 10 modelled scenarios. Certain cost and benefit variables are influenced by risk factors to account for additional uncertainty beyond the standard variable value ranges.

Impact of funding on the net present value of the decision

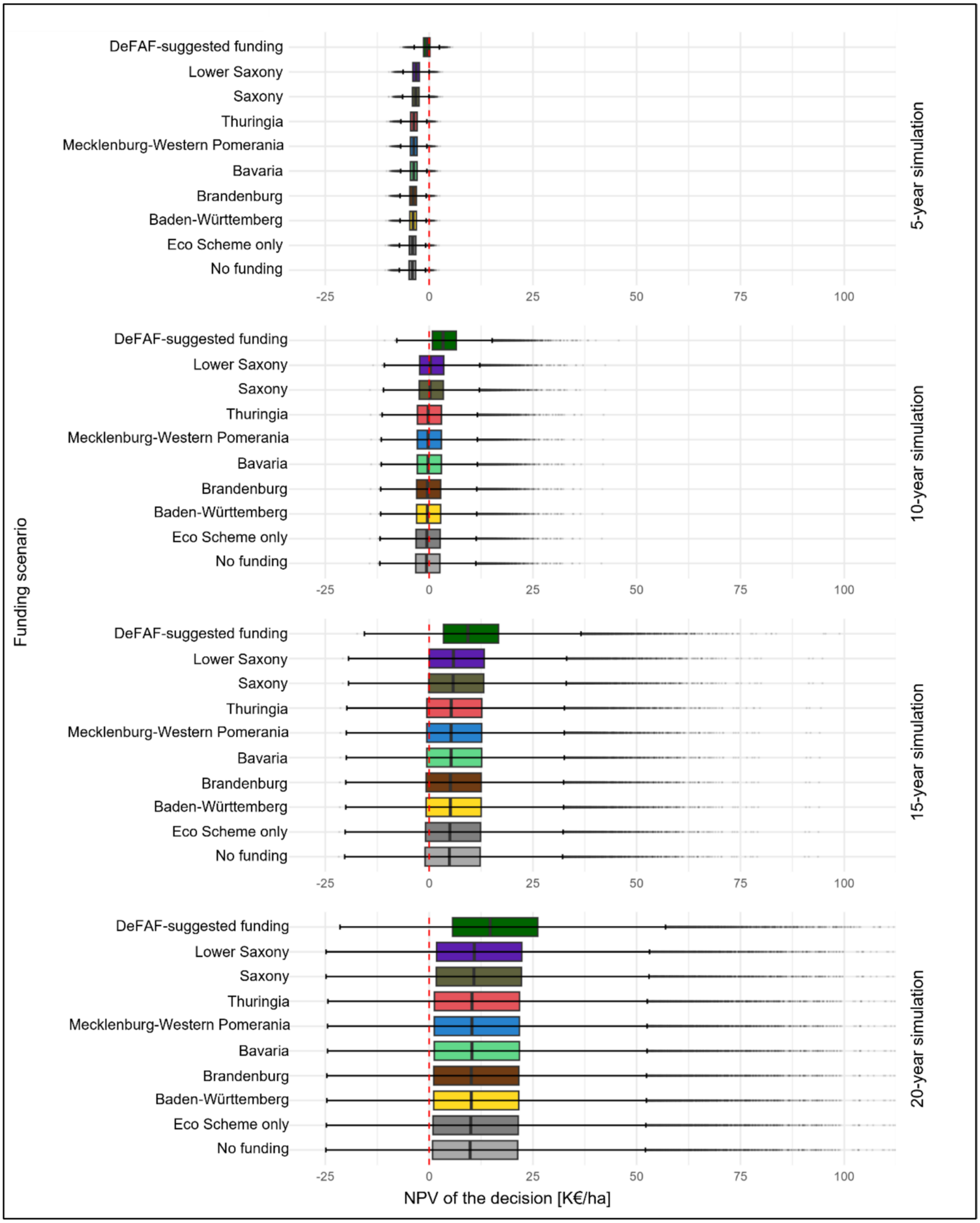
Building upon the conceptual model, MC simulations were conducted to generate probabilistic estimates of the NPV of adopting the AF system for 10 different funding scenarios across 4 simulation lengths of 5 years, 10 years, 15 years and 20 years (Fig. 5). The NPV of the decision was calculated by subtracting the net benefit (total benefit - total cost) of the baseline system from the net benefit of the AF system, for each individual run of the MC simulation. Positive NPV values indicate that the AF system outperforms the baseline system over the simulation length. As in many DA applications for complex agricultural systems, outcome distributions should be interpreted as decision-support metrics that describe plausible outcome ranges rather than predictions of future economic performance.

For the 5-year simulation, the NPV distributions across all funding scenarios were predominantly negative (Fig. 5). The distribution representing the scenario with no funding at all contains 99.90% negative values, compared to DeFAF-suggested funding, which has 69.69% negative values. Notably, the value ranges (excluding the outliers) consistently spanned ~ 6.3 k€/ha across all funding scenarios, suggesting no effect of funding on the certainty of the outcome of the intervention.

Comparing the different simulation lengths revealed critical insights. As the simulation length increased, the share of simulation outcomes with positive NPV values grew substantially. For the 10-year simulation, the proportion of negative values ranged from approximately 55.89% (no funding) to 17.99% (DeFAF-proposed scheme). Considering the same funding scenarios in the 15-year simulation, the proportion of negative outcomes decreased to 28.94–11.60%. For the 20-year simulation, this proportion further decreased to 22.66–11.01%. The range of the NPV distributions widens significantly with longer simulation periods. Compared to the 5-year simulation, the distributions were ~ 12.96 times wider for the 20-year simulation, spanning ~ 81.65 K€/ha, which indicates increased uncertainty about long-term outcomes.

Payback period

To gain insight into the timeline for recovering the initial economic disadvantage of adopting AF relative to the baseline, we calculated the payback period of the decision across the 10 funding scenarios (Table 1). The majority of scenarios (7 out of 10) are characterized by a median payback period of 11 years. Shorter median payback periods were computed for the scenarios based on the Lower Saxony funding (10 years), the Saxony funding (10 years) and the DeFAF-suggested funding (7 years). Examining the distributions further reveals that the 90% CI of the payback periods' distributions does not vary across existing funding scenarios. Except for the scenario with DeFAF-suggested funding, farmers must expect payback periods of 7 to > 20 years. The 50% CI of the payback periods' distributions behaves similarly, although not identically, across scenarios. While 5 out of 10 scenarios are characterized by payback periods of 9 to 17 years in 50% of cases, scenarios based on No funding, Only ES, Saxony, Lower Saxony and DeFAF-suggested funding show payback periods of 9 to 18, 9 to 18, 8 to 16, 8 to 16 and 1 to 9 years, respectively. It should be noted that the extreme values reflected in the 5th percentile (incremental payback periods > 20 years) are likely produced by the simultaneous occurrence of the most unfavourable input variable values in the MC simulation. The



median value as well as the 50% CI of the CCF distribution (Table 1) offer a more robust representation of typical expected outcomes.

◂**Fig. 5** Probabilistic impact of targeted subsidies on the NPV of the binary decision whether to implement a silvoarable AF system. The distributions show the difference between the NPV of the baseline system and the NPV of the AF intervention i.e., the NPV of the decision. The distributions are generated via Monte Carlo simulation with 100,000 simulation runs. Illustrated are the results for ten funding scenarios (different colours) and four simulation lengths. For each simulation length, the boxplots are ordered based on the median value of the NPV distribution (top to bottom: highest to lowest median)

Key uncertainties and decision preference

The output distributions (Fig. 5) and the payback period (Table 1) inform about possible decision outcomes and their associated likelihoods of occurrence. However, these metrics do not inform about key uncertainties associated with the input variables. The input variables that significantly influence the decision are assessed via VoI-analysis and are assigned an EVPI score.

The VoI-analysis for the 5-year simulation revealed minimal EVPI only for the input factor of maximum apple yield: 0.04 € for scenarios based on Lower Saxony and Saxony, and 4.15 € for the DeFAF-suggested funding. The low EVPI indicate a high certainty regarding the optimal decision. To illustrate how model outputs can inform decision-making, we define an example decision rule based on the share of simulated outcomes with positive incremental NPVs. In this illustrative case, we assume that a moderately risk-averse decision-maker may prefer adoption only when a clear majority of plausible outcomes indicates a favourable economic result. We therefore use a threshold of 70% positive NPVs as an example decision preference to demonstrate how decision-oriented interpretation of model outputs can be operationalised. This threshold is not intended as a normative criterion, but rather serves to illustrate how different assumptions regarding risk tolerance can be translated into decision recommendations. Alternative thresholds could be applied depending on the risk preferences of the decision-maker or policy objectives. Given the predominantly negative NPV distribution across scenarios (Fig. 5), a decision-maker prioritising economic outcomes over a 5-year time span should avoid implementing the AF system, regardless of the available funding.

For the 10-year simulation, the number of input variables with EVPI > 0 varied from 3 to 89, depending on the funding scenario. For the 'no funding' and 'Eco Scheme only' scenarios, 87 and 89 input variables showed EVPI > 0, respectively. The most significant input variables are the maximum apple yield, table apple price, apple harvest cost, the relative share of table apples in the total apple harvest and labour costs (Fig. 6). Their combined EVPIs are 29,997 € (no funding) and 28,244 € (Eco Scheme only). The existing German funding schemes reduce the number of decision-relevant variables. The number of input variables with EVPI > 0 drops to 41 in Baden-Württemberg, 40 in Brandenburg, 21 in Bavaria and Mecklenburg-Western Pomerania, 16 in Thuringia and 5 in Lower Saxony and Saxony. In the DeFAF-suggested scenario, 3 variables remain with EVPI > 0 – maximum apple yield, table apple price and apple harvest cost. The sum of the EVPIs of the 5 most significant input variables decreases to 25,336 € in Baden-Württemberg, 25,209 € in Brandenburg, 22,225 € in Bavaria and Mecklenburg-Western Pomerania, 21,845 € in Thuringia, 15,202 € in Saxony, 14,216 € in Lower Saxony and 1,142 € in the DeFAF-suggested scenario. The VoI-analysis revealed key uncertainties in all scenarios, indicating an overall low informative value of the decision model for a 10-year time frame. The combined analysis of the NPV distribution (Fig. 5) and the EVPI reveals that for 9 out of 10 scenarios, no clear recommendation can be drawn. The implementation of the AF system can only be recommended, when funding comparable to what is suggested by DeFAF is available. However, key uncertainties persist that should be addressed and minimised where possible.

The 15-year simulation revealed fewer significant variables. While for the DeFAF-suggested funding scenario the analysis revealed EVPI > 0 only for the maximum apple yield and the table apple price, all other scenarios also attribute information value to the costs incurred for harvesting apples. The total EVPI across scenarios shows values of 8,838 € (no funding), 8,527 € (Eco Scheme only), 8,186 € (Baden-Württemberg), 8,171 € (Brandenburg), 7,772 € (Bavaria and Mecklenburg-Western Pomerania), 7,719 € (Thuringia), 6,516 € (Saxony), 6,320 € (Lower Saxony) and 1,444 € (DeFAF-suggested funding). While the NPV distributions in Fig. 5 show predominantly positive values, the EVPIs remain high and indicate that key uncertainties must be addressed to reduce the inherent risk of the decision. However,

Table 1 Payback periods [years] of adopting AF relative to the baseline system across the 10 simulated funding scenarios, based on probabilistically computed cumulative cash flow (CCF) of the decision. The payback period is defined as the number of years it takes for the CCF to reach values ≥ 0

Scenarios	Payback period [years]		
	90% CI	50% CI	Median
DeFAF-suggested funding	1–> 20	1–9	7
Lower Saxony	7–> 20	8–16	10
Saxony	7–> 20	8–16	10
Thuringia	7–> 20	9–17	11
Meck.-Western Pomerania	7–> 20	9–17	11
Bavaria	7–> 20	9–17	11
Brandenburg	7–> 20	9–17	11
Baden-Württemberg	7–> 20	9–17	11
Eco Scheme only	7–> 20	9–18	11
No funding	7–> 20	9–18	11

considering a 15-year time span, the results suggest the AF intervention to be the preferable option across all funding scenarios, when applying our example decision rule described above.

At the 20-year simulation length, the scenarios with no funding, Eco Scheme only, Baden-Württemberg funding and Brandenburg funding found information value in 3 input factors: maximum apple yield, table apple price, and apple harvest cost. All other funding scenarios showed only the maximum apple yield and the table apple price to be significant. The total EVPIs across scenarios show values of 8,399 € (no funding), 8,141 € (Eco Scheme only), 7,894 € (Baden-Württemberg), 7,883 € (Brandenburg), 7,596 € (Bavaria and Mecklenburg-Western Pomerania), 7,556 € (Thuringia), 6,678 € (Saxony), 6,525 € (Lower Saxony) and 2,107 € (DeFAF-suggested funding). Similar to the results for the 15-year simulation, the EVPIs suggest the potential for further reduction in overall uncertainty of the decision to adopt AF. However, across all scenarios, the AF intervention is the preferable decision option.

The consistent gradient in the EVPI across funding scenarios for each simulation length – where no funding results in the highest EVPI scores while the DeFAF-suggested funding results in the lowest EVPI scores – is identical with the gradient in NPV-distributions across funding scenarios. This arrangement reveals critical insights into how funding schemes might affect farmers' decision-making processes. As total funding and consequently NPV increases, the overall EVPI decreases, indicating that a farmer might find reduced value in obtaining perfect information about the input variables' true values. Lower overall EVPI scores suggest clearer guidance to decision-makers regarding the decision on whether to implement the AF system.

It is worth noting that EVPI scores reflect both the importance of input factors regarding the decision-guiding value of the corresponding NPV distribution and the uncertainty regarding the variables' true values. Since the NPV distributions across all funding scenarios are generated from the same MC simulation — using identical input variables with consistent input distributions — comparisons across funding scenarios are valid and provide evidence about how funding affects the decision-supporting value of the model output.

Discussion

The following contextualises our results within the framework of AF adoption and policy design. We highlight the implications of funding schemes on the financial viability of the AF system, identify and interpret key uncertainty factors that influence decision making, and emphasize the importance of considering various time frames when assessing AF investments.

Impact of funding schemes on the economic profitability of the modelled AF system

Examining the NPV distributions of the decision model across funding scenarios revealed that, while funding does affect the overall profitability of the examined AF system, the impact of existing funding schemes on the model output is small. Our results from a plot-level case study reveal a minuscule effect of the current funding schemes on the NPV distribution across all scenarios. Despite differences in total financial support offered by the federal states of Germany, it is interesting to note that the NPV distributions showed remarkably similar profiles.

Only the DeFAF-suggested funding scenario, which combines 100% investment support with an annual financial maintenance support that is 3 times the available rate in 2025, affected the plot-level profitability in a meaningful way. This scenario reduced the share of values < 0 by 48 to 69%, compared to the scenario with no funding, across the different simulation lengths. Additionally, the median payback period was reduced to just 7 years, compared to 10- or 11-year periods in other scenarios. This finding suggests that, in this specific case, the main barrier to AF adoption might not be long-term profitability, but the temporal mismatch between initial costs and delayed returns. Substantial investment and maintenance support is needed to make AF financially more attractive relative to the baseline system, particularly within shorter time frames, which may be most relevant to farmers' decision-making. Even when AF is economically viable over longer time horizons, extended payback periods relative to the baseline system may discourage adoption among farmers with liquidity constraints or shorter planning horizons. This finding aligns with model results from Abdul-Salam et al. (2022), who, using a *Real Options analysis* approach, found that only providing an upfront payment of 80% of investment cost increased the comparative advantage of AF sufficiently, so that a rational decision-maker would choose AF over the baseline. Currently existing funding schemes in Germany fail to sufficiently increase the chance of the AF system outperforming the baseline and to sufficiently reduce the payback period, suggesting they are not effectively targeting the key economic barrier to adoption. Current funding options might therefore be insufficient to generate meaningful progress towards national targets of significantly accelerated AF adoption.

Uncertainty factors

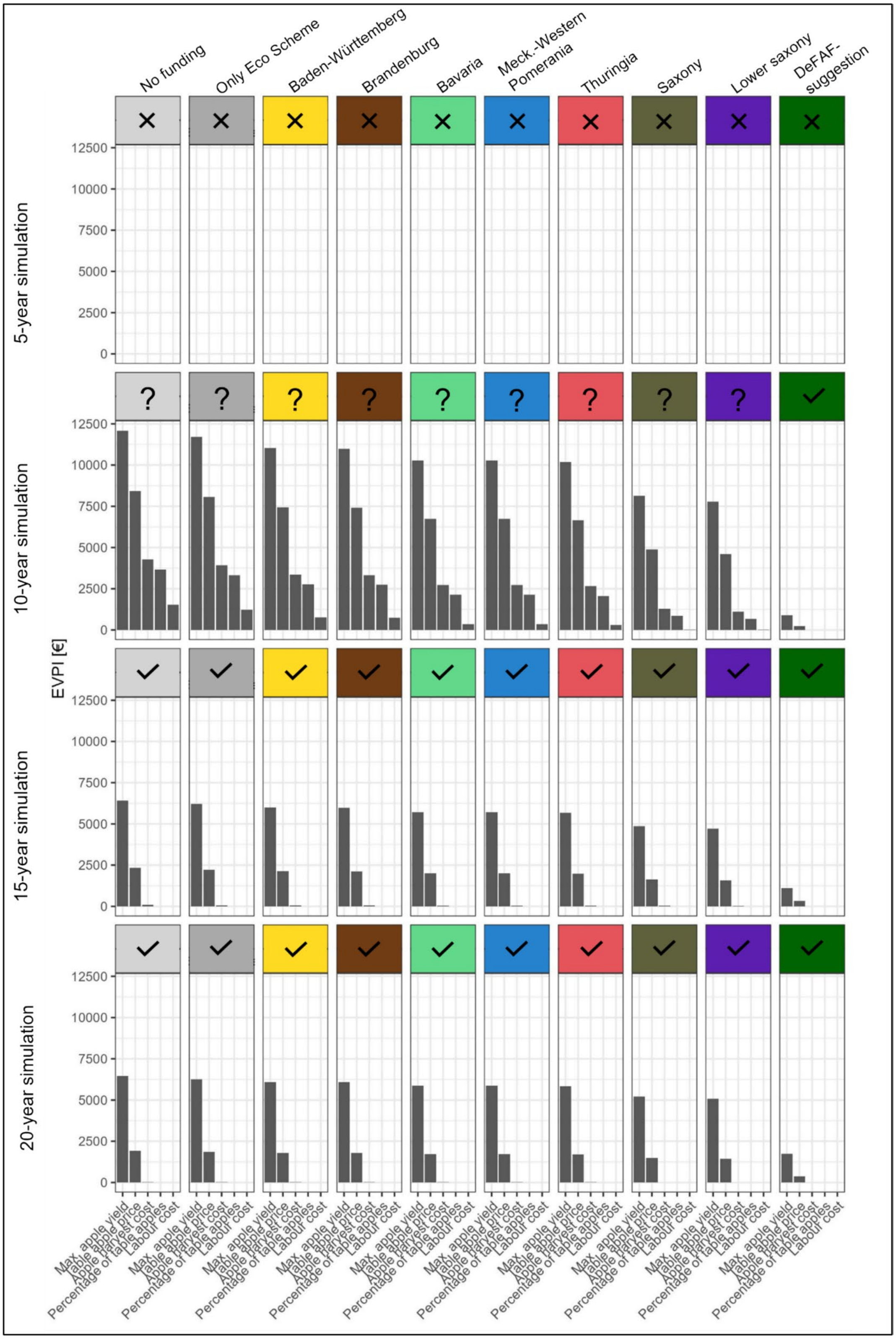
The VoI analysis identified and highlighted key uncertainties across funding scenarios as well as simulation lengths, with the maximum apple yield and the table apple price proving most critical. This result aligns with previous studies on the profitability of AF, pointing out the importance of a profitable tree crop to ensure competitiveness with standard arable cropping (Staton et al. 2022; Thiesmeier and Zander 2023; Thiesmeier 2024). Furthermore, our results indicate that an increase in overall funding levels reduces the EVPI. This reduction in the value of eliminating uncertainty about important input variables indicates that an increase in funding creates a clearer decision environment for farmers considering AF implementation. This is especially noticeable when considering intermediate time frames (10 years). Here, the model provides very limited decision support based on the NPV distributions, which is then highlighted by the high number of input variables with EVPI > 0. This result is particularly interesting when considering that the delayed economic return from tree crops is considered a major barrier to the adoption of AF systems (Tranchina et al. 2024).

Time horizon considerations in AF decision-making

Comparing NPV distributions as well as the EVPI, not only across several funding scenarios but also across multiple simulation lengths, reveals the critical importance of time horizons in AF decision-making. The proportion of negative NPV values decreased substantially as simulation length was extended — from predominantly negative outcomes in 5-year projections to significantly more favourable distributions in 20-year scenarios across all funding approaches. This temporal pattern reflects the inherent characteristics of tree-based agricultural systems, where initial investments and establishment periods precede revenue generation periods.

The widening NPV distribution with time (approximately 12.96 times wider in 20-year vs. 5-year simulations) indicates increasing uncertainty about long-term outcomes. This uncertainty creates a fundamental tension in the decision-making process: longer time frames improve the expected economic performance of the AF system but introduce greater uncertainty in potential outcomes. However, two types of uncertainty have to be distinguished: the uncertainty regarding the actual economic outcome of the AF intervention and the uncertainty about the comparative advantage of the AF system. A wide NPV distribution indicates an increase in uncertainty about the actual economic outcome of the AF intervention. Nonetheless, an increased proportion of positive values in the output distribution indicates higher certainty that the AF system will outperform the baseline system. The latter may be considered as harbouring a greater informative value in a decision-making context (Fig. 5).

Examining the changes in EVPI over time alone does not prove helpful in determining the optimal decision path. These insights must be integrated with


No funding
Only Eco Scheme
Baden-Württemberg
Brandenburg
Bavaria
Meck.-Western Pomerania
Thuringia
Saxony
Lower saxony
DeFAF-suggestion
5-year simulation
10-year simulation
15-year simulation
20-year simulation
EVPI [€]
0
2500
5000
7500
10000
12500
Max. apple yield
Table apple price
Apple harvest cost
Percentage of table apples
Labour cost

◂**Fig. 6** Expected value of perfect information (EVPI) scores, generated for all 10 decision scenarios across simulation lengths of 5, 10, 15 and 20 years. The plot shows only the input variables with the 5 greatest EVPI values in the 10-year simulation as some of these variables also ranked highest for 15 and 20-year simulations. The symbols within the coloured boxes indicate the decision recommendation, based on the current state of knowledge. The cross signals that the farmer should not choose the AF intervention, the tick mark signals that the farmer should choose the intervention, the question marks indicate no recommendation can directly be made based on the modelled outcome distributions. For illustration, we apply an example decision rule assuming adoption when at least 70% of simulated outcomes show positive incremental NPVs. This threshold is used solely to demonstrate how model outputs can be translated into decision recommendations

the examination of the NPV outputs from the decision model. A low overall EVPI merely indicates decision clarity, not necessarily preference for AF implementation or the maintenance of conventional management. This is evident in the 5-year simulation results, where minimal EVPI coupled with predominantly negative NPV distributions highlight the comparative advantage of maintaining the baseline system. In contrast, the 10-year simulation reveals a highly ambiguous decision, with NPV distributions showing similar shares of positive and negative values across most funding scenarios. The corresponding high numbers of input variables with EVPI > 0 and the high total EVPI emphasize this uncertainty. For longer time horizons (15 and 20 years), comparably lower overall EVPI and fewer variables with EVPI > 0 indicate reduced decision uncertainty. When these indicators are examined in combination with the NPV distributions, they collectively demonstrate that AF system implementation becomes the preferable option over extended time frames.

Implications for policy design

Our findings have substantial implications for policy design. By improving key metrics in the decision-making process, such as the NPV of the decision, the payback period and the EVPI, well-designed funding schemes have the potential to lower the ambiguity around AF decisions and make AF-implementation the favourable choice. However, especially when considering shorter time frames, it becomes obvious that even the examined schemes that provide relatively high investment support are unable to adequately increase the comparative advantage of AF compared to conventional arable cropping. These short to intermediate time horizons of 5 to 10 years might however be especially important to a farmer's decision-making. It therefore seems advisable to use the framework of this study for a decision-oriented ex-ante analysis, taking into consideration suggestions from AF-stakeholders, when designing future AF-support schemes aimed at facilitating the meeting of ambitious national targets. Considering not only the investment cost but also the initial establishment phase of AF systems, where high labour requirements meet low returns from the tree crop, seems particularly crucial. If funding levels are sufficient, farmers can make AF adoption decisions with greater confidence despite inherent uncertainties in agricultural production and market conditions. In practical terms, this means that comprehensive funding approaches such as the DeFAF-suggested scenario can improve expected returns and reduce the risk faced by farmers willing to adopt AF practices.

The emergence of apple yield as a significant input factor across all funding scenarios and simulation lengths reveals the importance of a profitable tree crop complementing arable production in an alley cropping system. It simultaneously shows the need for further research regarding apple yields that are to be expected from low-input cultivation systems such as the one modelled in this study. As table apple prices emerge as another significant input factor across all scenarios and timelines, it becomes evident that the profitability of AF systems depends also on marketing strategies and access to premium markets. Premium pricing may be achieved by developing favourable market mechanisms like a designated AF labelling scheme. The significance of the apple harvest cost across multiple scenarios and time frames suggests that suitable machinery might be needed to give apple AF systems a comparative advantage. These findings suggest that AF-supporting approaches complementing government funding, such as premium pricing of AF products, could enhance the effectiveness of direct financial support mechanisms.

Methodological contributions and limitations

This study showcases a methodological framework for evaluating agricultural policy support mechanisms by integrating probabilistic modelling with

VoI analysis using a decision analysis approach. This approach provides quantitative insights into both economic outcomes and decision-relevant uncertainties, offering a comprehensive basis for evaluating the impact of targeted funding on the plot-level profitability of agricultural interventions. The methodology explicitly acknowledges that agricultural decision-making happens under high levels of uncertainty and identifies which uncertainties most significantly affect decision-making under various funding scenarios for the modelled AF system.

We acknowledge that our study has inherent limitations. Most importantly, our analysis is constrained to a single case study intended to demonstrate the methodological approach. Consequently, our results should not be generalised far beyond this specific context. For example, cost structures associated with storage, processing, packaging or marketing infrastructure may vary depending on scale or marketing strategy. In the present case study, such investments were not required according to information obtained from the reference farm. However, these costs may become relevant in other AF systems. Further evidence on how funding schemes affect the overall profitability and comparative advantage of various types and combinations of AF systems should therefore be generated in future research. We suggest applying the methodological approach presented in this study to further representative AF systems in terms of crop combinations, rotation lengths, marketing strategies and management approaches.

Second, our analysis was limited to plot-level economic performance. While this provides crucial insights into the relative advantage of AF compared to the baseline system, it does not capture farm-level interactions, which may significantly influence a farmer's decision whether to adopt AF. Positive and negative interactions between plots, along with other farm management metrics such as periodic workloads and the availability of labour or machinery, might be essential considerations in a farmer's decision-making process when contemplating changes in the farming operation. Furthermore, we did not include disadvantageous effects of AF establishment, which are difficult to quantify in monetary terms, like the negative impact of tree planting on the short-term flexibility in farm management adaptation, once the decision for AF is made (Abdul-Salam et al. 2022). Lastly, we assumed the farmer to be an objective decision-maker and did not explicitly account for, e.g., strong heterogeneities in time preferences between different farmers when quantifying the discount rate as a key input factor to our model. We recommend that these and other such factors should be considered in future research.

Conclusion

Our study demonstrates the value of combining probabilistic modelling with decision analysis to support evidence-based design of direct funding instruments intended to steer agricultural land-use decisions towards societally desired outcomes. Although our analysis is limited to one case study, we provide meaningful insights into the probable effects of various existing and hypothetical funding schemes on the plot-level economics of an existing silvoarable AF system in Germany.

National and regional policies aiming to support widespread AF adoption must address temporal dynamics explored in this study, particularly by providing targeted support during the critical establishment phase. Our analysis indicates that the economic viability in the first 5 to 10 years after AF establishment is crucial and therefore requires financial support. Only then can land-use transformation processes, characterized by long payback periods, be initiated.

A comprehensive support strategy should combine one-time investment support and enhanced maintenance support during establishment with mechanisms to secure premium pricing, e.g., through specialised markets or labelling schemes. Integrated support is vital to ensure the short- to long-term viability of fruit-based AF systems similar to the one modelled in this study.

Supplementary materials.

The scripts containing the AF decision model, the code for the visualisation of the results and the input data file are available in a public repository: https://github.com/SimonSwatek/AF_Adoption_in_Germany.

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Author Contribution S.S. designed the study, collected data, wrote the scripts and wrote the manuscript; P.K.A. wrote the scripts and wrote the manuscript; E.L. critically reviewed the manuscript and provided comments on the contents and structure of the paper. All authors reviewed the final manuscript before submission.

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Data Availability The scripts containing the AF decision model, the code for the visualisation of the results and the input data file are available in a public repository: https://github.com/SimonSwatek/AF_Adoption_in_Germany.

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Competing Interests The authors declare no competing interests.

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