



Experts expect European agroforestry systems to stabilize crop yields under climate change

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Received: 11 February 2025 / Accepted: 26 May 2026
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Abstract

Climate change is having an impact on European agricultural systems and will increasingly do so into the future. Agroforestry, the integration of trees or shrubs in agricultural production systems, has been repeatedly described as a productive, sustainable, and resilient approach to food production. Quantifying agricultural benefits of agroforestry in the context of resilience to current and future climate change in Europe is challenging. To fill this knowledge gap, we gathered the assessments of 60 experts on the resilience of different forms of agroforestry (silvoarable, silvopastoral, and systems with hedgerows, riparian buffer strips, and windbreaks) in diverse European regions to various climate change variables. Across all regions and independently of the agroforestry system type, agroforestry systems were observed to show stable yields (0% change in yield compared to −8% in non-agroforestry systems). Experts expected yields in non-agroforestry to decline by 20% until 2050, while agroforestry systems were expected to maintain stable yields (0% change). This gap was highest in Central and Eastern Europe. In north-western and northern Europe, small yield increases were expected in agroforestry systems. Silvopastoral, silvoarable, and systems with hedgerows, riparian buffer strips, and windbreaks were similar in terms of observed and expected yield changes. The quality of saleable agricultural products until 2050 was estimated to be reduced in non-agroforestry systems, particularly in arable and hedgeless systems. Heavy precipitation events, prolonged drought, late frost, summer heat waves, and hail were the main threats by climate change–related threats listed by experts. Our online expert study is a novel approach to quantify agricultural benefits and emphasizes a general resilience of agroforestry systems to climate change impacts, regardless of the exact system type and climate region.

Keywords Agroforestry · Silvoarable · Silvopastoral · Hedgerows · Europe · Climate resilience

1 Introduction

Agriculture is the most vulnerable economic sector to climate change due to its strong dependency on weather parameters (Adams et al. 1998; Malhi et al. 2021). The Intergovernmental Panel on Climate Change (IPCC) foresees that warming in Europe will continue to rise faster than the global mean, widening risk disparities across Europe in the twenty-first century (Bednar-Friedl et al. 2023). Predicted reductions in yield related to climate change range from marginal decreases to drastic yield losses (Bibi and Rahman 2023; Malhi et al. 2021). Rising temperatures, varying precipitation patterns, and increased frequency of

extreme weather events such as heat waves, droughts, or floods directly affect plant and animal physiology in terms of respiration and transpiration rates; indirect effects include higher pest infestations, shifts in weed flora, and soil microbial communities and activities (Anderson et al. 2020; Malhi et al. 2021). On the other hand, yield increases are possible in some regions (especially in low latitudes) and for certain crops and management practices (Schlenker and Roberts 2009; Malhi et al. 2021).

The development of future agricultural systems in the face of climate change incorporates the aspect of resilience to maintain food security (Azadi et al. 2021). Agroforestry systems, i.e., the combined cultivation of woody elements and crops and/or livestock, are seen as a promising agricultural practice for maintaining productivity while being more resilient (Fig. 1) (Smith et al. 2013). They have repeatedly been cited in the scientific literature as a promising approach to agriculture that is both productive and resilient (Ong et al.

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Fig. 1 Agroforestry systems are diverse and observed to be more resilient than other agricultural production systems. Photo credit: left, Christina den Hond-Vaccaro; middle and right, AGROMIX project (Susanne Schnabel, Frank Wagener)

2015; Sollen-Norrlin et al. 2020). Due to the positive effects of trees and other woody elements on microclimate and soil properties, agroforestry systems are generally considered to be more resilient to weather extremes (Burgess et al. 2022). However, the quantification of resilience to climate change in agroforestry systems is even more challenging than in simpler agricultural systems with only a few annual crop species.

The resilience of a farming system can be defined as “its ability to ensure the provision of the system functions in the face of increasingly complex and accumulating economic, social, environmental and institutional shocks and stresses, through capacities of robustness, adaptability and transformability” (Meuwissen et al. 2019). Robustness is the capacity of the farming system to withstand stresses and shocks, while adaptability is the capacity to change the composition of inputs, production, and marketing in response to such stresses—without changing the structure of the system. Transformability, on the other hand, is the capacity to significantly change the internal structure of the system. Enhanced resilience of agricultural systems to climate change can be thought of as (i) a reduced exposure to climate variations, (ii) a reduced sensitivity to climate variability, and (iii) an increased adaptive capacity (Palma et al. (2024).

Compiling and quantifying the agricultural benefits of agroforestry in the context of resilience to current and future climate change is a challenge (Schievano et al. 2025). However, interviewing European agroforestry experts with in-depth knowledge and many years of experience makes it possible to gain an overview of the different perceptions and impacts of agroforestry systems. The objective of this online expert survey was to gather, firstly, the assessments of experts of the resilience of different forms of agroforestry in diverse European regions to various climate change variables and, secondly, to collect experts’ expertise for developing new approaches to improve resilience to climate change in European agroforestry.

The approach of evaluating the effects of certain climate variables (such as prolonged drought, temperature rise) on various agroforestry systems in comparison to

non-agroforestry systems and expressing assessments quantitatively is novel. The results of this expert survey can enhance the ongoing discussion at the European level on land use options that meet both food security and climate protection goals by providing a solid basis of quantitatively collected expert opinion. For many policy issues relating to food security, soil health, biodiversity, and the United Nations SDGs, there are (as yet) no results from experimental field research at the European level, while other issues relating to future projections could remain unanswered by field experiments or modeling. Gathering collective expert knowledge on different systems, from theory and practice, should help to make forward-looking assumptions, point the way for further research, and provide political decision-makers with a basis for decision-making today.

2 Materials and methods

An online survey was conducted between May and July 2023 to gain an overview of the different perceptions and impacts of agroforestry systems in the context of resilience to climate change. The online questionnaire was conducted via the platform SurveyHero (enuvo GmbH). A database of experts was compiled from the list of recipients of the newsletter of the European Agroforestry Federation (EURAF), members of agroforestry-related research projects such as the Horizon 2020 project AGROMIX and national European agroforestry networks such as the German Association on Agroforestry (DeFAF), the French Agroforestry Association Agroforesterie, and the UK Farm Woodland Forum. Experts were invited by email to participate, and answers were collected anonymously. The survey involved questions where numbers (percentages) had to be given as well as ratings on an ordinal scale, rankings, and open questions. Opening with five background questions on work sector, work experience, field of expertise, climate zone, and agroforestry system type, the questionnaire comprised 18 content-related questions to climate change impacts on yield, yield variability,

and quality of saleable products as well as the effects of environmental services and proposals for climate change resilience enhancement of agroforestry systems compared to non-agroforestry systems (Fig. 2). Three types of agroforestry system were distinguished: silvoarable, silvopastoral, and systems with hedgerows, riparian buffer strips, and windbreaks (“hedgerow systems” for short). Their woodless reference systems were arable, pastoral, and hedgeless agricultural systems, respectively.

Preliminary information on expected climatic changes in general and specifically for each climate zone (northern Europe, north-western Europe, central and eastern Europe, Mediterranean region) was given based on the State of the Environment Report (SOER) of the European Environment Agency (EEA) (EEA 2015). Due to low expert numbers from northern and north-western Europe, these two climate zones were pooled into one (northern and north-western Europe). If there were less than three experts per agricultural system within a climate zone, the data was excluded. The impact of nine climate change variables was queried on a 5-level Likert scale from −2 (severe reduction) to +2 (big increase) for climate change in general, temperature rise, summer heat waves, prolonged drought, heavy precipitation events, prolonged vegetation season, hail, fire, and late frost—in each case in the present (as current observation) and in the future (as expectation until 2050). The terms “severe reduction,” “minor reduction,” “small increase,” and “big increase” were not defined in detail, as they served to rank responses on a Likert scale. The full questionnaire can be found in the Supplementary Information (SI).

Data analysis was carried out with R version 4.3.2 (2023-10-31, R Core Team (2024)). The data were tested for normality of distribution and homogeneity of variance by the Shapiro-Wilk and Fligner-Killeen test, respectively. The non-parametric Wilcoxon test and Kruskal-Wallis test with Dunn’s post-hoc test were used for statistical analyses. Due to their robustness to outliers, fitness to non-normal distributions, and applicability with ordinal data, median values were used instead of arithmetic means. Figures were created with the ggplot2-package (Wickham 2016) and the sjPlot-package (Lüdtke 2024), respectively. Given the large amount of data, not all parts of the expert questionnaire can be shown in a single article; thus, a selection of the most important results is being presented. Additional material (full questionnaire, additional figures, and tables) can be found in the SI.

3 Results and discussion

3.1 Background of experts and limitations of the study

From 613 people viewing the online survey, 161 participants started and 60 completed it. Of those 60, 55% were self-declared experts for silvoarable agroforestry systems, 27% for silvopastoral agroforestry systems, and 18% for systems with hedgerows, riparian buffer strips, and windbreaks (SI Fig. 1). With respect to climate zone, 50% of the participants were self-declared experts for central and eastern Europe,

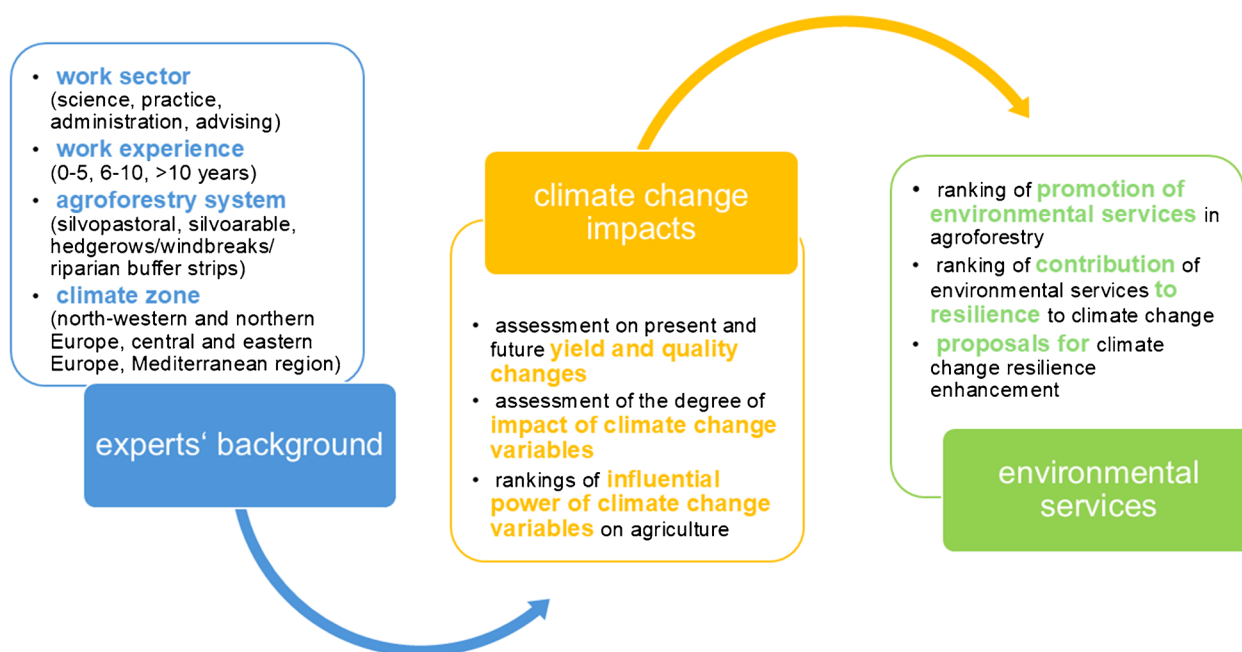


Fig. 2 Schematic representation of the three stages of the expert survey

23% for the Mediterranean region, and 13% for north-western and northern Europe (SI Fig. 1).

The professional background of the survey participants was science, practice, administration, and advising (SI Fig. 2). With respect to the field of expertise (plant production (crops, trees, hedges), livestock, climate, or other), the majority of participants were experts for plants (40% exclusively, 43% in combination with other fields of expertise); most (63%) of the participants had more than 10 years of work experience in their field, 25% up to 5 years and 12% between 6 and 10 years.

In general, there is still comparatively little knowledge about agroforestry. Modern agroforestry systems are sparse and young, which often hinders the conduction of scientific field studies (Luedeling et al. 2016; Sollen-Norrlin et al. 2020). It is therefore different to evaluate, if experts have realistic expectations on the capacity of agroforestry systems to increase climate resilience in the future. The relatively high variability of the ratings and rankings (SI Fig. 3) mirrors this uncertainty.

Survey participants voiced the difficulty to answer the questions in the questionnaire “in such a general type. Climate change affects different plants in a different way (for example fruits and vegetables compared with maize or winter cereals).” Effects of climate are thought to be “very crop- and system-specific, so difficult to generalize.” We acknowledge this, yet there is a gap in comparative studies in agroforestry (Torralba et al. 2016), arguing for studies attempting to close this gap.

The authors of this study acknowledge a possible inherent bias due to the fact that the survey design only allowed agroforestry experts to participate in the study (so that a comparison between agroforestry and non-agroforestry systems could be made per participant and thus per sample). We can critically question and assume that experts have tended to overestimate the magnitude of the benefits of agroforestry systems (Maas et al. 2021). Furthermore, it should be viewed critically that, particularly when analyzing subgroups in more detail (e.g., per climate zone), the sample size was sometimes very small in statistical terms. The expert visions still need to be validated by combining future field trials and modeling.

3.2 Yield and quality of saleable products

3.2.1 Observed and expected climate change effects on yield

The change in yield (defined as the amount of total saleable products), averaged across all agroforestry systems and climate zones, was assessed as 0% in agroforestry systems for both current and expected future climate changes, while a yield loss of -8% ($p < 0.001$) was currently observed in the

corresponding non-wood agricultural systems and expected to be -20% in the future ($p < 0.001$) (Fig. 1). Hence, experts expect that the difference between agroforestry and non-agroforestry systems in terms of their resilience to climate change impacts will continue to increase. More specifically, experts assume that while non-agroforestry systems will experience greater yield losses, agroforestry systems can accommodate the changes.

Across all climate zones, agroforestry systems were presently observed to show 0% (silvoarable, silvopastoral) to -2% (hedegrows) change in yield due to climate change, while arable, pastoral, and hedgeless systems showed a yield decrease of -5% to -10% ($p < 0.001$) (Fig. 1). In the future, agroforestry systems were expected to show either a small decrease (-5% for silvopastoral systems), no change (0% for silvoarable systems) or a small increase ($+5\%$ for hedgerow systems), while all non-agroforestry reference systems were clearly negative (-12% (pastoral), -20% (arable), -30% (hedgeless)) ($p < 0.001$). Statistically, the difference between hedgerow systems and hedgeless systems was not significant for estimations until 2050 ($p = 0.4$), despite distinct differences in median value ($+5\%$ vs -30%) because of high dispersion and significant differences in the distribution of the two groups.

Yield reductions due to climate change were presently reported in most woodless reference systems in all climate zones and ranged, for the major part, from -5% to -10% , except of silvopastoral systems in north-western and northern Europe ($+1\%$). In agroforestry systems, observed changes in yield were zero or minor (-5% to $+3\%$). The differences between agroforestry and non-agroforestry systems within a climate zone were statistically significant for all systems with the exception of hedgerows/hedgeless systems in central and eastern Europe, silvoarable/arable systems in the Mediterranean region, and silvopastoral/pastoral systems in north-western and northern Europe.

By 2050, the difference between woodless reference and agroforestry systems was expected to be highest in central and eastern Europe, with an expected yield decrease of -20% to -30% in woodless systems compared to -7% to $+5\%$ in agroforestry systems. In north-western and northern Europe, yield was expected to be stable in silvoarable and pastoral systems and to increase in silvopastoral ($+12\%$) and hedgerow systems ($+8\%$) while in arable (-15%) and hedgeless (-30%) systems a decrease was expected. In the Mediterranean region, a yield reduction was expected for all agricultural systems (non-wood and agroforestry) except for silvoarable systems, where a slight increase was expected. Again, the differences between agroforestry and non-agroforestry within a climate zone were statistically significant for all systems with the exception of hedgerows/hedgeless systems in central and eastern Europe, silvoarable/arable systems in the Mediterranean region, and silvopastoral/

pastoral systems in north-western and northern Europe (where they were albeit close to significance, $p = 0.0524$).

On an ordinal scale, the majority of present observations of yield changes due to climate change as a whole were clearly negative for non-agroforestry systems (75%, 68%, and 73% of experts for pastoral, arable, and hedgeless systems, respectively), whereas in agroforestry systems, observations were more balanced (for details, see Fig. 3). Future expectations for climate change effects on yield in general were more negative for all systems, in particular for non-agroforestry systems (81%, 84%, and 73% for pastoral, arable, and hedge-free systems). For agroforestry systems, future yield effects in hedgerow systems were estimated to be more evenly distributed (55% negative, 46% positive) than silvoarable (53% negative, 30% positive) or silvopastoral (64% negative, 21% positive) agroforestry.

The most adverse climate change variable for both present and future yield reductions was identified as being prolonged drought, followed by summer heat waves and—for arable crops in particular—late frost and hailstorms (Fig. 4). The effects were much less pronounced in agroforestry systems, which indicates that experts already

observe less yield variability in agroforestry systems and that they expect them to also mitigate the increasing climate change effects in the future. On the other hand, the prolonged vegetation season was seen and expected to have beneficial effects on yield, for both non-agroforestry and agroforestry systems.

For the economic success of farming activities, not only the yield as such but also the quality of the products is relevant, as it affects the price at which they can be sold or (for pastoral systems) the fodder quality and in turn the productivity of the livestock. Under current climate change, the quality of saleable agricultural products was perceived to be minorly reduced (47%, 41%, 70%) or not affected (47%, 55%, 30%) for pastoral, arable, and hedgeless systems, respectively. For agroforestry systems, most observations were between no effect (80%, 57%, and 55% for silvopastoral, silvoarable, and hedgerow systems, respectively) and a small to big increase for hedgerow systems (45%).

Estimations for the quality of saleable products until 2050 showed a more pronounced difference between non-agroforestry and agroforestry systems. For arable and hedgeless systems, 100% of experts expected quality to be severely or

		present observation		expectation until 2050	
		non-agroforestry	agroforestry	non-agroforestry	agroforestry
all systems		-8 (-70, 100)	0 (-40, 100)	-20 (-90, 100)	0 (-50, 100)
(silvo)arable		-5 (-70, 60)	0 (-40, 50)	-20 (-90, 80)	0 (-50, 60)
(silvo)pastoral		-8 (-30, 100)	0 (-10, 100)	-12 (-50, 80)	-5 (-20, 100)
hedgerows/hedgeless		-10 (-30, 20)	-2 (-20, 10)	-30 (-50, 100)	5 (-50, 30)
per climate zone					
Central and eastern Europe	all systems	-10 (-30, 50)	0 (-30, 50)	-30 (-70, 100)	-5 (-50, 60)
	(silvo)arable	-10 (-30, 50)	0 (-30, 50)	-30 (-70, 60)	-7 (-50, 60)
	(silvo)pastoral	-5 (-30, 0)	0 (-10, 10)	-20 (-50, -10)	-5 (-5, 20)
	hedgerows/hedgeless	-5 (-30, 20)	-2 (-20, 10)	-20 (-50, 100)	5 (-50, 25)
Mediterranean region	all systems	-10 (-70, 60)	-2 (-40, 30)	-15 (-90, 80)	-10 (-50, 50)
	(silvo)arable	-5 (-70, 60)	2 (-40, 30)	-15 (-90, 80)	5 (-50, 40)
	(silvo)pastoral	-10 (-25, 40)	-5 (-10, 30)	-18 (-40, 80)	-10 (-20, 50)
	hedgerows/hedgeless	no data		no data	
North-western and northern Europe	all systems	0 (-25, 100)	1 (-10, 100)	-10 (-40, 75)	5 (-20, 100)
	(silvo)arable	-5 (-25, 30)	0 (-10, 20)	-15 (-40, 50)	0 (-20, 55)
	(silvo)pastoral	1 (-10, 100)	1 (0, 100)	1 (-30, 75)	12 (-7, 100)
	hedgerows/hedgeless	-10 (-20, 3)	3 (-5, 10)	-30 (-30, 8)	8 (-20, 30)

Fig. 3 Presently observed and by 2050 expected effects of climate change on yield in % of yield change (median values with minimum and maximum values in brackets) between non-agroforestry and agroforestry systems in general and between silvopastoral, silvoarable agroforestry and hedgerow systems and their respective non-agrofor-

estry reference systems (across all systems $n = 60$, (silvo)pastoral $n = 16$, (silvo)arable $n = 33$, hedgerows/hedgeless systems $n = 11$). Comparisons between non-agroforestry and agroforestry, present observation and expectation until 2050, and between climate zones are visualized in SI Fig. 3 in the SI

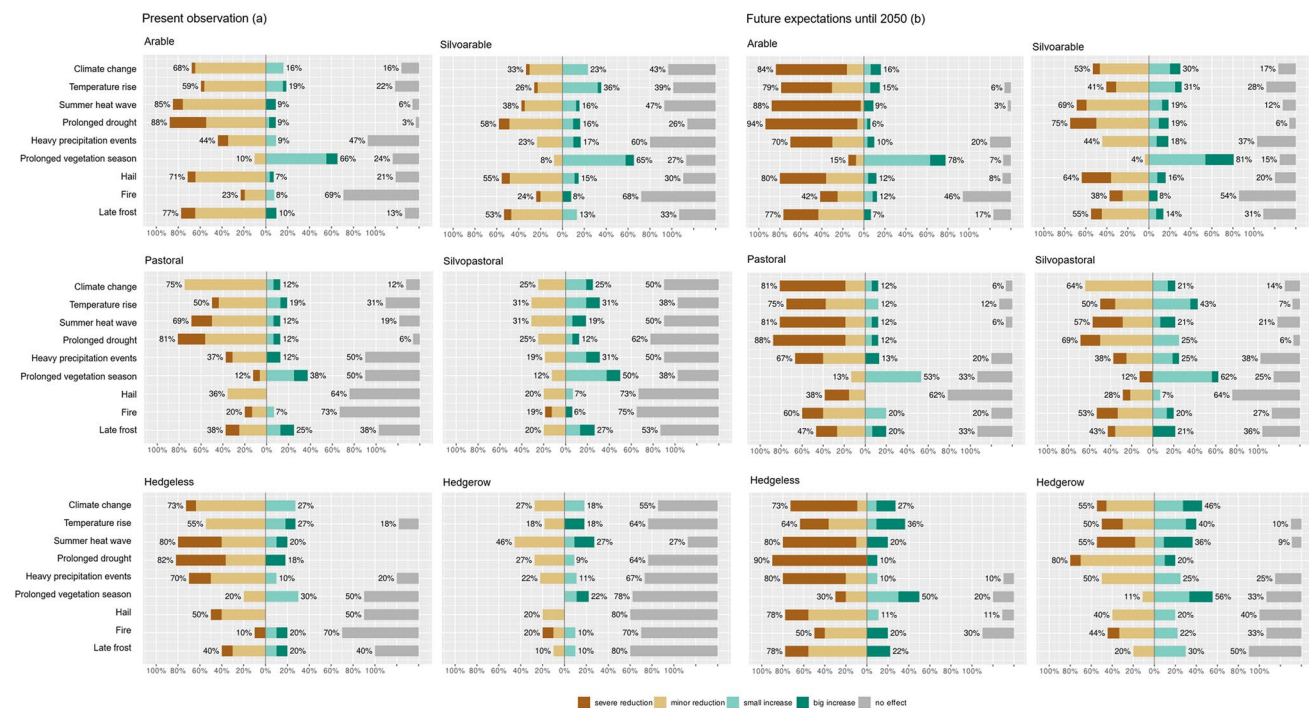


Fig. 4 Summary of experts' assessment of yield changes due to the impact of nine climate change variables on a five-level Likert scale from -2 (severe reduction) to +2 (big increase) for present observations in percent of responses. The non-agroforestry systems in the left-hand panels correspond to the respective agroforestry systems in

the right-hand panels, i.e., pastoral-silvopastoral, arable-silvoarable, and hedgeless systems-hedgerow systems for (a) current observations and (b) future expectations. The percentages at each bar represent the sum of both stacked bars. Observed and expected climate change impacts on quality of saleable products

minorly reduced, while only 48% and 55% thought so for silvoarable and hedgerow systems, respectively. In total, 26% (silvoarable) and 36% (hedgerow systems) expected small to big increases in quality. A summary of experts' assessment considering climate change in general and specific climate change variables is visualized in SI Fig. 4 and SI Fig. 5.

The climate variables that were expected to affect product quality are roughly the same as the ones identified for yield quantity. Most detrimental to quality were heavy precipitation events, prolonged drought, late frost, summer heat waves, and hail.

3.2.2 Considerations for (silvo)arable systems

Climatic conditions influence the growth and maturity of crops. Strong temperature variations, which are expected to increase in occurrence, are linked to changes in humidity levels, which promote, along wetter climate periods in some European regions, the appearance of plant diseases (IPCC 2021). Warmer temperatures and prolonged vegetation seasons are expected to enable certain pests to increase in numbers (Skendzic et al. 2021). The combination of these elements threatens quantitative yields as well as the quality of saleable products. Experts of this survey expect

that “agroforestry systems will gain advantages in the long run, as new beneficial insects are more likely to establish in sufficiently strong populations thanks to the higher diversity.” Yet, Tosh et al. (2024), based on a Boolean regulatory network parametrized with expert opinion, did not expect higher yield stability due to reduced biotic stress.

With respect to product quality, pest levels are expected to increase, so also the impact on crop quality with more pest-damaged crops. The negative impact on yield quality due to elevated CO₂ is discussed below (section “Climate Change Variables”); with respect to an increase in pests, an increase in pests and diseases was repeatedly mentioned in experts' comments of this survey and was also listed as “other variable” in the question about the most influential climate change variable in our questionnaire. This is in alignment with the state-of-the-art in scientific literature, for example, with respect to insects. Temperature is seen as the most important environmental factor affecting insect population dynamics. Global climate warming could trigger an expansion of their geographic range, increased overwintering survival, increased number of generations, increased risk of invasive insect species and insect-transmitted plant diseases, and changes in their interaction with host plants and natural enemies (Skendzic et al. 2021).

3.2.3 Considerations for (silvo)pastoral systems

Several experts voiced that “for animal products, welfare and free-range are very important and shade is absolutely necessary. [...] Heat stress is devastating for quality. With trees as ‘field pharmacy’, veterinary treatments and antibiotics can be phased out or minimised, this also improves quality [...]” Animal welfare was emphasized by many comments. Yield of grasslands is already being reduced due to drought events (Lei et al. 2020). Again, these effects could be buffered in silvopastoral systems through environmental services provided by agroforestry, such as soil erosion protection, temperature and humidity regulation, increased soil fertility, and enhancement of the hydrological cycle. Two statements explicitly addressed the applicability of silvopastoral systems: “Changing a treeless pasture to a wood pasture also wouldn’t be very difficult” and “agroforestry systems with poultry and fruit trees are certainly an easy and quick system to implement, the results of which can also be seen in the short term.”

A Swiss farmer pointed out that, in his/her opinion, climate change would not have a significant impact on the amount of animal products in Switzerland and that there would probably be no major increase or decrease since there are generally stables for all animals. They are not only kept on open pastures; hence, there are ways to protect the animals from hot temperatures. However, the farmer also acknowledged that this incurred costs.

3.2.4 Considerations for systems with(out) hedgerows, windbreaks, and riparian systems

Experts stated that “riparian buffer strips, windbreaks and hedgerows would be quite easy to establish” and that these systems “can also give results in the short to medium term, especially in terms of the associated increase in biodiversity that can promote pollination, pest and disease control.”

Our findings for agroforestry systems with hedgerows, windbreaks, and riparian buffer strips are statistically limited by the small sample size ($n=11$). They show an overall more pronounced difference between hedgeless and hedgerow systems compared to comparisons of arable and silvoarable and pastoral and silvopastoral systems, respectively.

3.3 Climate change variables

Experts were asked to rank the five most important climate change variables according to their power for agricultural production. Prolonged drought, fire, prolonged vegetation season, hail, and late frost were considered most influential (Table 1). Twenty-nine of experts ranked the climate change variables differently for agroforestry systems. They considered that for agroforestry, fire, hail, prolonged vegetation

season, late frost, and temperature rise are particularly relevant, whereas prolonged drought, being considered the most important climate change variable for agricultural production in general, was not among the top five of climate change variables for agroforestry (Calanca et al. 2022). This underlines an enhanced water-use efficiency in agroforestry, which has been widely reported, by an improved microclimate (i.e., by mitigating weather extremes) with a resulting lower water demand (lower evapotranspiration of the understory crop), enhanced soil quality (i.e., by high fresh organic matter inputs, high microbial diversity and activity, soil aggregate formation), leading to increased water storage (Rolo et al. 2023).

Some experts used the option “other variable” to specify not-listed climate change variables and named rainfall decrease/annual rainfall distribution, pests and diseases, storms/heavy winds, and CO₂ increase. The increase of the atmospheric CO₂ concentration was mentioned a few times in the comments. A researcher from the natural and economic/social sciences emphasized: “For future projections, it is crucial to account for the atmospheric CO₂ fertilization effect. If this is not included, future simulations are likely to show greater yield decrease compared to e.g., simulations that account for atmospheric CO₂. In other words, it has been shown that atmospheric CO₂ compensates for any e.g., yield reductions caused by temperature and rainfall change.” The crop response to CO₂-fertilization has been given a medium-to-high confidence by the IPCC (IPCC 2007), indicating yield increases in “unstressed” conditions. Long-term studies have confirmed this, showing that potential yield increase can be eliminated by nutrient and water limitation (Ainsworth and Long 2021; Reich et al. 2014). In addition, higher

Table 1 Ranking of climate change variables in order of importance for their influential power on agricultural production ($n=59$) and for agroforestry systems ($n=18$) in particular (1 = most influential). The sample size for agroforestry systems was smaller as only experts stating that they would rank these climate change variables differently for agroforestry systems were asked for a specific ranking. The scores represent the means of all given rankings.

Agricultural production in general		Specifically for agroforestry systems	
Climate change variable	Score	Climate change variable	Score
Prolonged drought	1.62	Fire	1.33
Fire	1.93	Hail	1.78
Prolonged vegetation season	2.20	Prolonged vegetation season	1.94
Hail	2.31	Late frost	2.39
Late frost	2.37	Temperature rise	2.44
Temperature rise	2.64	Prolonged drought	2.61
Heat waves	3.16	Heat waves	2.89
Heavy precipitation events	3.31	Heavy precipitation events	3.00

yields induced by elevated CO₂ levels may reduce crop quality, e.g., by lowering protein concentration by higher accumulation of photosynthetic assimilates of C and the decreased root N uptake associated with lower transpiration rate and mass flow (Wang and Liu 2021). An agronomist from northern Europe pointed out that “under enhanced CO₂ levels, in crops, an overall decrease in N and protein concentrations is expected, as well as overall decreases for most macronutrients and micronutrients, while increased temperatures (especially if coupled with drought stress) are often associated with production of smaller, more fibrous leaves, which usually exhibit changes in nutritional quality – for example, decreasing N and increasing tannins and phenols.”

Agricultural resilience to climate change impacts may occur through (i) a reduced exposure to climate variations (e.g., increasing soil organic matter content to reduce the risk of soil erosion from heavy rainfall), (ii) a reduced sensitivity to climate variability (e.g., using drought-resistant species and varieties) and (iii) an increased adaptive capacity (e.g., increasing the diversity of products) (Smith et al. 2023). Agroforestry systems address all three mechanisms. They reduce the exposure of crops, pasture, and livestock through an improved microclimate (reduced wind speed, light intensity, and surface runoff) (Jacobs et al. 2022). Woody plants evaporate a large amount of water through their foliage, which cools the temperature around these woody structures (Ellison et al. 2017) and can increase air humidity at the microclimatic level (den Hond-Vaccaro et al. 2025).

3.4 Approaches to improve resilience to climate change in agroforestry

Seventy percent of experts answered the question, to what extent environmental services could buffer the effects of climate change in Europe, with “much” or “very much.” On a 7-point scale from “less effective” (1) to “more effective” (7), 87% of experts rated agroforestry to be a more effective measure than other measures to improve climate resilience (5, 32%; 6, 35%; 7, 20%).

“System design” and “keyline design” were most often named in answers with respect to the question what biophysical measures could enhance climate change resilience in agroforestry systems, followed by “species choice.” Regarding system design, the importance of tree density and tree row orientation has become common knowledge (e.g., Dupraz et al. (2018); Dupraz et al. (2019)). Sensitivity to climate variability can also be reduced on agroforestry systems by planting adapted varieties of trees and/or crops or variety/crop mixtures. For example, an agronomist from the Mediterranean region expressed a need for “the identification and promotion of suitable tree species and varieties, e.g., looking to northern Africa for species suited to an arid environment.” Composite crop populations, representing a

high genetic pool, have a high potential for low-input, inhomogeneous conditions found in agroforestry, which has yet to be explored (den Hond-Vaccaro et al. 2023). A greater crop species/variety/crop population diversity also diversifies the land use on a given parcel and at the landscape scale.

A farmer from northern Europe explicitly stated: “We are hoping that the prolonged growing season will bring us new varieties of fruit and nuts, faster growth of trees and new grain varieties – maybe autumn sown. That might increase yields. On the other hand, if the weathers will not favor new, southern fruit varieties or winters are too harsh for new grains, we will have to wait years or decades to have proper cultivars that tolerate new conditions.”

4 Conclusion

Quantifying collective knowledge from scientists, advisors, and farmers on different agricultural systems provides a basis for discussion for policymakers and stakeholders. Stable yields are presently observed in European agroforestry systems by agroforestry experts, whereas yield losses of –8% are seen in their woodless reference systems. Experts expect differences between agroforestry and non-agroforestry systems to continue to diverge in terms of yield changes with woodless agricultural systems being expected to experience yield losses of, on average, –20% until 2050. In contrast, the corresponding agroforestry systems are expected to be able to accommodate the climatic changes. This general trend was visible for all agroforestry system types (silvoarable, silvopastoral, and systems with hedgerows, riparian buffer strips, and windbreaks) and was independent of climate region (Atlantic, continental, Mediterranean), but most pronounced in central and eastern Europe. With respect to quality of saleable agricultural products, in particular in arable and hedgeless systems, minor to severe reduction is expected until 2050. Our expert study underlines basic agreement between experts from various professional fields and work experience and emphasizes a general resilience of agroforestry systems to climate change impacts, regardless of the exact system type and climate region.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s13593-026-01119-5>.

Authors' contributions Draft and conception of the questionnaire: den Hond-Vaccaro C, Jarosch K, Kay S, Herzog F; conduction of the survey: den Hond-Vaccaro C; data analyses: den Hond-Vaccaro; drafting of the manuscript: den Hond-Vaccaro C with feedback from Jarosch K, Kay S, Li Y, and Herzog F. All authors read the final version of the manuscript and gave consent for its submission.

Funding Open access funding provided by Agroscope. The study has received funding by the European Union's Horizon 2020 research and innovation program under grant agreement 862993 (project AGROMIX).

Data availability The datasets are available from the corresponding author on reasonable request.

Code availability Custom code is available from the corresponding author on reasonable request.

Declarations

Ethics approval The ethical approval of the survey was provided by the ETH Zurich Ethics Commission (proposal EK-2023-N-113).

Consent to participate The consent of participation can be found in the questionnaire in the SI.

Consent for publication This study does not need publication consent.

Conflict of interest The authors declare no competing interests.

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