

Resilience of agroforestry practices to climate change in Europe: mechanisms, trade-offs and knowledge gaps

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Abstract

Agroforestry, the purposeful integration of woody vegetation and agriculture, is increasingly recognised as a nature-based solution to enhance the climate resilience of European farming systems. Despite growing policy support, robust comparative evidence on which practices deliver the greatest resilience across Europe's diverse climatic contexts remains lacking. To address this gap, we conducted three regional Delphi studies with 46 European agroforestry researchers covering Northern, Western & Central, and Southern Europe. There was strong consensus that all agroforestry practices offer greater resilience to climate impact drivers than cropping- or livestock-only baselines, with closed-canopy practices such as forest farming and forest grazing rated most resilient. Key resilience mechanisms are the protective functions of trees, interactions between components that improve tree, livestock, crop, or soil health, and higher agrobiodiversity that increases adaptive capacity. Consensus on resilience relative to tree-only baselines was limited, except in Southern Europe where agroforestry practices were recognised as reducing wildfire risk. Knowledge gaps remain around pest and disease dynamics, financial performance, and social resilience.

Keywords

Climate change resilience; European agroforestry; nature-based solutions; Delphi method; Vulnerability; Farmland trees

1. Introduction

Nature-based solutions for climate change adaptation of agricultural and forestry systems are increasingly embedded in European and international policy frameworks, including the European Union's (EU) Green Deal, Biodiversity Strategy for 2030, Forestry Strategy and the Farm to Fork Strategy^{1,2}. Agroforestry, including both the establishment of trees on farmland and the introduction of livestock and crops into forests, is put forward as a nature-based solution that can provide biophysical and socioeconomic benefits and increase system resilience against climate risk³. While its broad mitigation and adaptation potential is widely acknowledged⁴⁻⁶, comparative evidence on which specific practices deliver the greatest resilience across Europe's diverse agricultural and climatic contexts, and through what mechanisms, remains fragmented across disciplines, practices and regions³.

The predicted impacts of climate change on agriculture and forestry vary substantially across Europe, meaning that effective transition pathways towards more climate-resilient systems will necessarily differ by region. In southern and central Europe, forests are likely to be affected by drought, with consequences for tree growth, tree mortality, pest outbreaks and wildfire frequency⁷. Heat stress on livestock and crops, reduced water availability, and shifts in pest and disease occurrence are predicted across Europe, but most severely in the south^{8,9}. In addition, northern Europe is likely to experience increased flooding and windstorms, with associated impacts on forest¹⁰ and crop production, soil erosion and loss of grazing land⁸. There is therefore unlikely to be a single solution to increasing agroforestry resilience across the continent.

The IPCC AR6 report defines vulnerability in the context of climate change as “*the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*”¹¹. Agroforestry practices can reduce vulnerability and, therefore, increase resilience across the three components of the

vulnerability framework (Figure 1). First, they can reduce *exposure* to climate impact drivers: for example, tree canopies provide shade that directly moderates temperature extremes experienced by crops and livestock^{12,13}. Second, they can reduce the *sensitivity* of the farming system to those impacts: for example, trees improve soil structure and organic matter content, which increases water infiltration, reduces surface runoff, and consequently lowers flood risk¹⁴. Finally, by combining trees with crops and/or livestock, agroforestry systems are inherently more diverse than monoculture baselines, which increases *adaptive capacity* by broadening the range of management options available to farmers in response to changing conditions¹⁵.

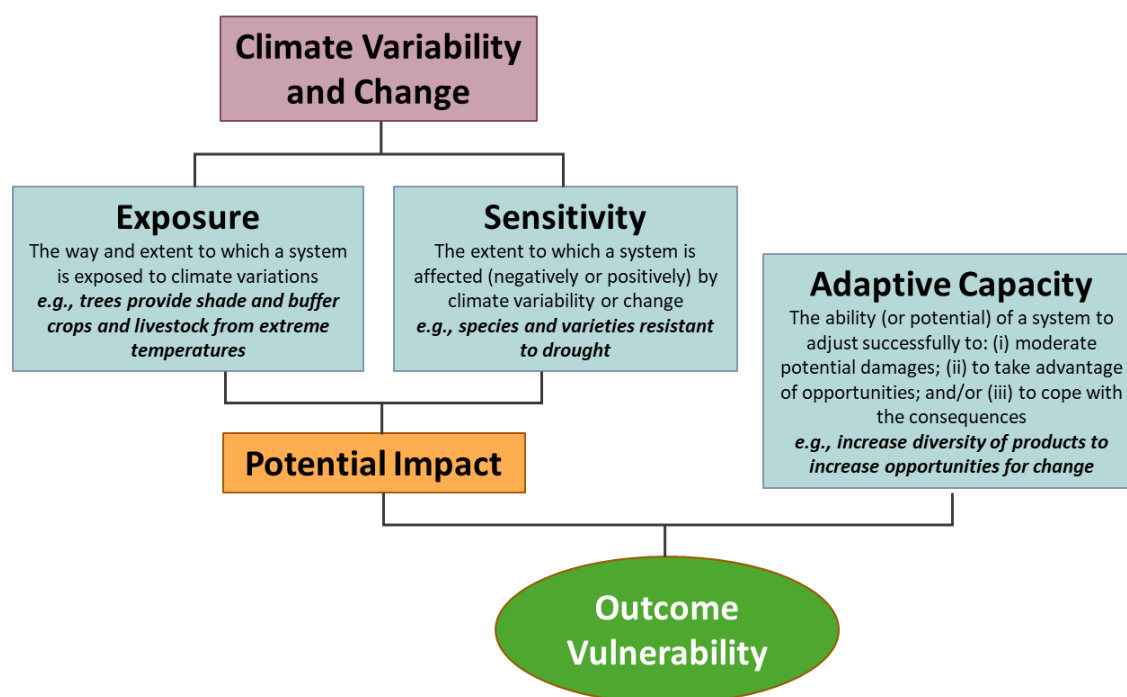


Figure 1. A vulnerability framework¹⁶ adapted to include mechanisms that may make agroforestry practices less vulnerable to climate change than agricultural, orchard or forestry monocultures.

The term ‘agroforestry’ encompasses a wide diversity of designs, components, and combinations^{17,18}. Agroforestry practices can be thought of as varying the balance among the three components: trees, livestock, and annual crops. Their diversity can also be expressed as a gradient of tree cover, ranging from closed canopies in forest farming and forest grazing systems, through lower levels of canopy cover in wood pastures and grazed or intercropped orchards, to alley cropping and boundary linear woody features such as hedgerows or riparian buffers where scant canopy cover is dominant (Table 1). This gradient of tree cover and integration is likely to have implications for climate change resilience, since practices with greater canopy cover and more diverse component interactions can be expected to deliver stronger reductions in exposure, sensitivity and adaptive capacity across a wider range of climate impact drivers^{3,19}. Conversely, practices with lower canopy cover and simpler component interactions, such as hedgerows and riparian buffers, may offer more targeted benefits, for example, reducing flood risk or providing localised shade, but associate with a narrower overall resilience profile.

145 Despite growing policy interest, farmer adoption of agroforestry remains limited, with agroforestry
146 covering between 6 and 9% of utilised agricultural area in Europe^{20,21}. Research on farmer perceptions
147 highlights concerns about management complexity, establishment costs and financial performance
148 relative to conventional alternatives^{22–24}. These barriers underline the importance of identifying not
149 only which practices are most resilient, but also which are most feasible for farmers to adopt. Although
150 the exposure-sensitivity-adaptive capacity framework provides a tractable basis for evaluating
151 agroforestry resilience, it has rarely been applied in a comparative manner across the diversity of
152 European practices and climatic regions. Existing evidence is largely biophysical, site-specific and
153 practice-specific, leaving unresolved which combinations of trees, crops and livestock offer the
154 greatest resilience under different climate projections, and why. This gap persists partly because the
155 inherent complexity and regional diversity of agroforestry systems make them poorly suited to
156 conventional biophysical modelling or standardised empirical measurement²⁵, and limits the ability of
157 policymakers and land managers to target agroforestry adoption where it will have the greatest
158 climate adaptation impact.

159 To address this gap, we undertook an iterative Delphi expert elicitation study with 46 European
160 agroforestry researchers, an approach uniquely suited to synthesising cross-disciplinary knowledge
161 into consensus-based assessments where empirical data are heterogeneous or limited²⁶. Three
162 separate Delphi processes were conducted to reflect the contrasting climate change projections for
163 Northern, Western and Central, and Southern Europe. This evidence base is needed to target policy
164 support towards the most impactful practices and to guide farmers and foresters in transitioning
165 towards more climate-resilient systems.

Table 1. Agroforestry practices considered in the Delphi study and their monoculture contrasts (livestock, annual cropping, orchards and forestry)

Agroforestry practice	Description	Illustration	Baseline comparisons			
						
Forest grazing	Livestock incorporated into woodland or forests		✓			✓
Forest farming	Cultivation of high-value crops under the protection of a managed tree canopy			✓		✓
Wood pasture	Livestock with scattered trees. The trees can be productive (e.g., fruit, timber, cork, fodder) or not.		✓			✓
Grazed orchards	Permanent woody crops (top fruit, nuts, vines, olives) with livestock		✓		✓	
Intercropped orchards	Permanent woody crops (top fruit, nuts, vines, olives) with temporary crops (arable, vegetables)			✓	✓	
Alley cropping	Within-field linear systems with temporary crops (arable, vegetables) grown in alleys between tree rows. The trees can be productive (e.g., fruit, timber, short rotation coppice) or not.			✓		
Alley systems with livestock	Within-field linear systems with pasture or forage grown in alleys between tree rows. The trees can be productive (e.g., fruit, timber, short rotation coppice, fodder) or not.		✓			
Agrosilvopastoral	Combination of trees, livestock and temporary crops (arable, vegetables) within the same system, usually on a rotation. The trees can be productive (e.g., fruit, timber, short rotation coppice, fodder) or not.		✓	✓		
Hedgerows, riparian buffers and shelterbelts(linear features)	Linear systems of shrubs and trees around field perimeters or adjacent to streams, rivers or wetlands. Trees can be productive (e.g., fruit, timber, short rotation coppice, fodder) or not.		✓	✓		

Results and discussion

Resilience of agroforestry practices relative to agricultural and livestock baselines

There was strong consensus that agroforestry practices offer higher resilience to climate impact drivers than annual cropping and livestock-only baselines (Table 2), consistent with the broader literature identifying agroforestry as a climate adaptation measure^{27,28}. Consensus of higher resilience was reached in 206 of 231 assessable combinations against these baselines. The single notable exception was the climate impact driver 'reduction in cold extremes', where consensus was not reached for most practices (20 of 33 combinations). This uncertainty reflects a genuine ambiguity: while trees can buffer crops and livestock against cold extremes²⁹, climate change is expected to reduce the frequency of cold extremes, diminishing the relevance of this mechanism. At the same time, several participants flagged the risk that reduced cold extremes may increase pest and disease pressure^{30,31}, and noted that agroforestry's role in supporting natural predators could help mitigate this risk, though currently insufficient evidence prevents consensus.

Practices with the highest canopy cover showed the strongest resilience effects. In Western & Central Europe and Southern Europe, forest grazing and forest farming were rated as having 'Much higher' resilience to extreme precipitation, drought and heat extremes. In Southern Europe, the same practices were rated 'Much higher' for heat extremes, drought and mean temperature changes, with agrosilvopastoral systems, the most structurally diverse practice assessed, also rated 'Much higher' for mean temperature and heat extremes. This pattern is consistent with evidence that denser canopies deliver stronger microclimate buffering, particularly under Mediterranean climates³² and with research showing that tree species richness and structural diversity enhance temperature buffering capacity³³. Weighted scores further confirmed this gradient, with forest farming, forest grazing and agrosilvopastoral practices scoring highest across multiple climate impact drivers (Table 3). These findings support the growing recognition that diversity and multifunctionality are central features of resilient farming systems³⁴, and suggest that the canopy cover gradient identified in Table 1 is a meaningful predictor of resilience potential.

Resilience of agroforestry practices relative to tree-only baselines

Consensus on resilience relative to tree-only baselines was substantially lower, with higher resilience agreed in only 11 of 105 combinations, while 12 combinations were rated as unknown and seven as equivalent to the baseline (Table 3). This reflects genuine uncertainty about the consequences of introducing crops or livestock into existing forestry or orchard systems; a transition that may reduce tree density, alter microclimate, or introduce competitive pressures that offset resilience benefits. The principal exception was Southern Europe, where consensus of higher resilience was reached for agroforestry practices compared with tree-only baselines under increasing drought, decreasing mean precipitation, and increasing heat extremes and mean temperatures. This aligns with empirical evidence from Southern European conifer plantations, where active density management via tree thinning has been shown to enhance growth and buffer tree sensitivity to both seasonal drought and thermal stress³⁵. Critically, managing understorey biomass through grazing or cropping was identified as a key mechanism for reducing wildfire risk, a key finding with direct policy relevance given the escalating fire risk across Mediterranean regions³⁶. This result is supported by field evidence from Mediterranean silvopastoral systems, where managed grazing has been shown to reduce understorey biomass and thereby lower fire risk^{37,38}.

Table 2. Participant consensus on the resilience of agroforestry practices to climate impact drivers, compared with annual cropping and livestock-only baseline systems. Weighted scores are shown to facilitate comparison between practices; cell colours indicate the consensus resilience level of the agroforestry practice relative to the baseline: dark green = 'Much higher'; light green = 'Higher'; orange = 'Same'. Grey cells indicate no consensus was reached either because most responses were 'I don't know' or 'There is no evidence'. White cells indicate no consensus was reached among directional responses. 'Linear features' refers to boundary linear woody features including hedgerows, riparian buffers and shelterbelts.

Baseline system	European region	Agroforestry practice	Mean temperature	Heat extremes	Cold extremes	Mean precipitation	Extreme precipitation	Drought	Windstorms
	Northern	Linear features	Higher 0.81	Higher 0.81	No consensus	Higher 0.81	Higher 0.85	Higher 0.80	Higher 0.86
		Alley cropping	Higher 0.82	Higher 0.88	Higher 0.79	Higher 0.83	Higher 0.83	Higher 0.82	Higher 0.84
		Agrosilvopastoral	Higher 0.85	Higher 0.89	Higher 0.79	Higher 0.83	Higher 0.84	Higher 0.82	Higher 0.81
		Intercropped orchards	Higher 0.78	Higher 0.84	No consensus	Higher 0.83	Higher 0.85	No consensus	Higher 0.80
		Forest farming	Higher 0.82	Higher 0.88	No consensus	Higher 0.83	Higher 0.86	No consensus	Higher 0.87
	Western & Central	Linear features	Higher 0.80	Higher 0.89	Higher 0.79	Higher 0.80	Higher 0.84	Higher 0.82	Higher 0.93
		Alley cropping	Higher 0.82	Higher 0.87	Higher 0.77	Higher 0.83	Higher 0.86	Higher 0.85	Higher 0.80
		Agrosilvopastoral	Higher 0.81	Higher 0.84	Higher 0.79	Higher 0.82	Higher 0.93	Higher 0.84	Higher 0.80
		Intercropped orchards	Higher 0.78	Higher 0.87	Higher 0.79	Higher 0.82	Higher 0.86	Higher 0.85	Higher 0.78
		Forest farming	Higher 0.95	Much higher 0.98	No consensus	Higher 0.93	Much higher 0.96	Much higher 0.96	Higher 0.90
	Southern	Linear features	Higher 0.81	Higher 0.84	Higher 0.84	Higher 0.80	Higher 0.85	Higher 0.83	Higher 0.83
		Alley cropping	Higher 0.87	Higher 0.87	Higher 0.80	Higher 0.78	Higher 0.84	Higher 0.82	Higher 0.82
		Agrosilvopastoral	Much higher 0.95	Higher 0.90	Higher 0.81	Higher 0.80	Higher 0.80	Higher 0.84	Higher 0.82
		Intercropped orchards	Higher 0.82	Higher 0.76	Higher 0.80	Higher 0.75	Higher 0.82	Higher 0.75	Higher 0.78
		Forest farming	Higher 0.94	Much higher 0.98	No consensus	Higher 0.83	Higher 0.93	Much higher 0.94	Higher 0.86
 	Northern	Linear features	Higher 0.86	Higher 0.84	No consensus	Higher 0.84	Higher 0.83	Higher 0.83	Higher 0.84
		Alley systems	Higher 0.87	Higher 0.92	No consensus	Higher 0.78	Higher 0.78	Higher 0.82	Higher 0.83
		Agrosilvopastoral	Higher 0.91	Higher 0.92	No consensus	Higher 0.83	Higher 0.83	Higher 0.83	No consensus
		Wood pasture	Higher 0.87	Higher 0.92	No consensus	Higher 0.81	Higher 0.81	Higher 0.82	No consensus
		Grazed orchards	Higher 0.87	Higher 0.85	No consensus	Higher 0.80	Higher 0.80	Higher 0.77	Higher 0.82
		Forest grazing	Higher 0.80	Higher 0.89	No consensus	Higher 0.85	Higher 0.82	Higher 0.83	No consensus
	Western & Central	Linear features	Higher 0.81	Higher 0.93	No consensus	Higher 0.80	Higher 0.83	Higher 0.82	Higher 0.81
		Alley systems	Higher 0.92	Higher 0.93	No consensus	Higher 0.81	Higher 0.84	Higher 0.85	Higher 0.76
		Agrosilvopastoral	Higher 0.90	Higher 0.90	No consensus	Higher 0.81	Higher 0.79	Higher 0.85	Higher 0.77
		Wood pasture	Higher 0.93	Higher 0.94	No consensus	Higher 0.81	Higher 0.80	Higher 0.84	Higher 0.78
		Grazed orchards	Higher 0.81	Higher 0.92	No consensus	Higher 0.81	Higher 0.80	Higher 0.85	Higher 0.75
		Forest grazing	Higher 0.89	Much higher 0.95	No consensus	Higher 0.93	Higher 0.82	Higher 0.94	Higher 0.81
	Southern	Linear features	Higher 0.80	Higher 0.84	Higher 0.87	Higher 0.82	Higher 0.84	Higher 0.84	Higher 0.82
		Alley systems	Higher 0.84	Higher 0.84	No consensus	Higher 0.83	Higher 0.84	Higher 0.85	Higher 0.82
		Agrosilvopastoral	Higher 0.92	Much higher 0.96	Higher 0.90	Higher 0.78	Higher 0.85	Higher 0.89	Higher 0.86
		Wood pasture	Higher 0.92	Higher 0.95	Higher 0.88	Higher 0.80	Higher 0.87	Higher 0.91	Higher 0.85
		Grazed orchards	Higher 0.83	Higher 0.87	No consensus	Higher 0.84	Higher 0.82	Higher 0.86	Higher 0.84
		Forest grazing	Much higher 0.97	Much higher 0.96	No consensus	Higher 0.82	Higher 0.85	Higher 0.85	Higher 0.85

Table 3. Participant consensus on the resilience of agroforestry practices to climate impact drivers, compared with orchards and forestry baselines. Weighted scores are shown to facilitate comparison between practices; cell colours indicate the consensus resilience level of the agroforestry practice relative to the baseline: dark green = 'Much higher'; light green = 'Higher'; orange = 'Same'. Grey cells indicate no consensus was reached either because most responses were 'I don't know' or 'There is no evidence'. White cells indicate no consensus was reached among directional responses. 'Linear features' refers to boundary linear woody features including hedgerows, riparian buffers and shelterbelts.

Baseline system	European region	Agroforestry practice	Mean temperature	Heat extremes	Cold extremes	Mean precipitation	Extreme precipitation	Drought	Windstorms
	Northern	Grazed orchards	No consensus	No consensus	Unknown	No consensus	No consensus	No consensus	No consensus
		Intercropped orchards	Unknown	No consensus	Unknown	No consensus	No consensus	No consensus	No consensus
	Western & Central	Grazed orchards	No consensus	No consensus	No consensus	No consensus	Same	No consensus	No consensus
		Intercropped orchards	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus
	Southern	Grazed orchards	No consensus	No consensus	Unknown	Higher 0.76	No consensus	No consensus	No consensus
		Intercropped orchards	Higher 0.76	No consensus	Unknown	No consensus	No consensus	Higher 0.74	No consensus
		Wood pasture	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus
	Northern	Forest grazing	No consensus	No consensus	Unknown	No consensus	No consensus	No consensus	No consensus
		Forest farming	Unknown	No consensus	Unknown	No consensus	No consensus	No consensus	No consensus
	Western & Central	Wood pasture	Same	Unknown	No consensus	No consensus	Same	No consensus	No consensus
		Forest grazing	Same	Same	No consensus	No consensus	Same	Same	No consensus
		Forest farming	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus	No consensus
	Southern	Wood pasture	Higher 0.80	Higher 0.85	Unknown	Higher 0.74	No consensus	Higher 0.76	No consensus
		Forest grazing	Higher 0.82	No consensus	Unknown	No consensus	No consensus	Higher 0.76	No consensus
		Forest farming	Higher 0.87	No consensus	Unknown	No consensus	No consensus	Higher 0.76	No consensus

Key mechanisms underpinning resilience

Thematic content analysis of over 7,200 researcher comments generated 249 codes, grouped into 11 themes and 20 sub-themes, which were allocated to the three components of the vulnerability framework: exposure, sensitivity and adaptive capacity (Figure 2; Tables S1–S3).

Reducing exposure. Shade and shelter were the most consistently cited mechanisms, moderating extremes of temperature, wind and precipitation by regulating microclimates around crops and livestock³⁹. Trees were also identified as physical barriers limiting the spread of pests and diseases, through increased landscape heterogeneity that supports natural predators and reduces pest pressure^{40–42}. As noted above, the management of understorey biomass through grazing or cropping was additionally highlighted as reducing wildfire exposure in forested systems³⁶.

Reducing sensitivity. Multiple interactions between system components were identified as mechanisms that improve tree, livestock, crop, or soil health and reduce sensitivity to climate impacts. Trees improve soil structure, organic matter and nutrient content^{14,43}, thereby buffering against precipitation variability and erosion risk⁴⁴. Livestock contribute to tree health through nutrient cycling

via manure deposition and through grazing that reduces weed and pest pressure^{10,45,46}. In turn, trees support livestock health and welfare during drought by providing alternative fodder, opportunities for self-medication, and shade for thermoregulation^{47,48}. At the system level, integrating multiple components increases habitat and functional biodiversity, enhancing pollinator support and natural pest control^{49–55}.

Increasing adaptive capacity. The inherent diversity of agroforestry systems relative to monoculture baselines was identified as the principal source of adaptive capacity^{15,28,34,56}. Two mechanisms were distinguished: first, the diversity of system components spreads the risk of climate impacts across trees, crops and livestock, so that productivity of one component can compensate for losses in another (e.g. tree fodder buffering forage shortages⁴⁸); second, multiple products diversify income streams, reducing dependency on single crops and enabling the system to respond flexibly to changing conditions and market opportunities⁵⁶.

Caveats, trade-offs and conditions of lower resilience. Participants consistently emphasised that resilience outcomes are not automatic but highly context dependent. Key caveats related to design and management characteristics, including tree species, density, height, canopy area and management regime, livestock species, stocking density and grazing intensity, crop species and tillage regime, as well as location-specific factors such as slope, soil type and geomorphology. These considerations echo prior work stressing that agroforestry outcomes are management-sensitive and site-specific^{51,57}.

Trade-offs were also prominent. Competition for light and water between system components was identified as potentially limiting yields under certain configurations or climates^{58–61}. Functional biodiversity, while generally beneficial, was noted as a potential source of ecosystem disservices, for example, increased pest refugia. Altered microclimates were identified as context-dependent: in hot conditions, shelter that reduces wind could also reduce its cooling effect or increase fly pressure on livestock. Participants attributed 'same' resilience outcomes to three main causes: trade-offs that cancel out, limited spatial extent of certain practices (notably boundary linear features, whose benefits are confined to field edges), and baseline systems that are already sufficiently resilient that additional components make no meaningful difference, which was a pattern particularly apparent for tree-only baselines.

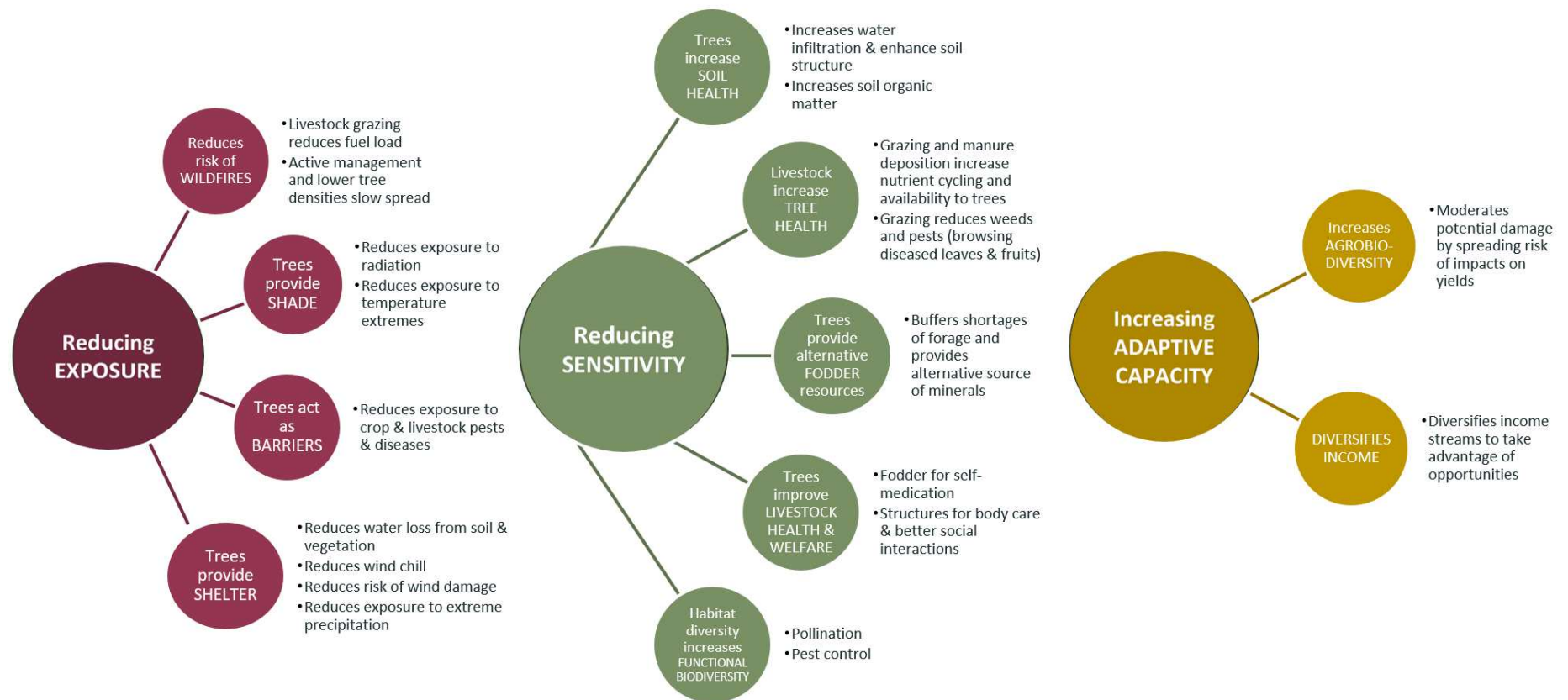


Figure 2. Key mechanisms and properties underpinning the resilience of agroforestry practices to climate change, when compared with agricultural or forestry/orchard baselines as identified by thematic content analysis.

Establishment, management and financial performance

There was a strong consensus that most agroforestry practices are harder to manage than their monoculture baselines (Table 4), consistent with research identifying management complexity as one of the primary barriers to agroforestry adoption^{23,62,63}. Exceptions included Northern Europe, where no consensus was reached for comparisons with orchard or forest baselines, and for linear boundary features, wood pasture and forest grazing compared with livestock-only baselines. Establishment costs were broadly perceived as higher than baselines, though with notable regional variation. In Western & Central Europe, transitions from cropping to agroforestry were generally seen as expensive, with the exception of cropping to forest farming where no consensus was reached. In Northern Europe, establishment costs were flagged as high for transitions from cropping or livestock to alley cropping, agrosilvopastoral systems and linear boundary features. In Southern Europe, no consensus was reached on establishment costs for transitions from cropping or livestock baselines, suggesting greater regional uncertainty. No consensus was reached for transitions from tree-only baselines across all regions, except in Western & Central Europe, where forestry to agroforestry was rated as 'unknown'. This regional variability likely reflects differences in subsidy availability, land prices and labour markets across Europe^{64–68}.

Financial performance was the area of greatest uncertainty across all regions and comparisons, with an almost complete absence of consensus (Table 4). The only exceptions were intercropped orchards in Southern Europe, seen as more profitable than both cropping-only and orchard-only baselines, and wood pasture compared with forest-only. This uncertainty is consistent with the mixed results of bio-economic modelling and empirical studies of agroforestry profitability, which are highly sensitive to time horizon, product prices and policy incentives^{69–72}. While long-term financial advantages from diversified outputs and reduced risk are plausible⁷¹, short-term profitability is often constrained by high establishment costs and delayed returns from tree components. The diversity of CAP implementation and national subsidy schemes across Europe almost certainly contributes to the lack of consensus, given the well-established sensitivity of agroforestry profitability assessments to subsidy design⁷³.

Table 4. Consensus on implementation, management and financial performance questions for agroforestry practices compared with agricultural and tree-only baselines (annual cropping, livestock, orchards and forestry). Colours highlight the performance of the agroforestry practice relative to the baseline (light green = better, brown = worse). 'Unknown'(grey cells) is a combination of 'I don't know' and 'There is no evidence' answers. 'Linear features' refer to boundary features, including hedgerows, riparian buffers, and shelterbelts.

Baseline system	European region	Agroforestry practice	Establishment costs	Management ease	Financial performance	
					With subsidies	Without subsidies
	Northern	Linear features	No consensus	Harder	No consensus	No consensus
		Alley cropping	Expensive	Harder	No consensus	No consensus
		Agrosilvopastoral	Expensive	Harder	No consensus	No consensus
		Intercropped orchards	No consensus	Harder	No consensus	No consensus
		Forest farming	No consensus	Harder	No consensus	No consensus
	Western & Central	Linear features	Expensive	Harder	No consensus	No consensus
		Alley cropping	Expensive	Harder	No consensus	No consensus
		Agrosilvopastoral	Expensive	Harder	No consensus	Unknown
		Intercropped orchards	Expensive	Harder	No consensus	No consensus
		Forest farming	No consensus	Harder	Unknown	Unknown
	Southern	Linear features	No consensus	Harder	No consensus	No consensus
		Alley cropping	No consensus	Harder	No consensus	No consensus
		Agrosilvopastoral	No consensus	Harder	No consensus	No consensus
		Intercropped orchards	No consensus	Harder	More profitable	No consensus
		Forest farming	No consensus	No consensus	No consensus	No consensus
	Northern	Linear features	Expensive	No consensus	No consensus	No consensus
		Alley systems	Expensive	Harder	No consensus	No consensus
		Agrosilvopastoral	Expensive	Harder	No consensus	No consensus
		Wood pasture	No consensus	No consensus	No consensus	No consensus
		Grazed orchards	No consensus	Harder	No consensus	No consensus
		Forest grazing	No consensus	No consensus	No consensus	Unknown
	Western & Central	Linear features	Expensive	Harder	No consensus	No consensus
		Alley systems	Expensive	Harder	No consensus	No consensus
		Agrosilvopastoral	Expensive	Harder	No consensus	Unknown
		Wood pasture	Expensive	Harder	No consensus	No consensus
		Grazed orchards	Expensive	Harder	No consensus	No consensus
		Forest grazing	Expensive	Harder	No consensus	Unknown
	Southern	Linear features	No consensus	Harder	No consensus	No consensus
		Alley systems	No consensus	Harder	No consensus	No consensus
		Agrosilvopastoral	No consensus	Harder	No consensus	No consensus
		Wood pasture	No consensus	Harder	No consensus	No consensus
		Grazed orchards	No consensus	Harder	No consensus	No consensus
		Forest grazing	No consensus	Harder	No consensus	Unknown
	Northern	Grazed orchards	No consensus	No consensus	No consensus	No consensus
		Intercropped orchards	No consensus	No consensus	No consensus	No consensus
	Western & Central	Grazed orchards	No consensus	Harder	Unknown	Unknown
		Intercropped orchards	No consensus	Harder	Unknown	Unknown
	Southern	Grazed orchards	No consensus	Harder	No consensus	Unknown
		Intercropped orchards	No consensus	Harder	More profitable	No consensus
	Northern	Wood pasture	No consensus	No consensus	No consensus	No consensus
		Forest grazing	No consensus	No consensus	No consensus	No consensus
		Forest farming	No consensus	No consensus	No consensus	No consensus
	Western & Central	Wood pasture	Unknown	Harder	Unknown	Unknown
		Forest grazing	Unknown	Harder	Unknown	Unknown
		Forest farming	Unknown	Harder	Unknown	Unknown
	Southern	Wood pasture	No consensus	Harder	More profitable	No consensus
		Forest grazing	No consensus	Harder	No consensus	No consensus
		Forest farming	No consensus	Harder	No consensus	No consensus

Evidence base and knowledge gaps

Participants contributed 251 references supporting their assessments, the majority from peer-reviewed journals and book chapters, with the remainder comprising project reports, theses and technical documents. Allocation of these references to the thematic framework (Figure 3) revealed substantial evidence base for the shade and shelter functions of trees and for the benefits of tree integration on soil health, while highlighting relative gaps in evidence on the role of trees as barriers to pest and disease spread and on the contribution of livestock to tree pest control and nutrient cycling. These gaps are particularly notable given that pest and disease dynamics under climate change were among the most frequently cited sources of uncertainty in participant comments.

Four main knowledge gap themes emerged from the thematic analysis. First, mechanistic and trade-off knowledge is lacking, particularly regarding the impacts of heat stress on crops and trees, the effects of precipitation on livestock, and livestock-tree interactions in pest and disease management. Second, socioeconomic evidence is insufficient, with limited research on the financial performance of specific agroforestry systems and on the social resilience of farming households managing these systems, a gap that is compounded by the predominantly natural science background of the participant panel and limits the social dimensions of this study's conclusions (although a recent review also identified a total absence of evidence for cultural ecosystem services⁷⁴). Third, certain practice types remain understudied, including riparian buffers, forest gardens, and transitions from tree-only systems to agroforestry. Finally, the effects of specific climate drivers on agroforestry, including reductions in cold extremes, increases in mean precipitation and windstorm frequency, remain poorly evidenced.

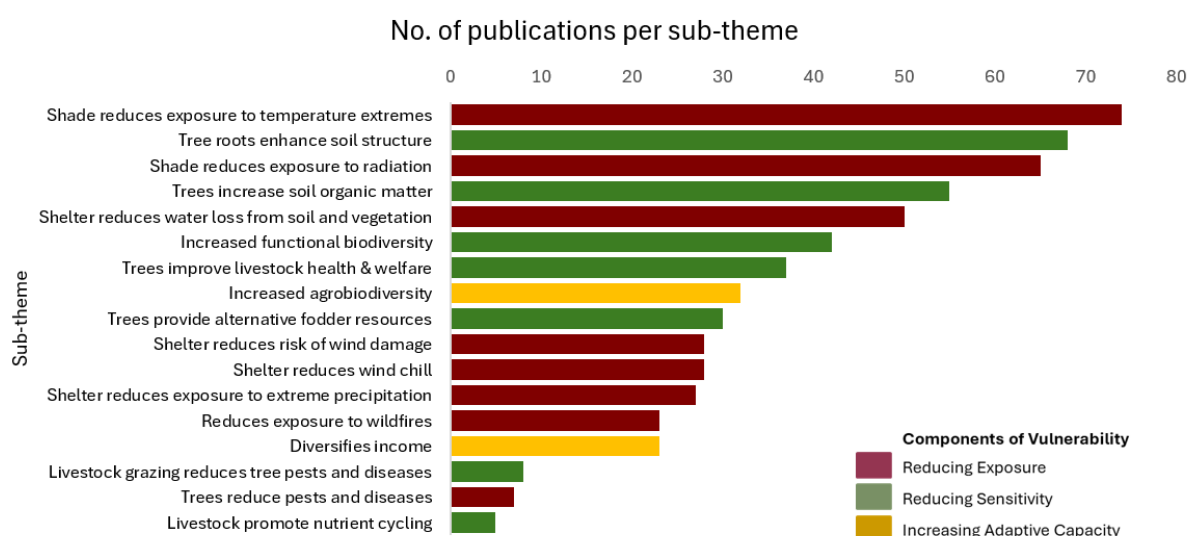


Figure 3. The number of scientific publications identified by the Delphi participants allocated to the themes and sub-themes of the key mechanisms and properties underpinning the resilience of agroforestry practices.

Limitations

Several limitations should be acknowledged. Participant selection was primarily based on knowledge of European agroforestry practices, which was essential for informed assessments, but may have introduced regional and disciplinary biases⁷⁵. The panel was predominantly composed of natural scientists, which is likely reflected in the near-absence of social mechanisms among the resilience

themes identified, though this may also partly reflect the framing of questions around biophysical climate impact drivers rather than social impacts. Targeted researchers represented predominantly the AGROMIX project consortium and affiliated networks, which may have introduced a systematic tendency towards more positive assessments of agroforestry, given the project's pro-agroforestry orientation; this should be borne in mind when interpreting consensus findings. Participant fatigue was evident across rounds in the reduction in the number and length of comments, despite all participants completing all three rounds⁷⁶. Future studies could explore hybrid approaches combining online questionnaires with in-person workshops to sustain engagement, though this would require careful consideration of the anonymity that is central to the Delphi method.

Implications for policy and practice

A central aim of this study was to identify which agroforestry practices offer the greatest climate change resilience, in order to inform targeted policy support. The results indicate that all agroforestry practices can contribute to increased resilience compared with cropping- or livestock-only baselines across most climate impact drivers, suggesting that policy frameworks should promote agroforestry broadly as a climate adaptation strategy rather than focusing narrowly on specific practice types. Within this broad framing, some regional prioritisation is warranted: in Southern Europe, practices such as forest farming, wood pasture and silvopasture deserve particular policy attention given their capacity to reduce both drought vulnerability and wildfire risk³⁶.

Forest farming emerges as one of the most resilient practices assessed, yet it currently receives limited coverage in European agroforestry policy frameworks. While typically small-scale and community-oriented, interest in forest farming, which includes food forests, has grown considerably in recent years, particularly in Northern Europe and in peri-urban settings⁷⁷. Bringing this practice more explicitly within policy frameworks, including through eligibility for agri-environment payments and knowledge exchange programmes, would better align support with the resilience evidence base. A key challenge in several European countries is forestry regulation, which does not permit any integration of agriculture on land classified as forestry³³.

The strong consensus on management complexity as a barrier underlines the need for practical support mechanisms alongside financial incentives. Policy responses should include tailored extension services and technical support for farmers establishing agroforestry systems, investment in long-term pilot projects and demonstration farms, and targeted research to generate the robust economic performance benchmarks that farmers need for informed decision-making⁷⁸. For farmers considering agroforestry adoption, the findings suggest that boundary practices such as hedgerows, shelterbelts and riparian buffers represent a low-risk entry point: they can deliver meaningful resilience benefits, particularly for flood risk, wind exposure and localised microclimate regulation, without requiring commitment to a fully integrated system. Progression to more complex and integrated practices such as alley cropping or agrosilvopastoral systems could follow as experience and confidence develop.

Conclusion

This study demonstrates that agroforestry practices are generally perceived as more resilient to climate change, especially compared with agricultural baselines. However, there is still much uncertainty, as illustrated by the sometimes-divergent answers from the participants, especially when comparing agroforestry practices with forest and orchard baselines. This uncertainty reflects the complexity of the practices and highlights the need for greater knowledge, financial incentives, and

support for extension services. More long-term experiments and observations of farmers' innovations are needed to reduce levels of uncertainty.

Methods

Agroforestry practices

The definition of agroforestry practices was based on a classification developed within the HORIZON Europe project AGROMIX⁷⁹, with a few modifications to align with the classification adopted by the European Agroforestry Federation⁸⁰. The final classification reflects the balance of the three components (trees, livestock and annual crops) which can also be considered on a gradient of tree cover, ranging from potentially closed canopies in forest farming and forest grazing systems, through to lower levels of canopy cover in wood pastures and grazed or intercropped orchards, to alley cropping and linear woody features where the agricultural components are dominant (Table 1). The baseline land-use systems considered are monoculture systems, for which the introduction of additional components could increase resilience to climate change impacts. In addition to three agricultural baselines (arable, livestock and orchards (includes vines and olives), we also included a forestry baseline. As part of the Delphi process, researchers were asked to consider the resilience of each agroforestry combination relative to these agricultural or forestry baselines.

Climate impact drivers, impacts and risks

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment report (AR6) defines climate impact-drivers as conditions of the physical climate system (e.g., means, events, extremes) that affect society and/or ecosystems⁸¹. Seven climate impact drivers were considered: mean warming, heat extremes, cold extremes, mean precipitation, heavy precipitation, drought, and severe windstorms. The IPCC AR6 also identified observed impacts and projected risks from the climate impact drivers, with many impacts/risks having multiple drivers that may interact to either exacerbate or mitigate potential impacts. As the direction of change for some climate impact drivers differs between regions of Europe, we conducted three separate Delphi studies (Northern Europe, Southern Europe (Mediterranean) and Western & Central Europe), based on the IPCC AR6 subdivisions of Europe⁸¹.

The Delphi Study

The Delphi technique is “a method of structuring a group communication process so that the process is effective in allowing a group of individuals as a whole to deal with a complex problem”⁸². By organising and structuring expert group debates on complex issues, the Delphi method enables diverse views and opinions to converge into a consensus through an iterative feedback process. Delphi studies typically consist of two or three rounds of structured questionnaires, each followed by the aggregation of responses and the provision of anonymous feedback to participants. After each questionnaire round, participants can review and confirm or amend their previous responses, considering the opinions and suggestions from other participants in the preceding round. The process is repeated until a consensus emerges; this is usually achieved after two or three rounds of questionnaires. This Delphi study was conducted entirely online to be efficient in terms of both time and cost, and throughout the process, all participants remained anonymous to one another.

Participant selection

The selection of ‘experts’ for participation in the Delphi process was based on objective criteria defined prior to the study. Experts needed to have knowledge and understanding of (1) European agroforestry practices, (2) climate impact drivers and climate change impacts, and (3) concepts of resilience of farming systems to climate change. We primarily selected researchers within the EU project AGROMIX consortium and complemented them with other researchers from current and previous projects (MIXED, DigitAF, ReForest) and country delegates of the European Agroforestry Federation, to ensure Europe-wide coverage. An email was sent to the identified researchers, explaining the goal and protocol of the Delphi study and inviting them to participate. When signing up, participants were asked to indicate which climatic region they were most familiar with, with the option to select multiple regions. This enabled us to ensure adequate coverage of all three climate zones (a minimum of seven experts per zone⁸³).

Questionnaire development and testing

The questionnaire was developed and piloted with four volunteers, who provided valuable feedback on its flow, content, and scope, as well as the accompanying support material. The final questionnaire contained seven questions on the resilience of each agroforestry practice to climate impact drivers and their associated impacts, and four questions on the cost of implementation, ease of management, and financial viability with and without subsidies compared to the baseline. Each question was divided into three subsections; the first subsection focused on agroforestry practices compared with an annual crop (arable/vegetable)-only baseline, the second on agroforestry practices compared with a livestock-only baseline, and the third on agroforestry practices compared with a tree-only baseline (i.e. orchard or forestry).

The first seven questions on resilience used a five-point scale ranging from ‘Much lower resilience’ to ‘Much higher resilience’, with options to choose ‘I don’t know’ or ‘There is no evidence’. Participants were asked to suggest the mechanisms or properties of the agroforestry practice that determine the level of resilience, with references where possible (in any language), and to add notes, limitations, or caveats. The next four questions, related to the implementation, management, and profitability of the agroforestry practices, also used a five-point scale, adapted to each question. Participants were also asked for further information to justify their score, with the option to add references and notes where appropriate. In the first Delphi round, participants were required to provide justifications for each score, whereas in subsequent rounds this was optional.

After each of the three rounds, responses were aggregated, and participants received anonymous feedback. Participants were asked to review and confirm or amend their previous responses, considering the opinions and suggestions from other participants in the preceding round.

The Delphi process was managed using the online platform ‘Welphi’ (www.welphi.com). This facilitated the entire process, from coordinating email invitations and follow-up reminders to participants, to creating and implementing rules of consensus for developing subsequent rounds, to analysing results and providing anonymous comments for each round. This study followed the ethics procedure set out by the AGROMIX project (Project Ethics H (Humans) – Requirement No. 1 Deliverable 9.1; approved by the European Commission) and was reviewed and approved by an

internal AGROMIX project Ethics board. Participants signed an Informed Consent Form before beginning Round 1. Personal data collected was restricted to the name and email address of participants. These were first collected via google forms to allow sign up to the Delphi process in the Welphi platform. The google form responses and summary were stored securely on the MVARC google drive.

Reaching consensus

There are different approaches to defining consensus in Delphi studies, including formal measures of agreement, degree of uncertainty around a point estimate, decreases in variance of group responses, or the proportion of participants agreeing to a particular viewpoint; the most common definition used is percent agreement⁸⁴. Consensus was initially defined as agreement by at least 70% of participants on the same resilience level for a given practice-driver combination. This applied both to directional responses ('Much lower' through to 'Much higher') and to non-directional responses, where a combination of 'I don't know' and 'There is no evidence' responses reaching 70% was recorded as 'Unknown'. Following Round 1, the consensus rule was modified in two ways. First, to reduce questionnaire fatigue in subsequent rounds, and second, to address the low rate of consensus achieved in Round 1, adjacent directional categories were combined: if 'Higher' and 'Much higher' responses together exceeded 70%, consensus of 'Higher' resilience was recorded; similarly, if 'Lower' and 'Much lower' responses together exceeded 70%, consensus of 'Lower' resilience was recorded. This modification allowed a broader signal of directional agreement to be captured while maintaining a meaningful consensus threshold.

Normalising the Delphi consensus scores

To facilitate comparison of resilience levels across agroforestry practices, a weighted score was calculated for each practice-driver-baseline combination where directional consensus ('Higher', 'Much higher', 'Lower' or 'Much lower') was reached. This was done by treating the five-point Likert scale as an interval scale and normalising responses as follows:

Step 1 — Assign numerical values to each response option. Each Likert option was assigned a score: Much lower resilience = 1; Lower = 2; Same = 3; Higher = 4; Much higher = 5. Responses of 'I don't know' and 'There is no evidence' were assigned a score of zero and excluded from the denominator in Step 3.

Step 2 — Calculate the total weighted score for each combination. For each practice-driver-baseline combination, the number of respondents selecting each option was multiplied by its assigned score, and the products were summed. For example, if two participants selected 'Much higher' and one selected 'Same', the total weighted score would be $(2 \times 5) + (1 \times 3) = 13$.

Step 3 — Calculate the maximum possible score. The maximum possible score was calculated by multiplying the number of respondents who gave a directional response (excluding 'I don't know' and 'There is no evidence') by the maximum Likert value of 5. In the example above, the maximum possible score would be $3 \times 5 = 15$.

Step 4 — Normalise to a 0–1 scale. The total weighted score was divided by the maximum possible score to produce a normalised value between 0 and 1. In the example above, $13 \div 15 = 0.87$.

Identifying key mechanisms and properties - thematic content analysis

Thematic content analysis was carried out on the participant comments. Thematic content analysis is a commonly used method in qualitative research that first identifies patterns of meaning across the data and develops codes to describe them. Through an iterative process, these codes are refined and grouped into overarching themes that ultimately relate directly to the research question⁸⁵. In this case, to identify key mechanisms and properties of agroforestry practices that affect resilience to climate change.

As an inductive (i.e. ground-up) approach, the initial round of coding was carried out without any preconceived notions of what the codes should be, i.e. the patterns came from the data itself; subsequently, aligning and grouping codes into themes was a reflexive process, where the researcher's subjective experience played an inherent part in making meaning from the data.

To efficiently process the large volume of data generated by the Delphi, artificial intelligence (AI) was employed in the initial stages of the thematic content analysis. AI has recently become part of the toolbox of software packages for qualitative analysis, which use AI to automatically generate codes (e.g., ATLAS.ti, NVivo) or to identify and summarise data related to specific codes (e.g., MAXQDA). The use of AI tools such as ChatGPT in qualitative research raises legitimate methodological concerns. However, a direct comparison between ChatGPT and manual thematic content analysis found that ChatGPT performed well overall, with the main limitation being a tendency towards concrete, descriptive themes rather than subtle, interpretative ones⁸⁶. For the purposes of this study, where the analytical goal was to identify key mechanisms and properties affecting resilience rather than to interpret nuanced perceptions or feelings, this characteristic is less of a concern and may in fact be advantageous, as descriptive, concrete coding is well-suited to identifying discrete functional mechanisms from expert justifications. On this basis, ChatGPT (model GPT-3.5) was used at the initial stage of code generation only, to produce and align a first set of codes from the participant comments. All subsequent analytical steps were conducted manually: codes were verified for accuracy and consistency, interpreted and grouped into sub-themes and themes, and finally allocated to the three components of the exposure, sensitivity and adaptive capacity vulnerability framework¹⁶. The AI-assisted stage, therefore, served as an efficient first pass to manage the volume of comments (over 7,200 in total), while interpretive judgment remained with the research team throughout.

Collating the evidence base

Participants were asked to support their comments on key mechanisms and properties of agroforestry that impact resilience to climate change with scientific references to provide an evidence base, or, conversely, to help identify knowledge gaps. References were collated into a Mendeley group (Mendeley Desktop Version 1.19.8 2008-2020 Mendeley Ltd). Based on their abstracts, references were then allocated to the themes developed from the comments. The full reference list and allocation to themes are available on Zenodo (<https://doi.org/10.5281/zenodo.21529359>).

Participant engagement

Three Delphi studies, covering Northern, Western & Central, and Southern Europe, ran from September to December 2023. Invitations were sent to 89 agroforestry researchers on 1-4 September, with researchers asked to confirm participation by 24 September. Round 1 ran from 25 September for three weeks, Round 2 from 30 October for three weeks, and Round 3 from 29 November to 15 December. In total, 46 researchers completed all three rounds (Table 5), exceeding the recommended minimum of seven participants per Delphi⁸⁷, and representing 19 countries. Across the three regional studies, 528 practice-driver-baseline combinations were assessed, with each participant rating 176 combinations for their selected region using a five-point resilience scale ranging from 'Much lower' to 'Much higher', with additional options for 'I don't know' and 'There is no evidence'. After three rounds, consensus — defined as at least 70% of participants agreeing on the same resilience level — was reached for 314 of the 528 combinations, while no consensus was reached for the remaining 214.

Table 5. Researcher participation in the different stages of the Delphi studies.

Delphi study	Invited	Completed Round 1	Completed Round 2	Completed Round 3
Northern Europe	23	17	16	16
Western and Central Europe	39	21	18	19
Southern Europe	27	15	12	11
Total	89	53	46	46

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Authors' contributions

Conception & design: JS, JHNP, VR, MLG, FH, CHV

Acquisition of data: All authors

Analysis & interpretation of data: JS, JHNP

Writing—Original Draft: JS, JHNP

Writing—Review & Editing: All authors

Data availability

The Delphi datasets generated during the current study are available from the corresponding author on reasonable request. The full reference list and allocation to themes are available on Zenodo (<https://zenodo.org/records/21529359>).

Competing interests

The authors declare no competing interests.

Supplementary information

Table S1-S3. Themes and sub-themes describing key mechanisms and properties of agroforestry practices that increase resilience to climate impact drivers.

Table S4-S5. Caveats and trade-offs

Table S6. Themes for comments justifying the agroforestry practice had the ‘same’, ‘lower’ and ‘much lower’ resilience as the baseline system.

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