

Structural heterogeneity shapes economic resilience and ecosystem-service trade-offs in Mediterranean Montado agroecosystems: a farm-level bioeconomic analysis

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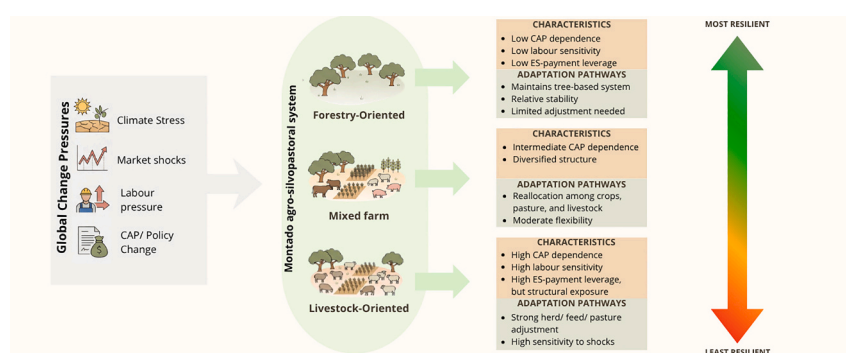
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HIGHLIGHTS

- Farm archetypes showed different resilience under shared shocks.
- Policy exposure drove the largest resilience gap among archetypes.
- Mixed farms were more climate-sensitive than livestock farms.
- Ecosystem-service opportunity costs were non-linear and case-specific.
- Marginal ES payments outperformed flat supplements in policy-exposed farms.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Mediterranean agro-silvopastoral systems provide both market outputs and ecosystem services, yet their economic capacity to remain viable under climate, market, and policy stress may depend strongly on farm structure. The Portuguese Montado exemplifies this challenge: beneath a shared landscape label lie structurally distinct farm archetypes whose economic responses to external shocks may differ markedly.

OBJECTIVE: This study examines whether structural heterogeneity, among three purposefully selected Montado farm archetypes, shapes their economic resilience profiles and ecosystem-service trade-offs under common external stressors.

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Climate change
CAP

METHODS: The forestry-oriented case was represented by a deterministic accounting model, whereas the mixed agro-silvopastoral and livestock-specialized cases used calibrated nonlinear optimization models. Economic resilience was evaluated using a Resilience Index, Conditional Value-at-Risk, operating-profit sensitivity, and scenario-specific viability outcomes.

RESULTS AND CONCLUSIONS: Economic resilience differed systematically across archetypes (RI: 0.907, 0.839, and 0.752, respectively). Policy exposure explained most of this divergence: the livestock-specialized farm became unprofitable under full Common Agricultural Policy (CAP) withdrawal (operating-profit proxy: -€19,242), indicating that public support is structurally enabling for this archetype. Climate responses were also heterogeneous: diversification did not buffer stress in the mixed system, which faced correlated vulnerabilities across feed supply, water availability, and livestock energy requirements. Ecosystem-service provision involved non-linear, archetype-specific opportunity costs, and marginal results-based payments outperformed flat supplements by inducing land-use adjustments that more than offset compliance costs in the most policy-exposed system (+42.2% operating-profit gain).

SIGNIFICANCE: Economic resilience in Mediterranean agroecosystems cannot be inferred from average-farm assessments. This study provides a replicable framework for archetype-sensitive agri-environmental policy design in Montado-type and other heterogeneous silvopastoral systems.

1. Introduction

Mediterranean agro-silvopastoral systems occupy a distinctive position in land management: they generate both market outputs and ecosystem services (carbon sequestration, biodiversity conservation, water regulation) on land with limited potential for conventional agriculture (Moreno et al., 2018; Plieninger et al., 2021; Torralba et al., 2016). Yet this ecological high value has not insulated these systems from mounting pressures. Across the Iberian Peninsula, farms managing these systems face accelerating climate change, agricultural policy reform, and recurring input market volatility (Pinto-Correia and Azeda, 2017; Plieninger et al., 2021). Whether these farms can remain economically viable under these combined pressures, and which structural configurations are most at risk, has direct consequences for land management, rural income, and ecosystem services provision.

The Montado of southern Portugal, together with the Spanish Dehesa, is one of the most prominent examples of Mediterranean agro-silvopastoral systems. Covering more than one million hectares in southern Portugal (Godinho et al., 2016; Plieninger et al., 2015), the system integrates open oak woodlands with understory pastures, annual forage crops, and extensive livestock grazing, forming a highly complex agro-silvo-pastoral system (Carreira et al., 2023). This layered structure delivers cork revenue, livestock products, acorn-based fodder, and ecosystem services including wildlife habitat and carbon storage (Bugalho et al., 2011; Helena Guimarães et al., 2023), making it a valuable case to examine the economic sustainability of integrated land-use systems under multiple stressors.

A critical and underrepresented feature of the Montado is its structural heterogeneity. Beneath the shared label of agro-silvopastoral management lies a spectrum of functionally and structurally distinct farm archetypes: from forestry-specialized cork producers reliant on tree products, to mixed farms combining crops, cattle, and sheep, to large extensive sheep farms where livestock dominates income (Fatahi et al., 2026). These archetypes differ in production logic, cost structures, input dependencies, subsidy exposure, adaptive capacity, pedoclimatic conditions, and provision of ecosystem services (Pinto-Correia et al., 2019; Plieninger et al., 2021). A cork farm and a sheep farm may face identical climate projections and Common Agricultural Policy (CAP) reforms however, their economic responses may be markedly different. This heterogeneity also constitutes a fundamental challenge for policy design, as instruments calibrated to an average farm profile risk being poorly targeted or counterproductive across structurally distinct types (Fatahi et al., 2026; Huber et al., 2024; Pinto-Correia and Azeda, 2017).

Additionally, climate change poses the most significant long-run threat to the productive and ecological foundations of Mediterranean farming. The Iberian Peninsula is projected to experience considerable warming and declining water availability, with strong implications for extensive farming systems dependent on rainfall, pasture, and tree

regeneration (Bisselink et al., 2020; Ali et al., 2022). For Montado farms, this translates into concurrent pressures across distinct productive channels, reduced pasture productivity, variable feed availability, heat stress on livestock, and difficulty sustaining oak stands under drought (Chauhan et al., 2023; Henry et al., 2018; Ribeiro et al., 2024; Serrano et al., 2023; Sucena-Paiva et al., 2022), whose economic consequences are unlikely to be uniform across farms.

These pressures are compounded by shorter-horizon stressors. Policy support has been shown to create tension between ecological sustainability and farm-level incentives, especially where livestock payments encourage intensification (Pinto-Correia and Azeda, 2017). Recent work also highlights the increasing emphasis on ecosystem-service delivery within Montado support schemes (Helena Guimarães et al., 2023). Input volatility adds a further dimension: where production depends more heavily on purchased feed, fertilizer, or energy, price shocks can erode farm margins quickly and unevenly across systems. These pressures interact: declining pasture productivity raises dependence on purchased feed precisely when input markets are unstable, while policy support reductions shrink the buffer available to absorb such shocks (Muñoz-Ulecia et al., 2023).

Despite the scale of these pressures, comparative farm-level quantitative analysis of economic resilience in the Montado remains limited. Previous work has focused predominantly on biophysical aspects such as pasture dynamics, climate impacts on tree regeneration, and the ecological functioning of the Montado system (Carreira et al., 2023; Ribeiro et al., 2024; Simionesei et al., 2018). Economic studies have focused on ecosystem-service valuation, environmental accounting, governance tensions, or land-use change, rather than direct comparison of farm types under common shock scenarios (Campos et al., 2020; dos Santos et al., 2022; Muñoz-Rojas et al., 2019). The potential of result-based ecosystem-service payments as a resilience mechanism also remains insufficiently explored in comparative farm-level terms (Helena Guimarães et al., 2023), limiting the evidence base for designing targeted support schemes.

This study addresses these gaps by developing calibrated farm-level models for three Montado archetypes from the Montado Agro-Forestry Production Systems (MAPS) typology, a forestry-specialized cork producer, a multifunctional mixed operation, and an extensive sheep enterprise (Fatahi et al., 2026), to examine how structural heterogeneity mediates economic viability and ecosystem-service provision under common external stressors. Our research makes four contributions. First, it delivers an archetype-based bioeconomic comparison of Montado farms across labor, market, policy, and climate shocks. Second, it compares the relative importance of these stressors within a single framework. Third, it quantifies the opportunity cost of additional ecosystem-service provision and evaluates how it varies with farm structure. Fourth, it assesses whether ecosystem-service-oriented payment design can improve economic resilience, particularly in subsidy-dependent

systems.

Resilience in farming systems is multidimensional, comprising robustness (capacity to withstand shocks), adaptability (capacity to adjust in response), and transformability (capacity to fundamentally reorganize) (Meuwissen et al., 2019; Urruty et al., 2016). This study focuses on one component, farm-level economic robustness, defined as the capacity of the modelled farm configuration to maintain economic performance under specified labour, market, policy, and climate disturbances. The models are comparative-static and do not simulate long-run adaptation or transformation.

This study addresses the overarching question: How does structural heterogeneity shape farm-level economic resilience and ecosystem-service trade-offs across three contrasting Montado case-study configurations? Four research questions guide the analysis. First, does vulnerability to external shocks differ across the three configurations? Second, which stressor category poses the greatest operating-profit risk to each configuration? Third, does the economic cost of additional ecosystem-service provision differ between the configurations where endogenous adjustment is possible, in ways that matter for results-based payment design? Fourth, can ecosystem-service payment mechanisms generate net positive economic outcomes under adverse conditions, and if so, for which configurations? Together, these questions examine how structural heterogeneity shapes economic resilience and ecosystem-service trade-offs, and whether policy design can address the identified vulnerabilities.

2. Materials and methods

2.1. Study area and farm selection

This study focuses on the Alentejo region of southern Portugal, where the Montado agro-silvopastoral system covers more than one million hectares (Serrano et al., 2021). The climate is Mediterranean, characterized by hot dry summers and marked inter-annual rainfall variability (500–700 mm year⁻¹), with a dry season from June to September that constrains pasture and crop production (Ferreira et al., 2010). Soils are nutrient-poor, derived from granite and schist, and

natural pasture productivity is highly variable across seasons (Carreira et al., 2023). Cork oak (*Quercus suber*) and holm oak (*Quercus rotundifolia*) stands are integrated with understory pastures, annual forage crops, and extensive livestock grazing.

The MAPS typology distinguishes six Montado production systems (A–F) based on climate, land use, forest structure, farm size, and livestock activity. These were grouped into the three archetypes analyzed here: forestry-oriented, mixed agro-silvopastoral, and livestock-oriented extensive (Fig. 1, Table S1 Supplementary Material (SM)). Full details are in Fatahi et al. (2026). Farm selection considered structural fit with the typology, data completeness, willingness to participate, and geographic distribution. While not exhaustive of Montado diversity, they provide a robust basis for analysing how global change may differentially affect contrasting archetypes. To test whether the results depend on the exact scale of the selected farms, we conducted a robustness test in which livestock numbers were scaled proportionally with area and forest share held constant (Supplementary Material S17).

Farm 1 (200 ha - ha) represents the forestry-oriented archetype, deriving income almost exclusively from cork production, with no integration of livestock or annual crops. Labor requirements are limited to specific, time-bound forestry operations such as pruning, cork harvesting, and shrub clearing. A minor share of income (approximately €1000 yr⁻¹, below 2% of operating-profit proxy) derives from hunting leases. Despite its apparent simplicity, maintaining tree health and relying solely on tree-based income constitute a high-risk, knowledge-intensive strategy.

Farm 2 (520 ha) represents the mixed agro-silvopastoral archetype, integrating cork and holm oak forestry with livestock production (suckler cows and ewes) and crops (irrigated maize, and rain-fed hay). Tree-related operations are outsourced to specialized service providers as needed. Holm oak acorns are further valorized through the seasonal fattening of Iberian pigs. Available water enables irrigated maize production, marketed when prices are favorable or retained for on-farm feeding. Both cattle and sheep are maintained, with stocking rates remaining below CAP thresholds. Cork production is also present but does not constitute the primary source of income. The system is the most complex to manage, operating through strong complementarities among

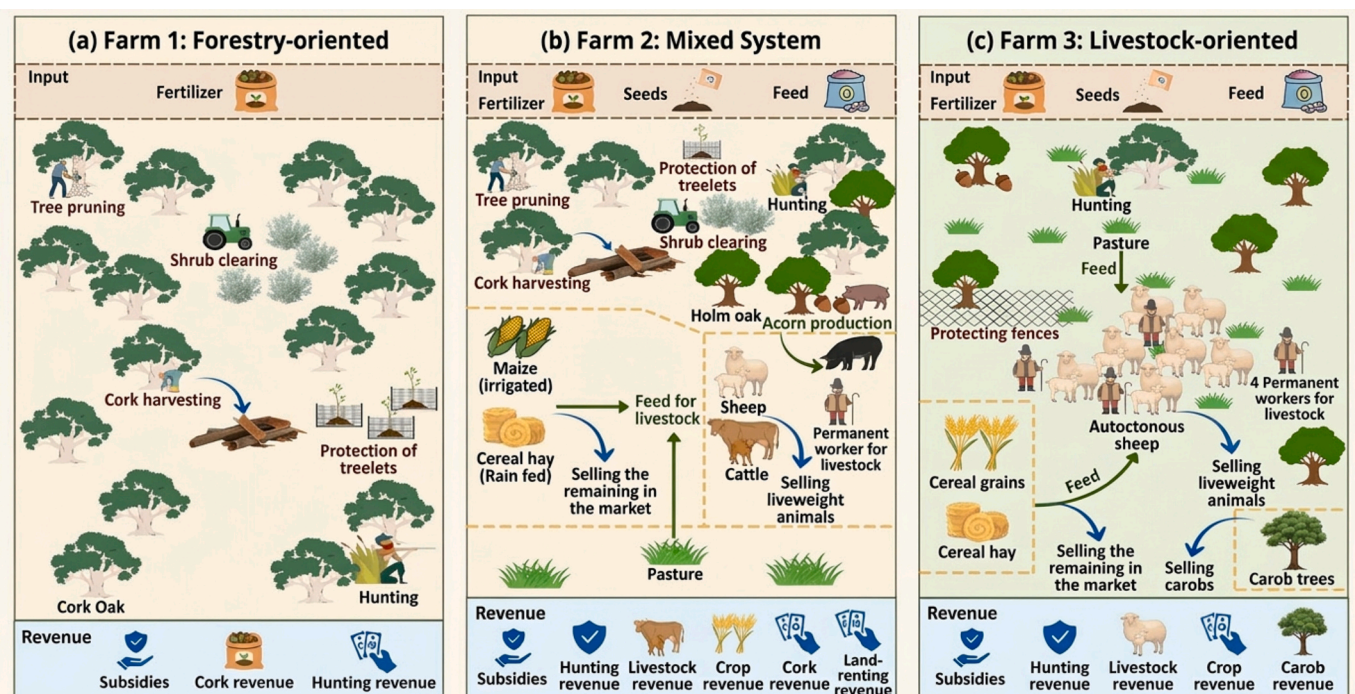


Fig. 1. Representative Montado farm archetypes: (a) forestry-oriented, (b) mixed agro-silvopastoral, (c) livestock-oriented extensive. Differences in tree, crop, livestock components, diversification, and labour organization are illustrated.

its components.

Farm 3 (948 ha) represents the livestock-oriented extensive archetype, centered on a flock of approximately 2000 ewes supported by predominantly holm oak, carob (*Ceratonia siliqua*), hay, and triticale. Livestock constitutes the main source of income. The large farm area allows extensive pasture use at relatively low stocking rates. Feeding relies primarily on pasture and on-farm crop production. The tree component plays a marginal productive role: stands are old and largely unproductive, and despite fencing, insufficient regeneration is driving a gradual decline in tree cover. Under these conditions, the farmer is actively seeking to diversify income, notably through the introduction of cash crops such as carob.

The bioeconomic models applied to these three archetypes capture interactions between ecological dynamics and management strategies under global change scenarios.

2.2. Bio-economic model framework

A separate bio-economic model was developed for each farm archetype to represent the observed functioning of the system, including its resource use, production organization, constraints, and income generation. The models are used for comparative-static stress testing over a 15-year policy and climate horizon. The ‘base-period reference configuration’ (hereafter ‘baseline’ for brevity) refers to the calibrated current farm configuration (2023–2024 data), representing the observed farm structure and baseline operating-profit proxy from which the reported economic deviations are measured. Scenario parameter values (e.g., +30% price shocks) are stylized representations of plausible changes over the 15-year horizon, not annual increment rates. The analysis does not simulate a business-as-usual trajectory or endogenous long-run adaptation. A 15-year horizon was preferred over longer timeframes typical of climate research, as projections beyond this threshold carry substantial uncertainty regarding prices and policy trajectories (Souissi et al., 2018).

The three cases were implemented in GAMS Distribution 52.5.0. For Farms 2 and 3, nonlinear mathematical programming determines the annual allocation of land, livestock numbers, feed resources, and labor. Farm 1 is represented by a deterministic accounting model with fixed productive activities and therefore does not solve an endogenous resource-allocation problem.

The static framework is deliberate, isolating the operating-profit effect of each shock without introducing uncertainty about the form or timing of long-run adaptation. Results should be interpreted as comparative-static estimates of exposure at the observed farm configuration, not as forecasts of long-term adjustment. The model thus serves as an analytical tool to examine how farm structure mediates trade-offs between economic performance and ecosystem-service provision.

Within the overall framework there were differences in the chosen model scheme. Farm 1 is a deterministic accounting model, because all productive activities have fixed areas and quantities. Farms 2 and 3 were formulated as Non-Linear Programmes (NLPs) because the quadratic cost terms introduced by the Positive Mathematical Programming (PMP) calibration procedure (Section 2.2.3) render the objective function non-linear. Annotated GAMS source code for all three baseline models is provided as SM S2 (Farm 1), S3 (Farm 2), and S4 (Farm 3).

The models treat each farm as an economically autonomous decision unit, appropriate for assessing how structural heterogeneity mediates farm-level economic resilience. System-level interactions such as resource sharing, local feed markets, and collective adaptation are not captured.

2.2.1. Model structure and objective function

The objective function aggregates all farm revenue and cost components into a single annual gross margin:

GM = \sum_a (R_a - C_a) + S - w^{perm} \tag{1}

where:

- GM: annual farm gross margin (€ year⁻¹)
- R_a: revenue from activity *a* (e.g., crops, livestock, trees) (€)
- C_a: cost of activity *a* (€)
- S: CAP Subsidies (€)
- w^{perm}: annual cost of hired/non-family permanent labour (€ year⁻¹); family labour is not included.

The optimization model maximizes the gross margin defined in Eq. (1). For reporting and viability assessment, the operating-profit proxy is defined as:

OP = GM - FOC \tag{1b}

where:

- OP: annual operating-profit proxy (€ year⁻¹)
- GM: gross margin from Eq. (1) (€ year⁻¹)
- FOC: annual fixed operating cost (€ year⁻¹; Table S12a).

Because FOC is constant across scenarios, it does not affect the optimal solution; it is subtracted only when reporting the operating-profit proxy. All percentage changes and resilience metrics are calculated relative to baseline operating profit.

2.2.2. Decision variables and constraints

The decision variables represent the key management choices that determine resource allocation and production activities in Farm 2 and 3.

Endogenous variables include crop areas, livestock numbers, feed purchases, and labour. Farm 1 has no endogenous variables (tree area fixed). Full variable lists in S5, and Table 1 summarizes the main farm structural differences and decision variables. (See Table 2.)

The model includes land allocation, livestock nutrition (energy, protein, dry matter intake), crop use (feed vs. market), water (irrigated maize), labour (monthly permanent + seasonal), minimum concentrate rations, CAP stocking rate eligibility, and CAP subsidy structure constraints. All constraint equations, seasonal nutritional parameters, and eligibility rules are provided in Supplementary S5-S9.

2.2.3. Model calibration

Standard mathematical programming models tend to produce corner solutions in which only the most profitable activity is operated (Howitt, 1995). To recover the observed diversified baseline as a model optimum, Positive Mathematical Programming (PMP) was applied following Howitt (1995) and (Paris and Howitt, 1998).

In Stage 1, calibration constraints restrict each activity to its observed level:

Table 1
Model structure and endogenous decisions across the three case-study farms.

Model element	Farm 1: Forestry	Farm 2: Mixed	Farm 3: Livestock
Model type	Deterministic accounting	PMP-calibrated nonlinear optimization	PMP-calibrated nonlinear optimization
Tree area	Fixed	Fixed	Fixed
Crop and pasture allocation	Not applicable	Endogenous	Endogenous
Livestock numbers	Not applicable	Endogenous: cattle and sheep	Endogenous: sheep
Feed use and purchases	Not applicable	Endogenous	Endogenous
Labour	No permanent labour; contracted-service requirements fixed	One permanent worker fixed; seasonal labour activity-dependent	Four permanent workers fixed; seasonal labour activity-dependent
Response to scenarios	Direct accounting response	Endogenous resource reallocation	Endogenous resource reallocation

Table 2

Scenario families, definitions, and shock magnitudes used in the model simulations.

Scenario family	Scenario	Shock assumption	Basis	Source
Labor cost increases	Variable labor = Seasonal labor and/or contracted services	+30% increase in contracted-service and variable labor costs	Based on the +30.0% increase in the Portuguese price index for goods and services currently consumed in agriculture in 2022; used as a reference for variable labor and outsourced service costs.	L1. Statistics Portugal / Eurostat (Eurostat, 2023a).
	Permanent labor	+30% increase in permanent labor costs	Based on the cumulative increase in the Portuguese statutory minimum wage from €665 (2021) to €870 (2025) (+30.8%), rounded to +30%.	L2. (DGERT, 2026).
	Combined labor	+30% increase applied to both permanent and contracted labor costs	Represents a joint labor-cost stress affecting both direct employees and outsourced labor-related services simultaneously.	L1–L2
Agricultural input market shocks	Feed spike	+30% increase in concentrate/feed prices	Based on the increase in EU animal feeding stuffs prices between Q4 2021 and Q4 2022 (about +29%), rounded to +30%.	M1. Eurostat agricultural price statistics (Eurostat, 2023b)
	Fertilizer spike	+30% increase in fertilizer prices	Based on the increase in EU fertilizers and soil improvers (+55%) between Q4 2021 and Q4 2022 (about +55%), +30% represents a moderate shock relative to peak increases.	M1 (Eurostat, 2023b)
	Global inflation	+30% increase applied simultaneously to multiple input costs (feed, fertilizer, seeds)	Based on the approximately +30% increase in the EU price index for goods and services currently consumed in agriculture in 2022 relative to 2021.	M1 (Eurostat, 2023a)
CAP policy reform	Pillar I -25%	25% reduction in CAP Pillar I payments	Exploratory CAP reform scenario representing a partial reduction in direct income support.	P1. Fellmann et al. (2025) , Scenar 2040: A scenario study on the Common Agricultural Policy, Joint Research Centre, JRC142503. The study explicitly includes a NoCAP scenario simulating removal of the entire CAP framework, providing the main literature basis for the full-withdrawal policy counterfactual and broader support for a gradient of CAP reform scenarios (Fellmann et al., 2025). P1 (Fellmann et al., 2025)
	No Pillar I	Full removal of CAP Pillar I payments, with agri-environment payments retained	Policy counterfactual isolating the contribution of Pillar I income support.	
	No CAP	Removal of all CAP payments	Extreme policy counterfactual consistent with the NoCAP scenario in JRC Scenar 2040.	P1 (Fellmann et al., 2025)
	ES Pay	Baseline CAP structure plus an ecosystem-service supplement equal to 10% of total computed ecosystem-service value	The payment is defined as an additional transfer equal to 10% of total computed ecosystem-service value under the simulated allocation.	P2. Study-specific policy design assumption.
	ES Pay + Stress	Baseline CAP structure plus an ecosystem-service land-use constraint and a marginal payment of €20 per additional ecosystem-service point above the unconstrained baseline	Policy stress-test scenario combining an ES floor with a marginal payment intended to compensate the opportunity cost of additional ecosystem-service provision.	P2
Climate stress	Moderate	Climate stress based on L1 high-impact and L2 low-impact parameter shocks	Based on literature-derived impact intervals retained through sensitivity analysis, representing a moderate bundle broadly aligned with RCP4.5-type conditions. Example parameters include cork yield, pasture productivity, and livestock heat stress.	C1. Supplementary Material 11 compiles the literature-based climate impact intervals used in the sensitivity analysis and scenario construction.
	Extreme	Climate stress based on L3 high-impact and L2 low-impact parameter shocks	Based on the same literature-derived intervals, using stronger shocks for the most influential parameters to represent a more severe bundle broadly aligned with RCP8.5-type conditions.	C1

Note: For labor and market scenarios, the reported percentages refer to the observed magnitude of recent cost movements used to define the shock size, not to expected annual changes over the full scenario horizon. Policy scenarios represent counterfactual design choices. Climate scenarios are based on literature-derived parameter ranges retained through sensitivity analysis, with full detail reported in Supplementary Material 11.

$$x_i \leq \bar{x}_i \quad \forall i \in I^{\text{cal}} \quad (2)$$

where:

x_i : optimized area or activity level of activity i

$\bar{x}_i$: observed baseline level of activity i

I^{cal} : set of calibrated activities (Farm 2: maize, hay, cattle, sheep; Farm 3: hay, triticale, ewes).

The Stage 1 shadow prices λ_i capture the implicit marginal value associated with restricting each calibrated activity to its observed level.

In Stage 2, these dual values are used, together with the observed accounting costs and activity levels, to construct the calibration cost term added to the objective:

$$GM^{cal} = GM - \sum_i \left[\alpha_i \cdot x_i + \frac{1}{2} \delta_i \cdot x_i^2 \right] \quad (3)$$

where:

GM^{cal} : calibrated gross margin (€)

GM : uncalibrated gross margin from Eq. (1) (€)

α_i : linear coefficient for activity i (€ per unit)

δ_i : quadratic calibration coefficient for activity i , constructed from the absolute value of the Stage 1 shadow price and the observed activity level. (€ per unit²).

Following the PMP construction of [Howitt \(1995\)](#), for crop activities, the coefficients are defined as $\alpha_i = c_i + \lambda_i - |\lambda_i|$ and $\delta_i = |\lambda_i|/x_i^-$, corresponding respectively to the linear (D_crop) and quadratic (Q_crop) terms implemented in GAMS. With the non-negative Stage 1 shadow prices obtained in the model, α_i reduces to c_i ; thus, the linear crop coefficient is fixed at the accounting marginal cost rather than independently calibrated. For livestock activities, $\alpha_i = \lambda_i - |\lambda_i|$ and $\delta_i = |\lambda_i|/x_i^-$, corresponding respectively to D_livestock and Q_livestock, with the endogenous livestock cost structure explicitly represented in the Stage 2 objective. For Farm 1, no PMP adjustment is required. The calibrated model was validated against farm interview data.

2.3. Data collection and parametrization

2.3.1. Farm structural and economic data

Primary data were gathered through semi-structured interviews (2023–2024) following the participatory protocol in [Fatahi et al. \(2026\)](#). Captured technical-economic indicators, including areas, livestock structure, yields, and input-output prices, alongside the qualitative management rationale for observed production mixes. A complete parameter listing is provided in Table S10.

2.3.2. Biophysical and nutritional parameters

Livestock nutritional requirements (energy requirements, digestible protein requirements and dry matter intake capacity) were defined by month and reproductive stage of each species according to [Tables INRA \(2007; updated 2010\)](#). The full monthly nutritional parameter matrix is provided in Table S6.

In Montado areas, pasture productivity was defined for open and under-canopy conditions using seasonal dry matter (DM) data (2019–2021) from Alentejo reference sites (2020 baseline; [Rodrigues et al., 2025](#); Mendeley Data: DOI:10.17632/f9n9s3p99t.6), with under-canopy DM set at 80% of open pasture to conservatively reflect reduced productivity ([Serrano et al., 2021](#)).

Nutritional quality parameters (specifically metabolizable energy and crude protein) were integrated from regional datasets to complement the DM values ([Lucas, 1995](#)). The full pasture parameters are provided in Supplementary Table S8 and S9.

2.3.3. Climate scenario parameterization

Parameter shock values were derived from a literature synthesis using published empirical estimates to define plausible change intervals over the 15-year horizon, approximately 2040. For each parameter, moderate and extreme shock levels were specified with reference to RCP4.5 and RCP8.5 trajectories, respectively ([Joint Research Centre, 2020](#); [Andrade et al., 2021](#); [Masson-Delmotte et al., 2021](#)). The full evidence table is provided as Supplementary Table S11.

2.4. Scenario design

The scenario design utilizes two structures to reflect distinct external pressures. Biophysical scenarios simulate climate stress by directly modifying production parameters, including pasture productivity, livestock feed requirements, and water availability, using empirical relationships calibrated to RCP4.5 and RCP8.5 trajectories ([Andrade et al., 2021](#); [Masson-Delmotte et al., 2021](#)), with causal links supported by the

literature. These scenarios also incorporate cascading effects, such as the inverse supply-price relationship in the Portuguese cork market, integrating biophysical shocks with realistic market price responses.

In contrast, economic, labor, and policy scenarios, encompassing CAP reform, input market shocks, and labor pressures, modify the economic environment rather than biophysical parameters. These are designed using historical variability and current policy proposals, to assess farm income sensitivity to institutional and market stressors likely to occur over the study horizon.

Four scenario families were constructed to capture the main categories of external stress affecting Montado systems: (i) labor cost increases, (ii) agricultural input market shocks, (iii) CAP policy reform, and (iv) climate stress. Within each family, scenarios are defined as stylized shocks consistent with either observed historical variability or literature-based projections. Scenario definitions, shock magnitudes, and implementation details are summarized in [Table 2](#).

Labor and market scenarios utilize observed cost fluctuations as 15-year benchmarks for medium-term stress testing. These include +30% shocks for permanent labor (L2) and contracted services (L1), alongside feed, fertilizer, and global inflation shocks (M1) calibrated to 2021–2022 EU price spikes. These values represent medium-term stress benchmarks, not representative annual changes.

The CAP policy reform scenarios represent counterfactual pathways spanning a gradient from partial reduction of Pillar I payments to full withdrawal, with the “No CAP” scenario aligned with the JRC Scenar 2040 framework (P1). Two distinct ecosystem-service instruments are examined: a flat 10% supplement of total ES value, serving as a value-linked income transfer, and a result-based design that pays a fixed marginal rate for ES points generated above a baseline. The first instrument is an income transfer linked to service value; the second compensates the marginal opportunity cost of additional ecosystem-service provision.

Climate scenarios are constructed from literature-derived parameter ranges retained through the sensitivity analysis and grouped into two internally consistent bundles broadly aligned with RCP4.5-type and RCP8.5-type conditions (C1; Supplementary Material 11). These bundles are stress-test scenarios rather than deterministic forecasts.

2.5. Ecosystem-service indicator and model integration

Ecosystem-service provision is represented by an area-weighted comparative indicator linked to land-use composition. Using a benefit-transfer approach, the indicator applies published per-hectare valuations of non-market ecosystem services from comparable Mediterranean agro-silvopastoral systems to each land-use class ([Costanza et al., 1997](#)). The purpose is not to estimate total economic value but to represent relative differences in ecosystem-service provision across land-use configurations:

$$V_{ES} = \sum_i A_i \cdot TES_i \quad (4)$$

where:

V_{ES} : Farm's total ecosystem-service value (€ yr⁻¹)

A_i : area of land-use activity i (ha)

TES_i : ecosystem-service value per hectare of activity i (€ ha⁻¹ yr⁻¹).

The silvopastoral woodland total ecosystem-service value (TES) coefficient (694 € ha⁻¹ yr⁻¹) was adapted from the Agroforestry Accounting System estimate reported by ([Campos et al., 2019](#)) for cork oak open woodlands in Andalusia, where total ecosystem services were valued at 694.4 € ha⁻¹ in 2010. This value, which aggregates provisioning, regulating, and cultural services, is used here as a stylized reference coefficient for Mediterranean oak silvopastoral systems. Open pasture and cropland are assigned €150 and €100 ha⁻¹ yr⁻¹ respectively ([dos Santos et al., 2022](#)). To avoid double-counting, grazing services are embedded within land-use coefficients rather than livestock values. The indicator is therefore a comparative, area-weighted proxy, not a farm-

specific marginal valuation.

The ES indicator is a comparative proxy and is sensitive to the area assigned to each land-use class. It does not capture management quality, ecological condition, or spatial interactions. Because Farm 1's woodland area is fixed and no crop-pasture substitution is possible, its ES outcome is structurally constrained. The marginal ES trade-off analysis is therefore most informative for Farms 2 and 3.

The ES value function is integrated into the model in two stages. In Stage 1, each farm is solved at its calibrated optimum without any ES constraint, and the resulting ES value is recorded as the baseline ES level (V_{ES0}). In Stage 2, ES-constrained scenarios impose a lower bound on the ES function:

$$V_{ES} \geq V_{ES0} \bullet (1 + \tau) \quad (5)$$

where τ is the ES tolerance parameter ($\tau \geq 0$).

Since tree area is structurally fixed, the constraint is equivalent to a floor on the combined open pasture and cropland ES contribution. As τ increases, the model substitutes cropland for open pasture to satisfy the ES threshold, since open pasture carries a higher TES coefficient (150 vs. 100€ ha⁻¹ yr⁻¹). This substitution directly reduces the farm's highest-margin crop activities. The ES scenario analysis progressively increases τ in 0.5% steps to identify the feasibility boundary, the point at which the ES requirement can no longer be satisfied within land, livestock, and nutritional constraints, and characterize the income-ES trade-off curve. Farm 1 is excluded from this analysis because the ES value is structurally invariant to optimization decisions.

2.6. Resilience

Metrics

The resilience metrics used in this study measure economic robustness, the capacity to maintain positive operating profit under external shocks, rather than ecological or social resilience.

To compare economic shock absorption, five metrics were computed for each farm archetype across feasible "standard scenarios", comprising individual specified shock scenarios across labor, market, policy, and climate shocks. Each metric captures a distinct dimension of resilience: average operating-profit loss, tail exposure, income variability, solvency rate, and policy drag.

Resilience Index (RI): RI measures a farm's average capacity to absorb operating profit shocks across all feasible standard scenarios (Meuwissen et al., 2019; Urruty et al., 2016). For each scenario s , the percentage change in operating profit relative to the baseline is denoted $\Delta OP\%_s$. The per-scenario resilience component is defined as:

$$RI_s = 1 - \left| \frac{\Delta OP\%_s}{100} \right|$$

where a value of 1 indicates no change from baseline, while lower values indicate larger absolute deviations, whether gains or losses. The overall RI for farm f is the arithmetic mean across all N_s feasible standard scenarios:

$$RI_f = \frac{1}{N_s} \sum_{s=1}^{N_s} \left(1 - \left| \frac{\Delta OP\%_s}{100} \right| \right)$$

The index is capped at 1 (no loss).

An operating-profit proxy was calculated (Eq. (1b)) by subtracting the available annual fixed operating costs (€3800, €5500, and €7000 for Farms 1–3, respectively), covering maintenance, insurance, administration, machinery and, where applicable, irrigation (both including equipment amortization). These costs are held constant across scenarios; therefore, productive decisions remain unchanged, while all reported scenario percentage changes and resilience metrics are calculated relative to baseline operating profit. Because other depreciation (buildings, land improvements, plantations/trees), financing, land and family-labour opportunity costs remain excluded, this measure should be

interpreted as a partial operating-profit proxy rather than comprehensive net profit.

Conditional Value-at-Risk (CVaR): Tail risk is measured using the Conditional Value-at-Risk framework (Rockafellar and Uryasev, 2000), which quantifies the expected loss in the worst tail of the scenario distribution. CvaR is applied at the 75th percentile of losses (CvaR₇₅): the mean $\Delta OP\%$ across the worst 25% of standard scenarios, those with the largest negative operating profit changes. Let Q^{75} denote the 75th percentile of the $\Delta OP\%$ distribution for farm f . Then:

$$CVaR_f = \text{mean}(\Delta OP\%_s \mid (\Delta OP\%_s \leq Q^{75}))$$

CVaR is reported as a percentage of baseline operating profit. A more negative CVaR indicates a more severe expected loss in the tail of the distribution, capturing downside risk beyond what the mean RI reflects.

Operating-Profit Volatility: Volatility is the standard deviation (SD) of $\Delta OP\%$ across all feasible standard scenarios for each farm (Bell et al., 2021):

$$\sigma_f = SD(\Delta OP\%_s)$$

This measure captures the dispersion of operating-profit outcomes across the full scenario set, rather than focusing on losses alone. A high σ indicates that a farm's economic performance is sensitive to scenario choice. Volatility is reported in percentage points (pp).

Solvency Rate: The proportion of scenarios where operating-profit proxy remains positive ($OP > 0$), identifying whether any shock is sufficient to render the farm economically unviable.

Policy Drag: The policy sub-group's contribution to overall resilience:

$$\text{Policy Drag}_f = RI_f^{\text{overall}} - RI_f^{\text{policy}}$$

A larger positive value indicates that the farm's policy sub-index lies below its overall RI, reflecting disproportionate policy-driven vulnerability.

These farms are analytically representative of the principal MAPS archetypes, not a statistically representative sample; the purpose is structured comparison of distinct configurations under common stress tests, not inference to the full population. This distinction is important for interpretation of both the economic resilience metrics and the policy conclusions.

3. Results

3.1. Baseline economic performance

This section summarizes the baseline economic and structural characteristics of the three case study farms (Fig. 2), providing the reference point for interpreting scenario responses.

Farm 1 (200 ha forestry; pure cork) generates a baseline operating-profit proxy €88,540 from €116,724 total revenue, with the lowest subsidy dependency (18.5%). Farm 2 (520 ha mixed agro-silvopastoral) records a €199,360 OP from €379,422 revenue (23.2% subsidies). Farm 3 (948 ha livestock; 2000 ewes) achieves the highest absolute OP (€213,771) and revenue (€571,003) but relies most heavily on subsidies (46.0%).

Per hectare, Farm 1 achieves the highest OP (€443 ha⁻¹), followed by Farm 2 (€383 ha⁻¹) and Farm 3 (€225 ha⁻¹). This gradient reflects contrasting production logics: cork generates high value with limited variable inputs, whereas extensive sheep systems require larger land areas for grazing. High feed self-sufficiency (94.8% for Farm 2; 98.4% for Farm 3) suggests low baseline vulnerability to purchased feed costs. These results align with regional Alentejo benchmarks of €384⁻¹, 833 ha⁻¹ and reflect the income heterogeneity typical of Montado systems (Fragoso and Falcão Marques, 2003; Helena Guimarães et al., 2023).

The three systems also show contrasting labor-income profiles. Farm

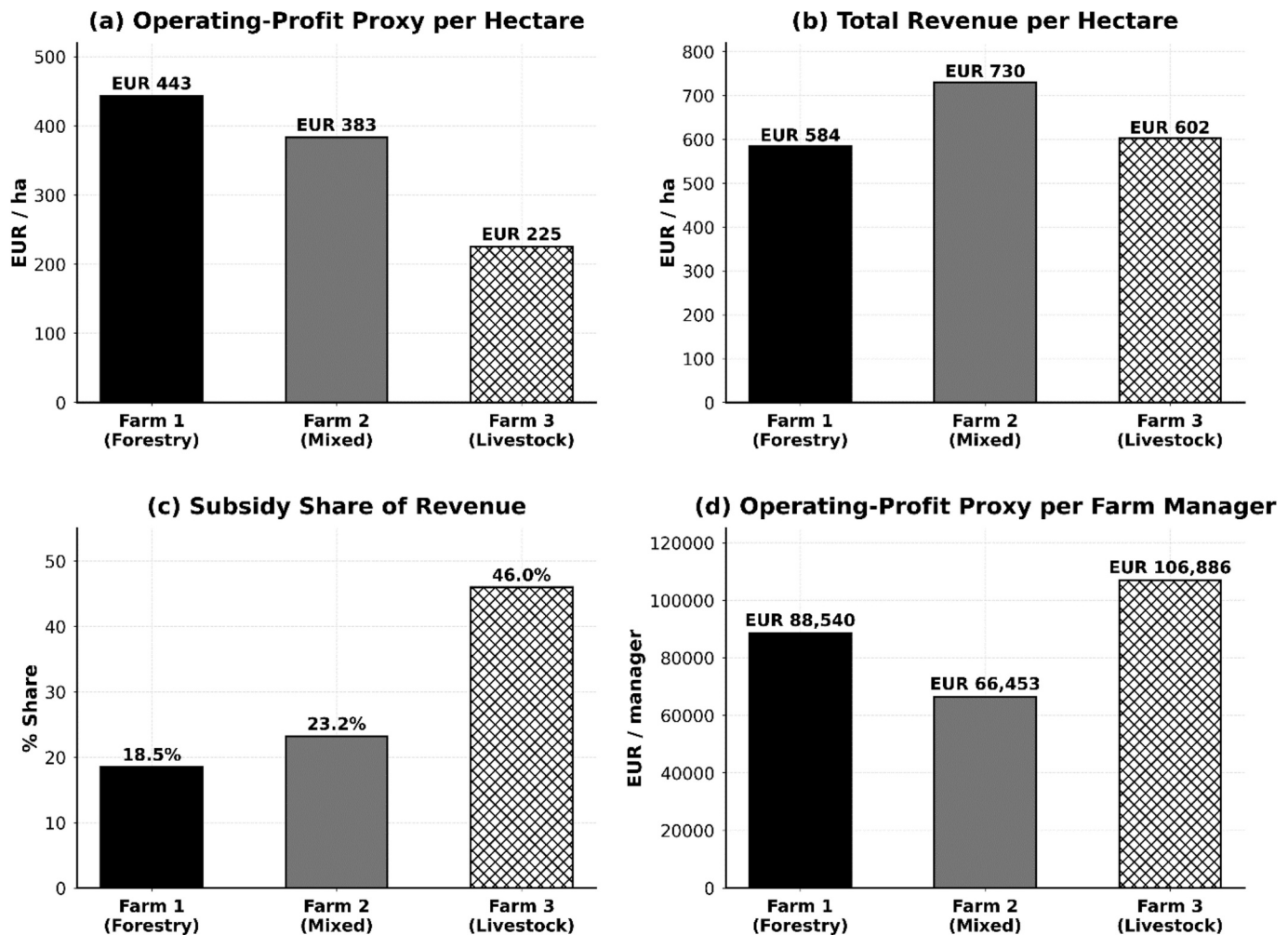


Fig. 2. Baseline economic characterization of the three Montado farm archetypes: operating-profit proxy per hectare (a), total revenue per hectare (b), subsidy share of revenue (c), and operating-profit proxy per farm manager (d).

1 is managed by one person and generates €88,540 per manager. Farm 2, with three managers, yields €66,453 per manager, while Farm 3 (two managers) achieves the highest ratio at €106,886 per manager. Yet with 46.0% of revenue from Common Agricultural Policy (CAP) transfers, Farm 3 is the most exposed to future policy reform.

Base-period reference values refer to the calibrated current farm configuration based on 2023–2024 interview data. All scenario results are expressed as percentage deviations from this baseline.

3.2. Ecosystem service value tolerance and the cost of ES provision

Before testing the scenario families, a preliminary analysis was conducted to determine the feasible range and economic cost of imposing the ecosystem service (ES) constraint. The ES value function was progressively increased in 0.5% increments above the unconstrained optimum (Fig. 3). Farm 1 was excluded from the analysis because its baseline allocation already maximizes ES value structurally.

ES opportunity costs are non-linear: initially modest, they rise sharply once cropland reallocation is exhausted. Farm 2 adjusts primarily through land-use substitution, while Farm 3 spreads adjustment across land use, herd reduction, and external feed.

In Farm 2, adjustment occurs almost entirely through land reallocation while preserving livestock at 334 head (Table S12b). Open pasture expands to 310.9 ha (+41.3%) as crop area contracts to 9.1 ha (−90.9%) at the +2.5% tolerance level. This shift causes crop income to decline by 87.0% (€112.8 k to €14.6 k). To sustain the herd, concentrate

purchases increase by 54.2% (43.4 to 67.0 t), as internal crop feed falls by 76.1%. Consequently, operating profit losses remain limited at low tolerance (−0.5% at +0.5%) but accelerate to −27.8% at +2.5% before reaching infeasibility at +3.0%. This steep decline reflects a narrow adjustment margin: once cropland is exhausted, the farm cannot sustain its livestock without prohibitive costs.

In Farm 3, the response is more gradual and diversified. As the ES threshold increases (Table S12b, Supplementary Material), pasture expands 18.0% and crop area declines 95.3%, while total livestock units decrease slightly (−4.0%). This distributed adjustment delays the economic penalty; OP declines only 7.8% up to the +2.5% tolerance level. However, beyond +3.0%, the crop component collapses and concentrate purchases rise drastically (from 16.4 to 81.8 t), causing OP losses to deepen to −17.6% at the +3.5% feasibility boundary. Farm 3 thus maintains a wider feasibility range than Farm 2, which reaches its limit earlier by sacrificing the crop component to preserve livestock.

3.3. Labor cost scenarios

Labor scenarios test the effects of a +30% increase in variable/contracted service costs (Sc1), permanent labor costs (Sc2), and both simultaneously (Sc3). Results are reported in Table S13 and Fig. 4. Farm 1, which relies entirely on contracted services for periodic forestry management, sees a 5.4% operating-profit proxy reduction under Sc1. Because it has no permanent staff, it is unaffected by Sc2.

Under the combined scenario, Farm 2 and Farm 3 lose 8.8% and

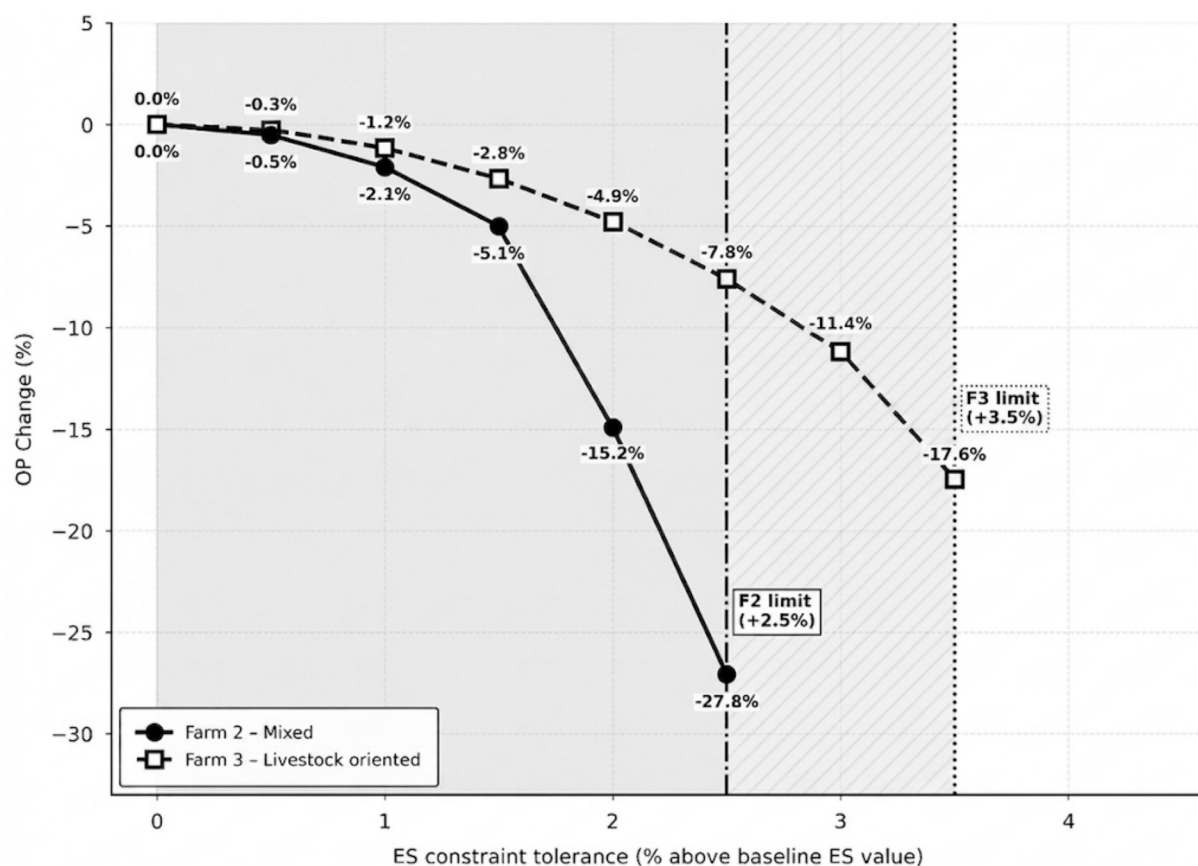


Fig. 3. Operating-Profit proxy (OP) response to increasing ecosystem service (ES) constraints in mixed (Farm 2) and livestock (Farm 3) systems. ES constraints are expressed as the percentage increase in ES value relative to baseline. Points show OP changes at each constraint level, with dashed vertical lines indicating feasibility limits (+2.5% for Farm 2 and +3.5% for Farm 3). Shaded areas denote the common and extended scenario ranges. The steeper decline for Farm 2 indicates lower economic resilience to ES constraints.

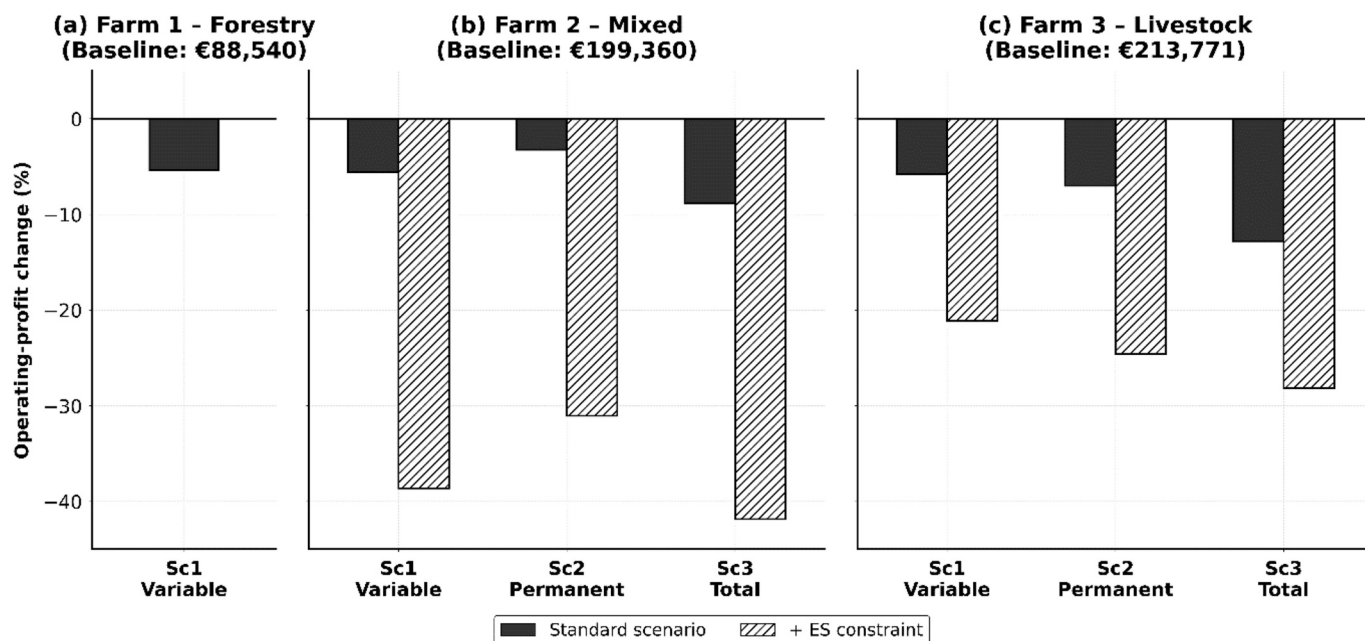


Fig. 4. Operating-Profit proxy (OP) change (%) relative to baseline under three labor shock scenarios (Sc1 Variable, Sc2 Permanent, Sc3 Combined) for Farm 1: Forestry (Baseline: 88,540€; no permanent worker, no livestock labor), Farm 2: Mixed (Baseline: 199,360€; 1 permanent worker + seasonal livestock labor), and Farm 3: Livestock (Baseline: 213,771€; 4 permanent workers + seasonal livestock labor). Solid bars = standard scenario, applied without ES constraint; hatched bars = scenario with additional ES constraint.

12.8% of OP, respectively. Losses are strictly additive (Sc1 + Sc2), indicating no interaction effects. Sensitivity varies by farm structure: Farm 2 is more vulnerable to contracted costs (Sc1: -5.6% vs Sc2: -3.2%) because it employs only one permanent worker, outsourcing most tree and crop operations. Conversely, Farm 3 is more sensitive to permanent labor (Sc1: -5.8% vs Sc2: -7.0%) due to its €50,000 annual wage bill for four permanent employees.

The shocks trigger distinct economic mechanisms across archetypes. Under Sc1, Farms 2 and 3 reallocate land from crops to open pasture as rising contractor fees reduce cropping profitability. Sc2, by contrast, acts as a pure income reduction; fixed in the model, it does not alter the marginal conditions governing land-use choice. Farm 1 shows no behavioral adjustment under Sc1 because its forestry-only system contains no decision variables, resulting in a direct OP loss. Farm 3's greater labour sensitivity is therefore expected given its four permanent employees and higher fixed wage bill.

Combined with the ES constraint, which alone reduces OP by 27.8% and 17.6%, labor shocks remain additive. In all ES-constrained scenarios, the production structure converges to the same configuration regardless of the labor shock applied. This confirms that once binding, the ES constraint dictates land use independently of labor costs, with shocks affecting only the residual operating profit.

3.4. Market Price scenarios

Market scenarios test three +30% input-price shocks: Feed Spike, Fertilizer Spike, and Global Inflation (simultaneous increase in all input prices) (Table S14; Fig. 5). The income effect is determined by the input's share of total costs at the calibrated optimum. Farm 1 is exposed only to the Fertilizer Spike, losing 2.9% of operating profit, reflecting the modest fertilizer required to maintain soil quality around trees.

For Farm 2, the Fertilizer Spike causes a 0.8% loss, while the Feed Spike induces a 2.6% loss, directly reflecting its exposure to external concentrate markets. Farm 3's Feed Spike loss is minimal (0.9%), as concentrate remains secondary to grazing infrastructure. Its Fertilizer Spike loss (2.2%) is larger, driven by the cost of maintaining its 134-ha crop area. A small flock contraction to 1987 ewes helps Farm 3 buffer the

feed shock by retaining only the most cost-efficient production levels.

The shocks activate different behavioral channels. The Feed Spike triggers a small herd contraction (Farm 2: to 149.3 cows; Farm 3: to 1987 ewes) without altering land use, as the model adjusts to marginal production costs. The Fertilizer Spike increases cropping costs, inducing a crop-to-pasture reallocation: Farm 2 reduces crops to 97.5 ha, and Farm 3 to 124.3 ha. Global Inflation activates both channels simultaneously, producing the largest overall losses (-6.3% for Farm 2 and -9.0% for Farm 3) and combining land-use shifts with herd reductions.

The ES constraint exposes structural limits and infeasibilities not seen in previous scenarios. For Farm 2, the Feed and Fertilizer spikes remain feasible through the “cropland-collapse” mechanism, but Global Inflation is infeasible. The ES floor forces cropland to near-zero while simultaneously high feed and harvesting costs eliminate all cost-effective nutritional substitution pathways. Farm 3 reaches this limit even earlier; only the Feed Spike remains feasible under the ES constraint. This “nutritional bottleneck” occurs because the ES floor forces crop area toward zero, but ewes require a minimum forage level that pasture alone cannot meet (0.80 UFV/kg DM). When fertilizer costs also rise, the system cannot satisfy the ES floor, nutritional requirements, and elevated input costs.

3.5. CAP policy reform scenarios

Policy scenarios test four CAP reform counterfactuals, a 25% Pillar I reduction (Pil1-25%), full Pillar I removal (No Pil1), complete CAP withdrawal (No CAP), and an ecosystem-service payment layer on top of the existing CAP measures (ES Pay), with ES-constrained variants for Farms 2 and 3. Results are reported in Table S15 and Fig. 6.

Across all systems, policy sensitivity mirrors subsidy dependency. Farm 1 (18.5% subsidy share) loses 24.4% of its operating profit under No CAP, while Farm 2 (23.2% share) loses 48.8%. Farm 3 (46.0% share) suffers a structural failure, with OP falling to -€19,242. This negative result confirms that public support for the livestock-oriented system is not merely income-enhancing but structurally enabling: market revenues alone cannot cover annual fixed operating costs.

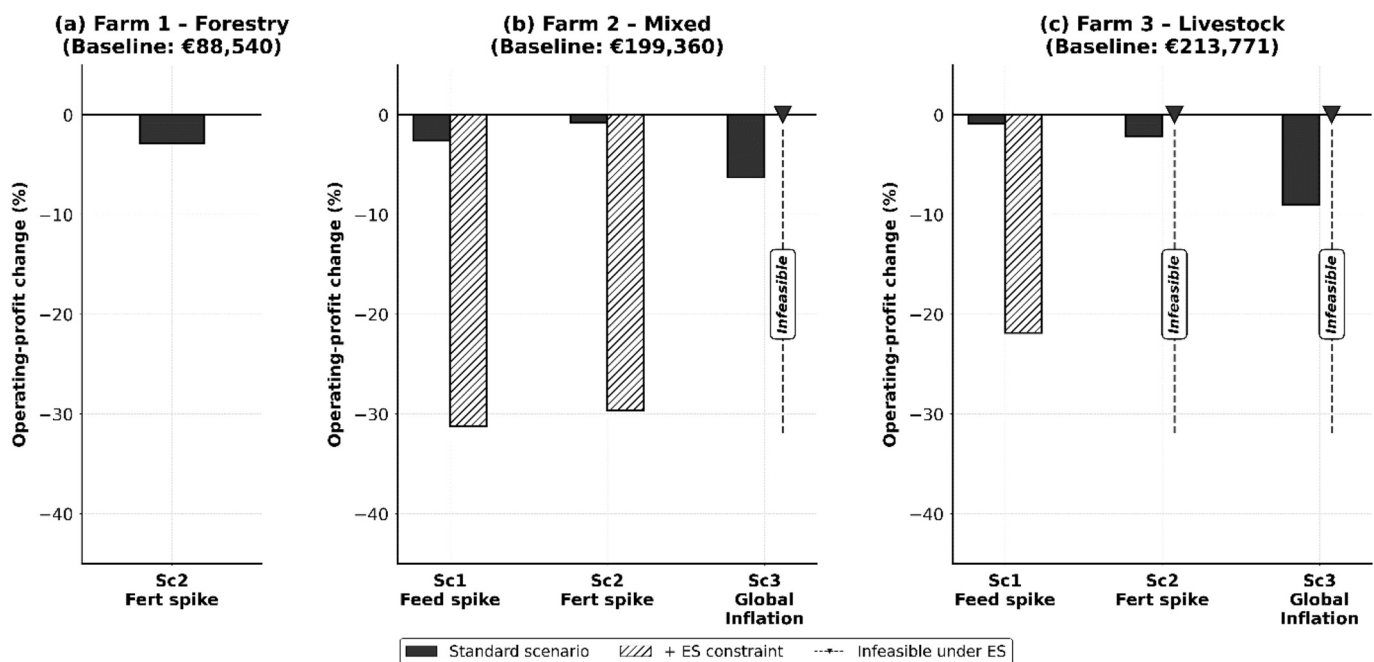


Fig. 5. Operating-profit proxy change (%) under market price shock scenarios for three farm types: fertilizer spike, feed spike, and global inflation (+30% each), comparing standard farm optimization against solutions with an ecosystem service (ES) constraint; Farm 1: Forestry is only exposed to the fertilizer shock; infeasible cases indicate scenarios where no solution satisfying the ES constraint could be found.

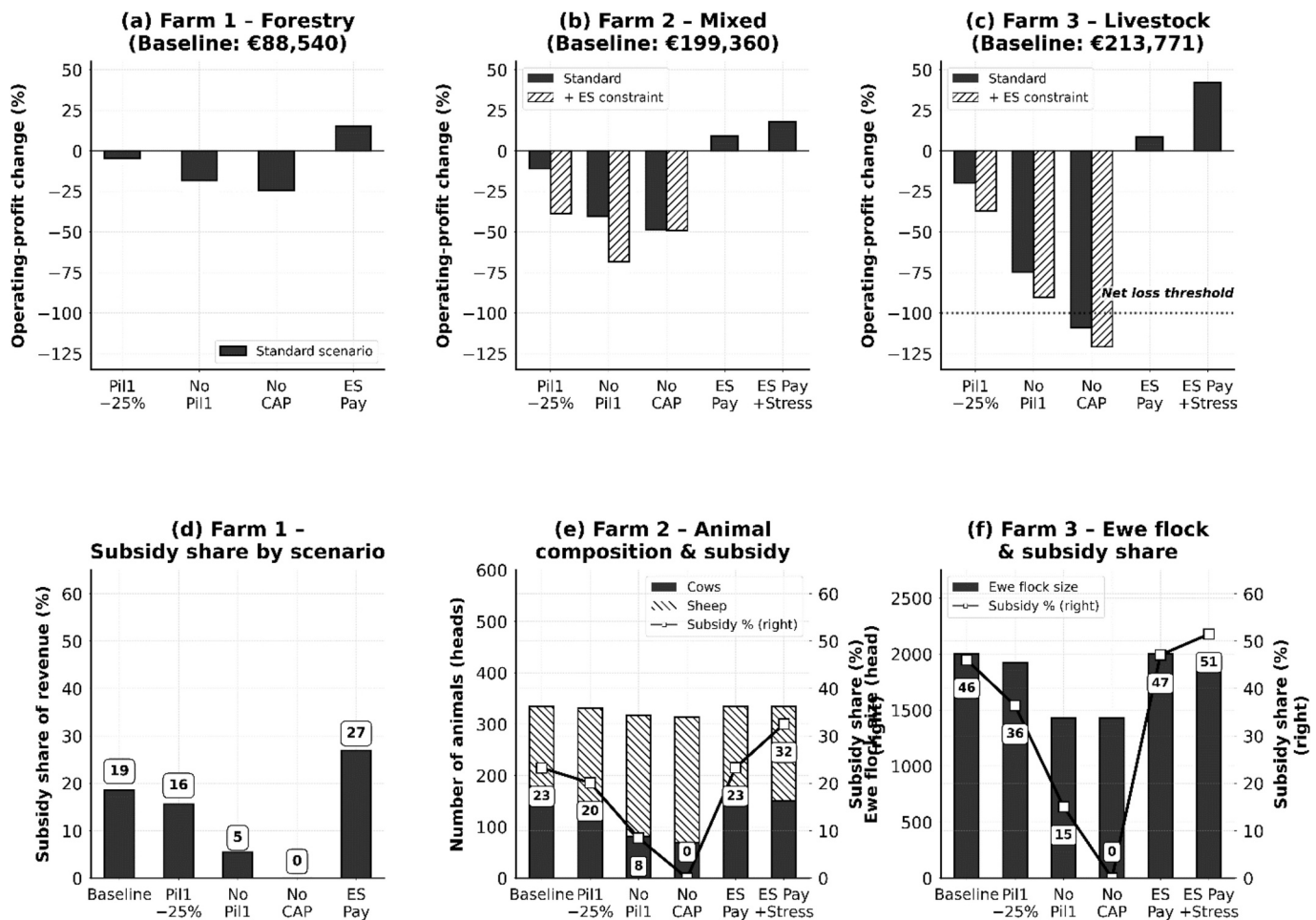


Fig. 6. Operating-profit change and structural adaptation under CAP policy reform scenarios: effects of Pillar I reduction or removal, full subsidy removal, and current measures + ecosystem service payment schemes across three Montado farm archetypes.

Pillar I scenarios reveal how coupled payments drive livestock choices. In Farm 2, a 25% Pillar I cut triggers a species rebalancing: cows fall by 8.8% while sheep rise by 5.3%. As suckler cow subsidies exceed sheep payments, reducing them shifts the relative profitability toward sheep. In Farm 3, the removal of Pillar I support reduces the flock from 2000 to 1430 ewes. The income loss exceeds direct subsidy withdrawal, as the smaller herd also generates less sales revenue, compounding the shock.

The No CAP scenario highlights the role of agri-environment payments in maintaining extensification. For Farm 2, removing all subsidies causes open pasture to collapse from 220 to 83.2 ha while crop area expands. Without grassland payments, the higher crop margin dominates land-use logic. For Farm 3, losing the steppe bird payment (totaling €16,080 yr⁻¹) reduces the incentive for cropping, causing a modest shift toward pasture. When combined with ES constraints, No CAP losses for Farm 3 deepen to -€44,629, as the farm must bear restructuring costs without public support.

The two ES-payment scenarios illustrate different policy designs. The “ES Pay” scenario acts primarily as an income supplement, providing gains of +15.1% for Farm 1, +9.1% for Farm 2, and +8.5% for Farm 3 with minimal behavioral change. The “ES Pay + Stress” design, which pays €20 per additional ES point above baseline, triggers significant land-use shifts. This results-based payment is large enough to more than offset the opportunity costs of ES compliance, raising operating profit by 17.8% for Farm 2 and 42.2% for Farm 3. While this demonstrates the power of results-based incentives, the magnitude of gains suggests careful calibration is needed to avoid over-compensating farms beyond

their empirical compliance costs.

3.6. Sensitivity analysis and climate scenario calibration

A one-at-a-time sensitivity analysis identified the parameters with the greatest influence on operating profit to guide climate-scenario construction (Fig. 7; Table S11). Parameters were tested across three levels (L1–L3) based on literature-derived ranges. Those triggering an operating-profit change greater than 5% at the maximum shock (L3) were classified as “high-impact” and used to differentiate between Moderate (L1) and Extreme (L3) scenarios. Low-impact parameters were held at the midpoint (L2) to ensure internal consistency.

Farm 1 is dominated by cork-related variables. Cork price produces the largest OP response (+37.2%), while yields and area reductions cause losses of -16.0% and -15.4%, respectively. This near-equivalence between price premiums and physical losses explains the positive OP response under the Moderate climate scenario.

Farm 2 shows the strongest sensitivity to animal energy requirements (-19.4%), fertility (-15.3%), and water availability (-13.9%), identifying a “livestock-crop-water nexus” as its primary vulnerability. Corn (+13.9%) and hay prices (+8.8%) show positive sensitivity, as the model reallocates land toward these outputs when their value rises.

Farm 3 is governed by ewe fertility (-14.6%), hay price (+13.9%), and forage variables such as energy requirements (-7.6%) and hay yield (-6.9%). This confirms that the livestock-specialized system is driven by flock performance and forage balance rather than crop or forestry

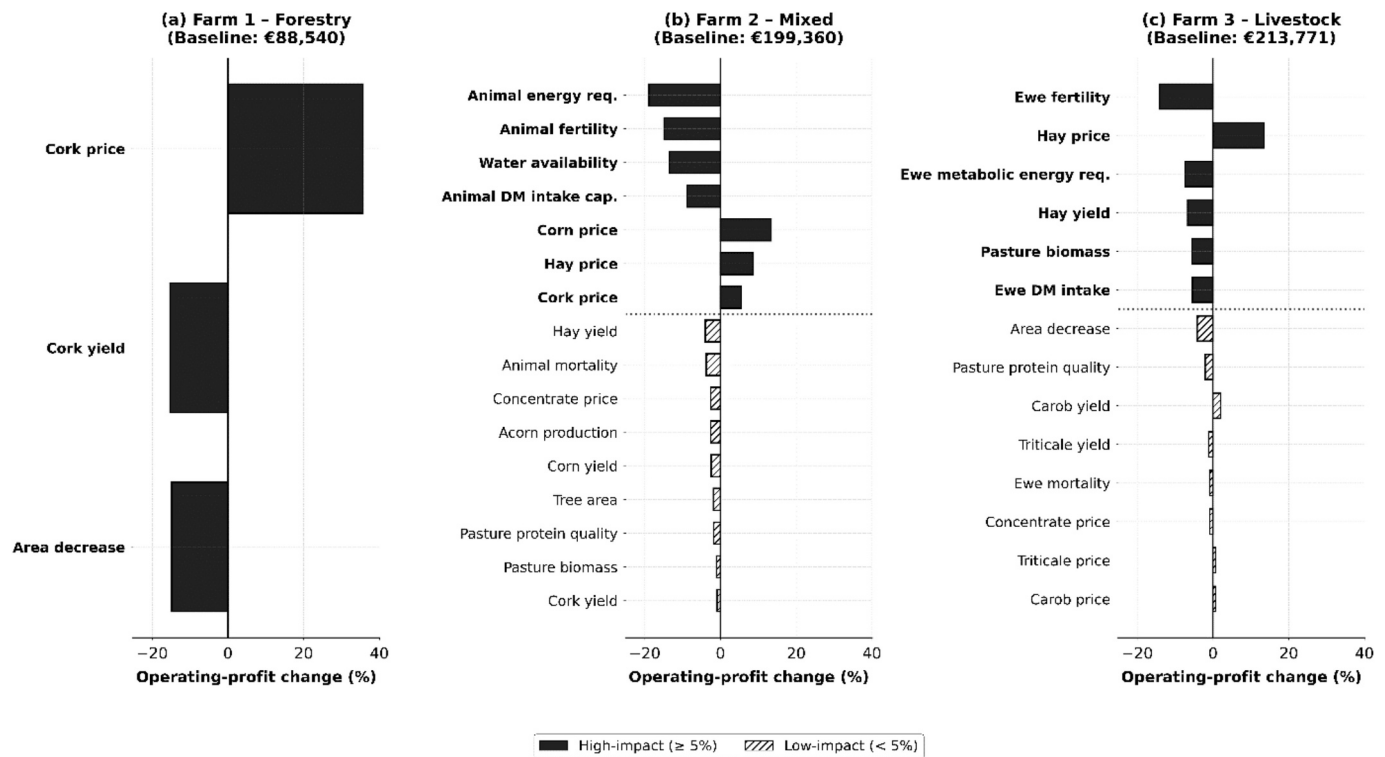


Fig. 7. One-at-a-time sensitivity analysis of operating-profit change (%) to individual parameter maximum shock level. Bold solid bars = high-impact parameters assigned differentiated shocks (L1 moderate / L3 extreme) in climate scenarios; hatched bars = low-impact parameters held at the intermediate fixed value (L2) in both climate scenarios. Dotted line separates the two tiers.

market dynamics.

These profiles reveal structurally distinct vulnerabilities: Farm 1 is governed by a single commodity's price-yield relationship, Farm 2 by mixed-system interactions, and Farm 3 by the forage-livestock balance.

3.7. Climate stress scenarios

Climate scenarios simulate Moderate and Extreme biophysical stress conditions, with high-impact parameters differentiated according to the sensitivity analysis (Section 3.6). Results are reported in Fig. 8 and Table S16.

The three archetypes respond in qualitatively different ways.

Farm 1 (forestry-oriented) produces a counterintuitive +1.9% operating-profit gain (€90,239) under the Moderate scenario. Although tree area and cork yield fall by 7% and 5%, respectively, a +15% cork price increase, reflecting market supply restrictions, acts as an income hedge. Per-hectare revenue rises by 9.3%, more than offsetting physical losses. However, under the Extreme scenario, physical losses (area –15%, yield –15%) dominate the 35% price premium, causing operating profit to fall by 2.2%. Market dynamics thus provide a short-term buffer without guaranteeing broader ecological robustness.

Farm 2 (mixed farm) exhibits the highest climate sensitivity, losing 19.1% of operating profit under Moderate and 36.0% under Extreme. This severity is driven by a “compound shock”: feed supply falls (pasture DM –30%) while heat stress increases animal energy requirements (+15% for cattle). The model responds by expanding pasture (+18.2%) at the expense of crops, yet the total feed base remains insufficient; LSU falls by 15.4% under Moderate and collapses by 65.7% under Extreme. Under Extreme stress, herd contraction is so severe that freed land reverts to cropping, as livestock feeding becomes economically prohibitive.

Farm 3 (livestock-oriented) occupies an intermediate position, losing 8.9% under Moderate and 22.1% under Extreme. Its economic resilience is aided by milder pasture productivity shocks and a non-

climate income boost from maturing carob trees (rising from €3024 to €8176/yr). Under Moderate stress, the ewe flock contracts slightly (–4.9%), while crops expand marginally due to higher hay prices (+15%). Under Extreme stress, however, the flock contracts sharply to 1484 ewes (–25.8%), and concentrate purchases double as the farm struggles to supplement a depleted forage base.

The ecosystem services constraint reveals an asymmetric feasibility pattern. For **Farm 2**, Moderate ES is infeasible, while Extreme ES is feasible (OP –58.2%). Under Moderate stress, the remaining herd (211.3 LSU) cannot be nutritionally sustained once the ES floor forces cropland to near-zero. Under Extreme stress, the herd has already collapsed to 85.7 LSU, making the ES-compliant land configuration feasible to support the smaller population. For **Farm 3**, the pattern is reversed: Moderate ES is feasible, but Extreme ES is infeasible. Under Extreme stress, sharper pasture and hay yield reductions create a “forage bottleneck” in which the ES floor and nutritional requirements cannot be satisfied simultaneously.

Feed self-sufficiency declines with shock intensity. Farm 2 drops from 94.8% to 89.2% as energy requirements rise and pasture falls. Farm 3 maintains higher self-sufficiency (falling only to 95.9% under Extreme), consistent with its less severe pasture productivity shocks.

3.8. Cross-farm resilience comparison

Fig. 9 presents the operating-profit sensitivity of each farm across all feasible standard scenarios, expressed as percentage change from the calibrated baseline. This heatmap forms the empirical basis for all economic resilience and risk metrics reported in this section, each of which is derived directly from the scenario-level $\Delta OP\%$ values it displays.

The heatmap reveals three structurally distinct performance profiles. **Farm 1** shows a narrow band of consistent, moderate losses with occasional gains, indicating low exposure across all shock domains. **Farm 2** exhibits a more variable profile, with sharp declines specifically under policy and climate stress. **Farm 3** displays the widest range, spanning

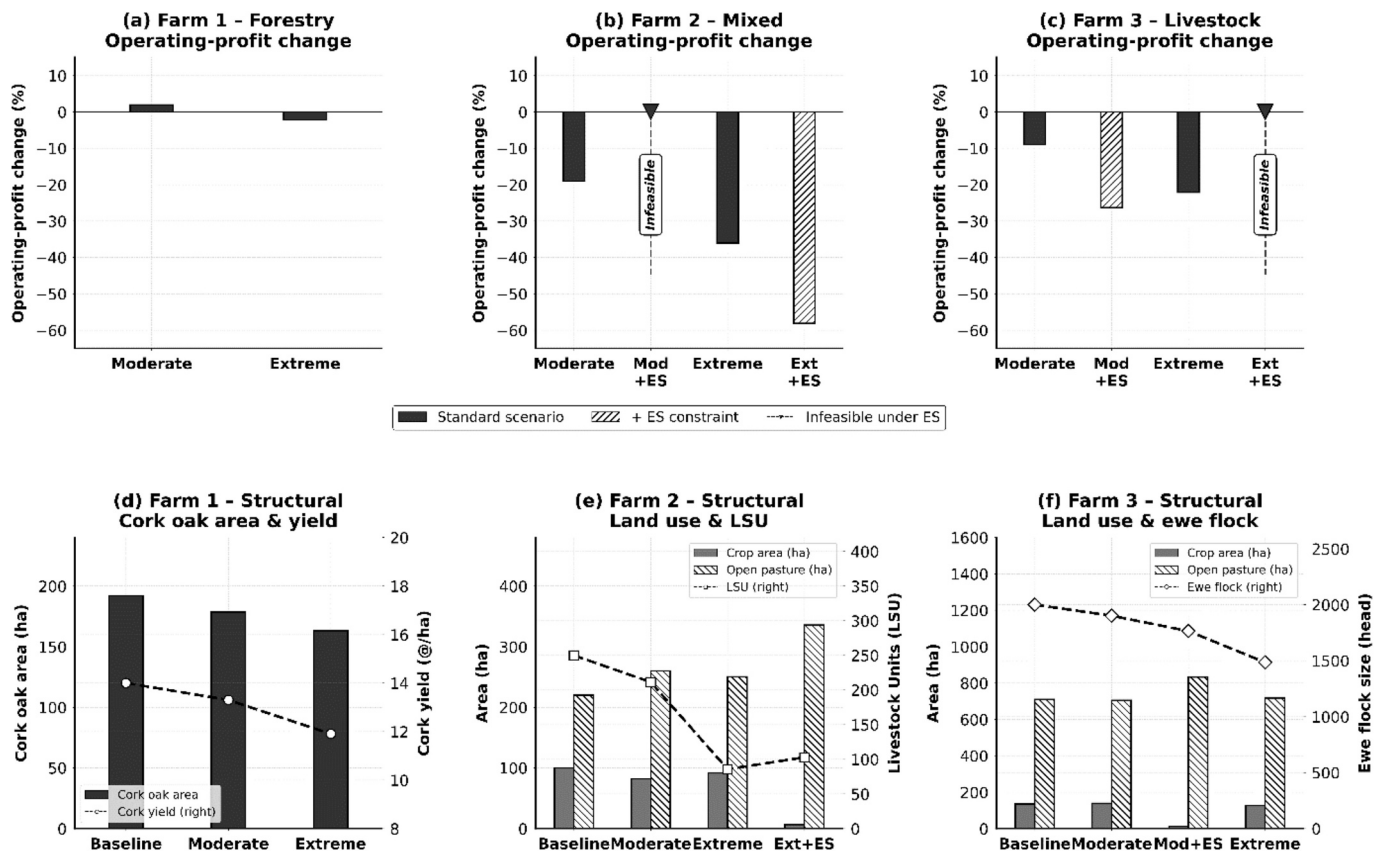


Fig. 8. Operating-profit change and structural adaptation under moderate and extreme climate stress scenarios across three Montado farm archetypes; Top row: operating-profit change (%) relative to the calibrated baseline under standard and ES-constrained conditions. Bottom row: corresponding structural adjustments (cork oak area and annualised yield for Farm 1; crop and open pasture area with livestock numbers for Farms 2 and 3). Moderate = RCP4.5 consistent parameter shocks (L1 high-impact + L2 low-impact); Extreme = RCP8.5 consistent shocks (L3 high-impact + L2 low-impact). Hatched bars = ES provision requirement imposed simultaneously with climate shock. Triangle markers indicate infeasible scenarios under ES constraint.

the study's largest loss (No CAP, −109.0%) and its largest gain (ES Pay + Stress, +42.2%), confirming it is simultaneously the most vulnerable and most policy-responsive archetype.

The **Resilience Index** summarizes these distributions into a single measure (Fig. 10; Table 3). Farm 1 records the highest overall RI (0.907), followed by Farm 2 (0.839) and Farm 3 (0.752). This establishes a clear resilience gradient moving from forestry-specialized to livestock-specialized systems. Farm 1's market-family RI is slightly inflated by exposure to only one feasible scenario (the Fertilizer Spike), though this does not alter the overall ranking. Farm 1's higher RI should be interpreted cautiously, as its fixed accounting structure limits endogenous adjustment and the RI is proportional rather than absolute.

Breaking the RI down by scenario family highlights where this gradient is most pronounced:

- **Policy Family:** This domain produces the strongest divergence. Farm 3 records the lowest policy RI (0.491) and is the only archetype to become unprofitable under a feasible standard scenario (No CAP, RI component = −0.090).
- **Climate Family:** Farm 3's climate RI (0.845) is higher than Farm 2's (0.725). This confirms that Farm 3's most severe vulnerability is institutional rather than biophysical.
- **Labor and Market Families:** These show the smallest divergence across archetypes, reflected by the narrow, uniform band of moderate losses across the heatmap.

The scale-sensitivity analysis (Supplementary Material S17) showed that Farm 1's RI remained nearly invariant across the tested scales (0.906–0.907), although this partly reflects its deterministic model

structure. Farm 3's policy exposure persisted across all scales. Farm 2 was the most scale-sensitive, with raw RI values ranging from 0.752 to 0.889; using the common feasible scenario subset narrowed this range to approximately 0.819–0.889. After harmonizing scenario feasibility, the overall RI ordering (Farm 1 highest, Farm 2 intermediate, and Farm 3 lowest) remained consistent across scales. Thus, some vulnerability patterns were not solely determined by baseline farm size, although response magnitudes remained scale-dependent.

The operating-profit proxy did not alter the positive/negative classification for the representative configurations. However, the scale analysis identified a boundary case: at 1366 ha, the livestock-specialized No CAP scenario retained a positive gross margin (€3426) but produced a negative operating-profit proxy (−€3574). Gross margin can therefore overstate capacity to cover costs near the viability threshold.

CVaR and volatility metrics (Table 3; Fig. 10) capture tail risks that the mean RI misses. CVaR (worst 25% of scenarios) confirms the economic resilience ranking: Farm 1 has the lowest risk (−21.3%), followed by Farm 2 (−36.1%) and Farm 3 (−56.4%). Operating profit volatility follows the same order: ±11.3 pp. for Farm 1, ±18.6 pp. for Farm 2, and ±36.0 pp. for Farm 3. Farm 3's high volatility reflects its wide performance range, from severe losses to significant gains under ES payment scenarios.

Solvency and policy drag metrics (Table 3; Fig. 10) further isolate policy-specific vulnerabilities. Farm 1 and Farm 2 remain solvent across all standard scenarios (8/8 and 13/13, respectively), whereas Farm 3 becomes insolvent in the “No CAP” scenario (12/13). Policy drag is 0.063 for Farm 1, 0.093 for Farm 2, and 0.260 for Farm 3. Farm 3's high policy drag underscores its disproportionate vulnerability to subsidy removal. Together, these metrics confirm that economic resilience is

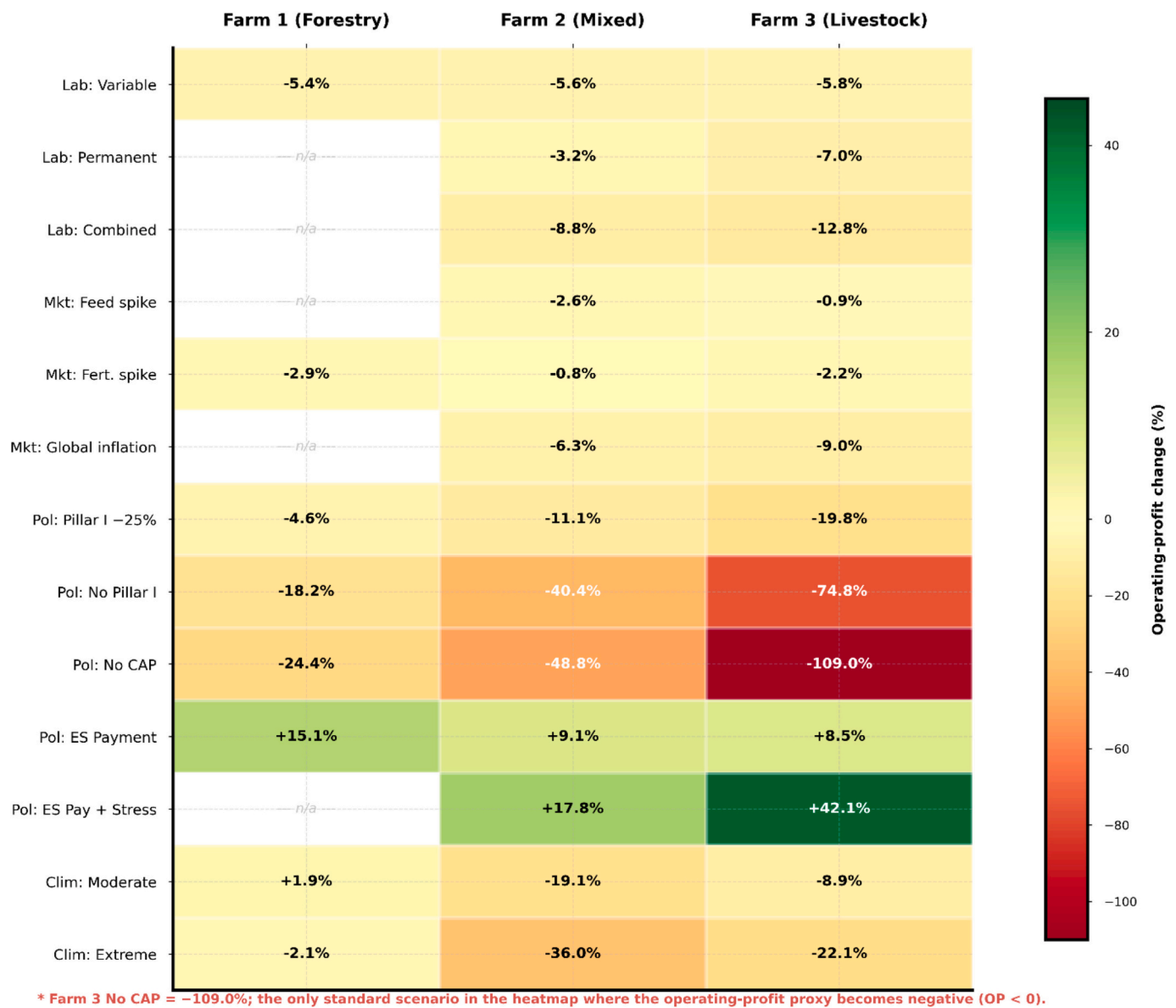


Fig. 9. Heatmap of operating-profit sensitivity (% change from baseline) to labor, market, policy, and climate shocks across three farm types; green cells indicate positive outcomes, red cells indicate losses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

multidimensional: baseline economic strength does not preclude severe tail exposure.

Three structural features explain the observed resilience gradient:

- **Diversification:** Diversification dampens shocks, enabling the mixed farm (Farm 2) to outperform the livestock-oriented farm (Farm 3) despite its stronger exposure to water and energy stress.
- **Subsidy Dependency:** High dependency is the dominant source of downside vulnerability, particularly for Farm 3, where it drives both the lowest policy RI and the highest policy drag.
- **ES Payments:** Results-based payments function as a genuine economic resilience instrument, producing the only consistently positive outcomes under adverse conditions and most strongly benefiting the most policy-exposed archetypes.

4. Discussion

4.1. Structural heterogeneity as the primary determinant of economic resilience

The central finding is that economic resilience in the Montado is shaped by farm configuration rather than by the shared landscape label alone. Resilience indices ranged from 0.907 in the forestry-specialized archetype to 0.752 in the livestock-specialized archetype, showing that farms embedded in the same agroecosystem can respond very differently to the same external shocks. This answers the first research question and indicates that farm structure is a primary determinant of how economic viability and ecosystem-service provision are maintained under stress.

The operating-profit per hectare gradient, highest in forestry-specialized, intermediate in mixed, and lowest in livestock-specialized systems, suggests that the most resilient archetype is also the most land-efficient in income terms. This is consistent with findings that cork-oriented systems generate high total value by combining market outputs

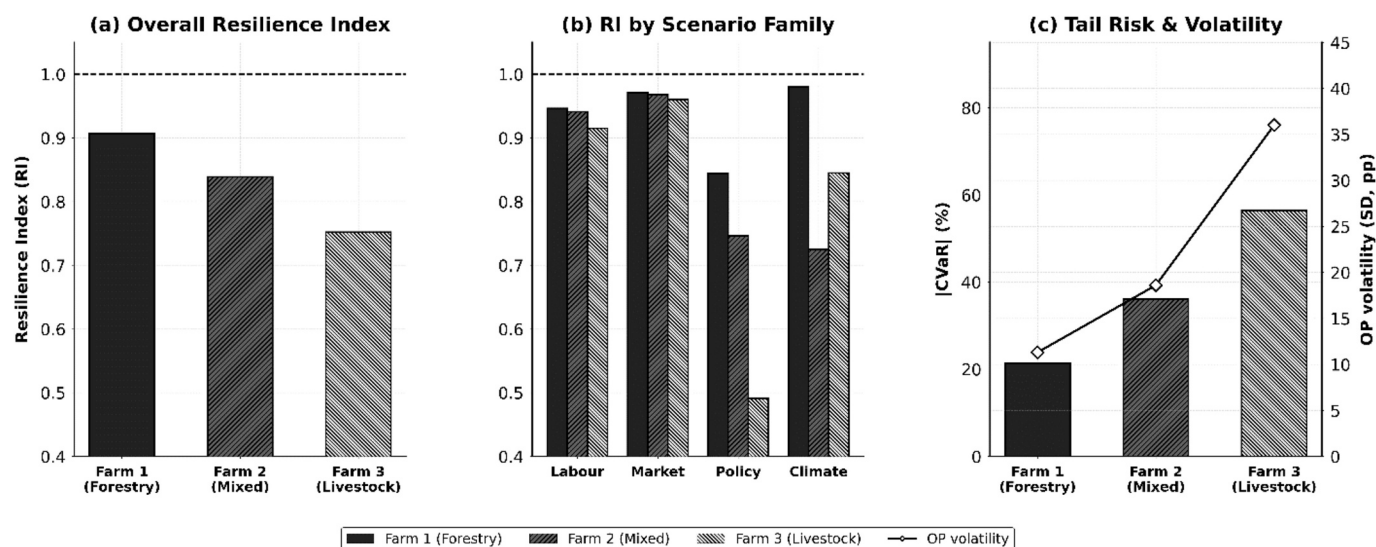


Fig. 10. Cross-farm resilience assessment: overall and scenario-specific resilience indices (RI), conditional value-at-risk (CVaR, mean loss in worst 25% of scenarios), and operating-profit volatility across labor, market, policy, and climate shock families.

Table 3

Summary resilience and risk metrics by farm.

Metric	Farm 1 (Forestry)	Farm 2 (Mixed)	Farm 3 (Livestock)
Overall RI	0.907	0.839	0.752
Labor RI	0.946	0.941	0.915
Market RI	0.971	0.968	0.960
Policy RI	0.844	0.746	0.491*
Climate RI	0.980	0.725	0.845
CVaR (worst 25%)	−21.3%	−36.1%	−56.4%
OP volatility (SD)	±11.3 pp	±18.6 pp	±36.0 pp
Solvency rate	8/8	13/13	12/13
Policy drag on RI	0.063	0.093	0.260

RI = mean of $(1 - |\Delta\text{OP}\%|/100)$ across all feasible standard scenarios. CVaR = mean $\Delta\text{OP}\%$ of worst 25% loss scenarios. Policy drag = overall RI minus policy-family RI. pp. = percentage points. OP = operating-profit proxy.

* Farm 3 Policy RI is depressed by the No CAP scenario, in which the operating-profit proxy becomes negative ($\Delta\text{OP} = -109.0\%$; RI component = -0.090).

with ecosystem-service benefits (von Essen et al., 2019). The structural attributes underlying this value, particularly low dependence on variable costs and purchased inputs, also confer greater economic stability under stress.

Montado economic resilience thus derives from how trees, pasture, crops, livestock, and subsidies integrate at the farm level. The Montado literature has predominantly treated the system as a multifunctional landscape at governance or landscape scale rather than through differentiated farm economics (Muñoz-Rojas et al., 2019; Pinto-Correia et al., 2019). These results add a farm-level dimension by showing that structurally distinct configurations respond differently to policy, climate, labor, and market stress.

This interpretation is reinforced by comparison with the expert-based scenario assessment by (Fatahi et al., 2026), which analyzed these three archetypes using conceptual models and expert scoring. That study found that the forestry-oriented systems balanced environmental performance with labor and market sensitivity, livestock system prioritized short-term economic performance at the expense of ecological indicators, and mixed systems showed the most balanced sustainability profile through diversification. The quantitative results presented here are broadly consistent with those qualitative patterns, while also identifying the economic mechanisms underlying them, notably subsidy dependency, feed self-sufficiency, input exposure, and land-use rigidity. This convergence between methodologically distinct approaches

increases confidence that the economic resilience differences identified here reflect robust structural properties rather than artifacts of a single analytical method.

Beyond the tested scenario, additional diversification pathways may also shape future resilience. These include carbon-market participation, low-input aromatic and medicinal plants, rural agrotourism, and carefully designed agrivoltaics arrangements. These options will not replace the structural reforms identified in the scenario analysis, but could reduce income dependence on the main stressor domains examined here and deserve consideration in future modelling and policy work.

4.2. The dual role of diversification: buffer or binding constraint?

The stressor categories posing income risk are not uniform across systems. A particularly important result is that the mixed archetype is more climate-vulnerable than the livestock-specialized archetype despite being more diversified. This is analytically important because diversification is often assumed to improve resilience (Dumont et al., 2022).

Diversification is an attribute of general resilience (Cabell and Oelofse, 2012). However, in this study it did not improve specific resilience to climate stress, as diversified activities created correlated vulnerabilities (irrigated crops, water constraints, feed-energy interactions). In this case, diversification also creates additional points of exposure: irrigated crop dependence, water constraints, labor complexity, and tighter interactions between feed requirements and purchased inputs. Diversification thus improves resilience only when it reduces net dependency, not when it introduces new binding constraints. This may also help to interpret economic resilience differences in other Mediterranean mixed farming systems, including Dehesa-type and semi-arid silvopastoral systems, where diversification is often treated as beneficial without distinguishing between buffering and dependency-creating forms of diversification (Dumont et al., 2022).

By contrast, the livestock-specialized system's relatively stronger performance under climate stress is linked to very high feed self-sufficiency. Feed autonomy functions as an economic resilience buffer, preventing biophysical shocks from propagating into greater input-market dependence. Under adverse pasture conditions, the livestock-specialized system primarily adjusts through flock contraction, whereas the mixed system is more exposed to the combined effect of production loss and cost escalation. Feed self-sufficiency thus emerges as one of the clearest structural buffers against climate stress in extensive

livestock systems, with implications for targeting resilience-building interventions across Mediterranean dryland contexts.

The forestry-specialized system presents a different pattern. Under the moderate climate scenario, it records a small positive operating-profit response because the cork price increase outweighs the reduction in productive area and yield. This should not be interpreted as ecological security, however: recent evidence highlights long-term threats from tree decline, regeneration failure, and hydric stress (Arosa et al., 2017; Sucena-Paiva et al., 2022). Our result likely reflects a short to medium-term income effect within a static framework: the same price-quantity dynamic that temporarily buffers income could reverse sharply if climate stress compounds with cork oak decline, pathogen outbreaks, or failed regeneration, thus, exposing a commodity-concentration vulnerability that standard scenarios only partially address.

Labor constitutes another structural exposure that price-shock scenarios only partially capture. The labor scenarios model a cost increase applied to contracted and permanent labor, but farmers also pointed to two qualitative dimensions of labor risk that fall outside the model scope. First, the availability of workers with the specialized skills required for cork harvesting and pruning is declining in rural southern Portugal as younger people move to urban employment and artisanal knowledge is progressively lost. Cork harvesting requires trained operators, since mistakes in bark stripping can damage trees for an entire nine-year production cycle. Second, labor availability is especially constrained during narrow, weather-dependent peak periods when many farms require the same skilled workers simultaneously. Skill erosion and seasonal unavailability deserve explicit treatment in future resilience assessments.

The market scenarios reinforce this structural reading. Input price shocks remain economically relevant, but their impact is strongly mediated by baseline input dependence. Both livestock farms have high feed autonomy, which insulates them from the sector-wide commodity price dynamics observed in 2021–2022. Extensive systems are thus not inherently fragile to market shocks; exposure arises when their production model is coupled to external input-market dependence. This distinction matters because discussions of agricultural vulnerability often collapse very different forms of exposure into a single extensive versus intensive comparison (Giannakis, 2010). What matters more is the specific dependency structure of each farm, a point that applies equally to Montado, Dehesa, and other Mediterranean silvopastoral systems where structural heterogeneity is large but analytical differentiation has remained limited (Plieninger et al., 2021).

4.3. Policy design as a resilience instrument: from income support to ecosystem service provision

The fact that the most subsidy-dependent archetype is also the most exposed to subsidy withdrawal is expected. The contribution of the analysis lies less in the direction of this result than in three quantities it makes explicit: the magnitude of exposure (No CAP reduces Farm 3's operating profit by 109.0% at baseline scale), the point at which support removal crosses the viability threshold (operating-profit proxy turning negative), and the differing structural buffers available to each configuration, diversification in the mixed system versus feed self-sufficiency in the livestock-specialized system. Read this way, the policy scenarios characterize not only which farm is most sensitive, but how far and through which mechanisms that sensitivity operates.

Farm 1's relatively high ES value partly reflects its fixed woodland area and the higher coefficient assigned to oak woodland. It should not be interpreted as direct evidence of superior ecological condition or management quality, which the indicator does not measure.

The ecosystem-service scenarios show two closely related results. First, the opportunity cost of additional ES provision is non-linear: it remains modest at low ambition levels but rises sharply once farms exhaust their least costly adjustment margin, primarily cropland

reallocation. Second, the economic effect of ES-oriented policy depends strongly on instrument design. A proportional payment linked to computed ES value mainly acts as an income supplement, whereas a marginal payment tied to additional ES generation can materially alter the production plan and, at sufficiently high rates, more than compensate the opportunity cost of compliance.

This has direct implications for payment design. A flat-rate payment calibrated to an average compliance cost is unlikely to perform well in a structurally heterogeneous landscape. Farms with narrow adjustment margins may be under-compensated once ES requirements become binding, while farms with wider adjustment margins may be over-compensated. The source of this non-linearity is not the ES metric itself, but the farm's production structure, specifically its capacity to substitute among crops, pasture, and livestock while remaining nutritionally and financially feasible. These results reinforce arguments for results-based approaches that reward ecological outcomes rather than prescribe uniform management actions (Helena Guimarães et al., 2023), while adding that compensation must reflect marginal opportunity cost, not only average ES value.

The broader implication is that economic resilience cannot be inferred from the level of support alone, what matters is its architecture. Where direct income support dominates, economic resilience may be maintained only superficially because the farm's underlying market position remains fragile. By contrast, payments aligned with ecosystem-service provision can improve both ecological targeting and economic viability when they reward structures that are already service-rich (Helena Guimarães et al., 2023). The very large gains under the constrained marginal-payment scenario nonetheless indicate that calibration discipline is essential to avoid systematic over-compensation.

Taken together, the scenario families point to several principles for future policy design. First, moving away from coupled direct-income support toward result-based payments, rewarding service-rich configurations, could reduce the viability threshold risk revealed by the No CAP scenario. Second, ES payments appear most effective when introduced alongside baseline structural support, since the ES Pay + Stress scenario generates the strongest positive outcomes in a system already operating within a supportive policy environment. Third, the non-linearity of ES provision costs suggests that schemes targeting lower levels of the ES ambition curve may deliver greater ecological benefit per euro spent, whereas schemes set near structural feasibility limits impose disproportionately high costs that flat-rate payments are unlikely to cover. These principles align with the broader Montado governance literature showing that the form, not only the level, of support shapes farm viability and ecological outcomes over the medium term (Muñoz-Rojas et al., 2019; Pinto-Correia and Azeda, 2017).

4.4. Implications for policy design and future research

The findings of this study point toward a broader reframing of resilience in agro-silvopastoral systems. In the Montado, economic resilience is not an intrinsic property of the landscape itself, but of the specific economic configuration through which that landscape is managed. This has implications beyond Portugal. The Dehesa, which shares the Montado's ecological identity but contains its own gradient of specialized, mixed, and livestock-dominated farm structures, is likely to exhibit comparable patterns of differentiated vulnerability and similar opportunities for archetype-sensitive policy design (Plieninger et al., 2021). The same rationale applies to other Mediterranean dryland systems where the interaction of subsidy architecture, input dependency, and land-use flexibility shapes the economic viability of farms that also deliver significant public goods.

One implication not immediately surfaced by the resilience gradient is that the forestry-specialized archetype, while the most economically stable, is effectively unreplicable for farms that have already undergone tree cover degradation. Even where livestock or mixed-system farmers recognise the structural advantages of a cork-dominant model,

transitioning toward it requires investment in tree regeneration whose returns materialize only after approximately 25 to 30 years from planting to first cork harvest.

Regeneration is not only long-horizon but also costly and ecologically uncertain: success rates are sensitive to grazing pressure, competing vegetation, and increasingly to the very climate stresses this study documents. For farmers already in the latter stage of their working lives, a demographic well represented among current Montado managers, investing in an activity whose returns lie beyond their own farming horizon represents a rational barrier. This barrier is compounded by the operational reality of sustaining existing activities under financial and climatic pressure while initiating a parallel multi-decade regeneration programme, a dual demand whose risk of failure on either front adds further dissuasion. Policy instruments designed to support tree regeneration therefore need to account for this structural constraint explicitly, through long-term contracts, upfront establishment payments, and intergenerational succession incentives, rather than assuming that the economic logic of the forestry model is sufficient to generate spontaneous structural transition.

Several limitations of our study should be kept explicit. First, the analysis is based on three archetype-representative case studies rather than a statistically representative farm sample. Second, the framework is static and comparative, so it captures exposure at the observed farm configuration but not endogenous long-term adaptation, investment, entry-exit, or inter-temporal tree-regeneration dynamics. Third, the ecosystem-service coefficients are stylized comparative proxies rather than farm-specific marginal valuations. Fourth, the scenario bundles are structured stress tests, not forecasts. A natural next step is therefore to move from static comparative analysis toward dynamic modelling of farm trajectories under compound shocks, in which climate stress, policy reform, and market volatility interact simultaneously rather than being tested in isolation. These interactions appear non-additive: the mixed system reaches feasibility limits under combined climate and ES constraints that neither stressor triggers alone, while the livestock-specialized system's worst-case policy exposure is dramatically altered by ES-payment design. Understanding when such interactions become binding, and for which archetypes, would materially improve the evidence base for CAP reform and climate-adaptation planning across Mediterranean agro-silvopastoral systems. Also, model architecture limits comparison: Farm 1 is deterministic, whereas Farms 2 and 3 optimize endogenously. Another limitation is that the analysis does not capture interactions among farms or with the wider Montado system. Landscape-scale or agent-based modelling would be needed to assess these interdependencies. Finally, each management configuration is represented by one case-study farm, which prevents statistical inference. The robustness test assesses dependence on farm size but does not replace independent replication across farms.

More broadly, the study suggests that farm typology should become a standard input into agri-environmental policy assessment in heterogeneous landscape systems. Instruments calibrated to an average farm profile risk being poorly targeted across structurally distinct types, misaligning support with both viability needs and ecosystem-service outcomes. The combination of calibrated farm-level modelling, archetype-based scenario analysis, and resilience metrics developed here offers a replicable framework for generating that typology-informed evidence, both within the Montado and across Mediterranean agroecosystems facing the converging pressures of climate change and agricultural policy reform.

5. Conclusions

This study shows that the Montado should not be analyzed, or governed, as a single economically or ecologically uniform agroecosystem. Beneath the shared landscape label lie structurally distinct farm archetypes whose economic resilience differs markedly under the same external shocks and whose ecosystem-service trade-offs are not

equivalent. By comparing three case-study farms representing different Montado archetypes, the analysis found that the forestry-specialized archetype is the most resilient overall, the mixed archetype is the most climate-sensitive, and the livestock-specialized archetype is the most policy-exposed. These differences arise from structural characteristics, especially subsidy dependence, feed autonomy, and land-use flexibility, rather than from farm size alone.

The paper also shows that the economic cost of additional ecosystem-service provision is highly non-linear and archetype-specific. As ES requirements become more restrictive, costs rise sharply once the least costly land-use adjustments are exhausted. At the same time, the results demonstrate that policy design can materially alter resilience outcomes. A proportional ES payment mainly supplements income, whereas a marginal results-based payment can substantially reshape incentives and, if calibrated generously, more than offset the opportunity cost of compliance. This confirms that policy architecture matters as much as policy volume.

Across the three archetypes, economic resilience was strongly conditioned by structural configuration. The forestry-oriented archetype was the most resilient, the mixed archetype showed the strongest climate sensitivity, and the livestock-specialized archetype was the most policy dependent. Ecosystem-service provision also generated non-linear and archetype-specific opportunity costs, indicating that uniform agri-environmental payments are unlikely to be efficient across structurally heterogeneous farms. The main implication is that agri-environmental policy for Montado-type systems should be archetype-sensitive rather than calibrated to an average farm profile. More broadly, the findings show that economic resilience in Mediterranean agroecosystems is inseparable from farm structure, land-use composition, and policy design.

CRedit authorship contribution statement

Nour-Elhouda Fatahi: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Seyed-Ali Hosseini-Yekani:** Writing – review & editing, Validation, Software. **Teresa Pinto-Correia:** Supervision, Resources, Conceptualization. **Maria de Belém Costa Freitas:** Validation, Resources, Methodology. **João Tiago Marques:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization. **Hatem Belhoucette:** Writing – review & editing, Validation, Supervision, Software, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agry.2026.105014>.

Data availability

Data will be made available on request.

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