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# Adapting Mediterranean Agroforestry to Global Change: Trade-Offs and Lessons from the Montado

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## Abstract

The Montado, a traditional Mediterranean agro-silvopastoral system, has historically sustained ecological and economic functions through the integration of trees, livestock, and crops. Today, its multifunctionality is increasingly threatened by climate variability, market volatility, and evolving policy frameworks. While previous research has examined Montado dynamics at landscape or plot scales, less attention has been paid to sustainability trajectories at the farm level, where management decisions are made. This study bridges that gap by assessing the sustainability dynamics of farms through a participatory, typology based, scenario approach grounded in a regional typology. We characterized three representative farm archetypes (forestry-focused, mixed agro-silvopastoral, and livestock-focused) and evaluated their trajectories under plausible future scenarios driven by climate, market, and policy pressures. Scenario outcomes were assessed using expert-based scoring (five-point scale), revealing score differences of up to two points across sustainability dimensions between farm archetypes and scenarios. Findings reveal marked trade-offs: Tree-focused farms maintain high environmental value but remain vulnerable to market and labor constraints, while livestock-specialized farms achieve higher economic output at the expense of ecological integrity. Mixed systems demonstrate greater resilience through diversification but face significant labor intensity challenges. We conclude that current "one-size-fits-all" policies generate contradictory incentives. Therefore, adaptive governance frameworks (e.g., results-based payment schemes) are essential to realign farm economics with ecological stewardship. Beyond the Montado, the approach provides insights relevant to other Mediterranean agroforestry systems facing similar sustainability challenges.

**Keywords:** multifunctionality; agro-silvopastoral systems; Montado; common agricultural policy; mediterranean

## 1. Introduction

Mediterranean agricultural systems have evolved over centuries in response to local climatic, topographic, and resource constraints. These conditions favored diversified, low-input systems integrating crops, livestock, trees, and wetlands into resilient and complementary production mosaics. Such systems maintained socio-ecological functioning through synergies among components, contributing to relatively closed nutrient, biomass, and water cycles [1]. Extensive practices such as rotational grazing and low stocking rates, supported by farmers' knowledge, traditions, and rural institutions, contributed to sustaining multifunctionality (in this paper, the term "multifunctionality" is used to describe the capacity of the system to perform multiple functions simultaneously, delivering a range of economic, environmental, social, and cultural benefits) and ecosystem services, including biodiversity conservation and fire risk regulation [2]. These systems gave rise to High Nature Value (HNV) landscapes that deliver agricultural products alongside regulating and cultural ecosystem services, while maintaining low dependence on external inputs [3,4]. While these systems operate across multiple spatial scales, this study focuses on the farm level, where management decisions mediate interactions between ecological processes, economic constraints, and policy frameworks.

Currently, this functional balance is increasingly challenged. Climate change affects the productivity and stability of Mediterranean agricultural systems by altering inter- and intra-annual water availability and increasing temperature extremes. These effects reduce pasture productivity and quality, intensify stress on livestock and perennial species, and increase exposure to pests, diseases, and wildfires [5,6]. In parallel, policy frameworks, particularly within the European Union Common Agricultural Policy (CAP), combined with market dynamics, contribute to divergent development trajectories. These include intensification, often favoring heavier livestock species, or abandonment of marginal lands [7,8]. While technological advances and irrigation expansion have increased productivity in some contexts, they have also modified land-use patterns and increased pressure on water resources [5].

Together, these climatic, economic, policy, and technical drivers challenge the long-term functioning and multifunctionality of Mediterranean agricultural systems, with implications for farm viability, biodiversity conservation, and landscape dynamics [1,9]. This raises the question of how these agricultural landscapes may evolve under ongoing global change and which management and policy pathways could support their sustainability.

The Portuguese Montado, functionally equivalent to the Spanish Dehesa, is a well-documented example of Mediterranean agro-silvopastoral systems. Covering approximately one million hectares, it is adapted to the low soil fertility and semi-arid climatic conditions of southern Portugal [10]. The Montado combines low-density cork oak (Quercus suber) and/or holm oak (Quercus rotundifolia) stands with understory or open pastures and annual crops. This configuration results in an agroforestry system where ecological values and management objectives are closely interlinked [11,12]. Livestock grazing is integrated to valorize pasture resources, alongside complementary activities such as hunting, mushroom picking, and rural tourism, contributing to system multifunctionality [13–15].

Despite its adaptive management history, the Montado has faced increasing pressures since the mid-twentieth century [12,16]. Tree density and land cover decline have been widely documented in Montado systems [17,18]. These trends have been associated with a combination of interacting drivers, including livestock stocking rates, soil compaction linked to mechanization, land abandonment, fire, disease, and recurrent droughts, as discussed in the cited literature. Differing policy priorities across governance levels further exacerbate these pressures, with the Common Agricultural Policy (CAP) constituting a key institutional driver shaping farm-level decisions in Montado systems. Since Portugal's ac-

cession to the EU, successive CAP reforms have influenced livestock composition, land-use choices, and incentives for maintaining integrated silvo-pastoral practices. For instance, CAP Pillar I coupled, and direct payments have often incentivized livestock intensification, particularly shifts from sheep to cattle. Such shifts have undermined conservation objectives embedded in Pillar II Agri-Environmental Schemes (AES), limiting tree regeneration and soil protection [19–23]. The resulting weakening of tree–pasture–livestock synergies increases system vulnerability and raises concerns regarding the long-term sustainability of the Montado. These contradictions highlight deeper tensions between land-use and management paradigms (productivist, conservationist, and multifunctional) that shape land managers' decisions and contribute to the limited progress in slowing Montado decline [20,24]. This motivates the explicit treatment of CAP-related constraints in the analysis that follows.

Research on Mediterranean agro-silvo-pastoral systems has largely focused on two main analytical scales, as illustrated by a range of previous studies. Territorial and landscape-scale studies have documented land-use dynamics and multifunctionality in Mediterranean agro-silvopastoral systems, including analyses of landscape structure, management intensity, and their evolution over time [25,26]. In contrast, plot-scale studies have focused on ecological and biophysical processes such as tree-grass interactions, grazing impacts, and soil and water-related constraints affecting system functioning, often through field-based or process-oriented analyses [27–30].

By comparison, relatively few studies adopt a holistic farm-level perspective that integrates environmental, economic, and social dimensions, and those that do, rarely incorporate forward-looking scenario assessments under global change [31,32]. Existing farm-level approaches provide valuable insights but tend to remain retrospective. Therefore, they may underrepresent farm-scale decision-making processes, where managers balance economic, ecological, and social trade-offs within highly heterogeneous contexts. As a result, system-wide assessments may mask farm-specific strategies and vulnerabilities, limiting the capacity to anticipate differentiated responses to global change.

To address these limitations, this study adopts a typology-based and scenario-driven approach that explicitly centers the farm as the primary unit of analysis. By combining representative farm archetypes, holistic conceptual models, and exploratory scenarios, the approach allows examination of how contrasting Montado farm systems may respond to future climatic, economic, and policy pressures. This framework makes it possible to explore differentiated sustainability trajectories and trade-offs while accounting for farm-level decision-making within broader territorial and institutional constraints.

First, we apply a typology-based selection of representative farms grounded in regional structural diversity. Second, we develop holistic conceptual models of contrasting Montado farm systems that integrate biophysical components, management practices, economic organization, labor, and policy context. Third, we use expert-based exploratory scenarios to assess medium-term (15–20 years) sustainability trajectories and trade-offs at the farm level under climatic, economic, and policy change. By placing the farm at the core of the analysis while explicitly accounting for territorial and institutional constraints, this approach allows for a differentiated understanding of how contrasting Montado farms respond to global change. Beyond the Portuguese context, it offers a transferable framework for assessing sustainability trade-offs in other Mediterranean and HNV agroforestry systems.

Scenario analysis based on intuitive logic structures the exploration of non-linear dynamics and systemic complexity through stakeholder-based storylines, moving beyond short-term quantitative trends [33,34]. This enables characterization of heterogeneous farm trajectories under global change, grounded in empirically informed system representations and stakeholder-derived narratives. At the same time, such exploratory scenarios rely

on explicit assumptions and expert judgment and are intended to illustrate plausible trajectories and trade-offs rather than to provide predictive forecasts.

Accordingly, the main aim of this study is to assess the sustainability dynamics of Montado farms through a participatory, typology-based, scenario approach grounded in a regional typology. To address this overarching aim, we pursue the following specific objectives: (1) to identify and characterize representative Montado farm archetypes, capturing their structural diversity, strengths, and vulnerabilities; and (2) to assess their sustainability trajectories under combined climatic, economic, and policy pressures, highlighting critical trade-offs and implications for farm-level management and policy design.

## 2. Materials and Methods

### 2.1. Study Area Context

The Montado, mainly located in the Alentejo region of southern Portugal, is shaped by a Mediterranean climate characterized by hot summers and high inter- and intra-annual rainfall irregularity [15]. This climatic variability leads to fluctuations in grass production and forage availability [15]. Average annual temperatures range from 14 to 17 °C, while average annual rainfall varies between 500 and 700 mm, primarily during the cooler months [35]. Soils in Alentejo, derived from granite and schist, are generally nutrient-poor [35]. Natural pastures support grazing by cows and sheep, with farmers actively managing soil fertilization and grazing intensity. However, these natural pastures face challenges due to low soil fertility and a diverse but low-productivity flora.

To enhance their farms, farmers employ diverse management practices related to tree cover, including fertilization, shrub clearing, and tree pruning. The spatial and temporal heterogeneity of the Montado has been widely documented in previous studies and is associated with increased richness of herbaceous, shrubby, and tree plants [36]. In addition to providing multiple products, such as cork, firewood, meat (beef, sheep, pig, and goat), mushrooms, aromatic herbs, and honey, Montado also provides a vast array of ecosystem services. These include the regulation of the water cycle, carbon sequestration, erosion prevention, high biodiversity, recreation and leisure activities, and the support of local identity [36].

Analysis of empirical data collected from the public website of Portugal's National Statistics Institute shows the development of Alentejo farms from 1989 up to 2019, when the latest agronomic census was conducted.

This historical background helps to explain the structural changes in Alentejo's agricultural landscape. The transition from annual arable crops to livestock farming (Figure 1a) was driven by both economic and political motivations, resulting in larger (from 38 ha/farm on average in 1989 to 70 ha/farm in 2019), more specialized farms. Agriculture in Alentejo experienced an increased specialization in livestock production in the 1980s and 1990s. In the 2000s, livestock farming became a major activity, with a marked shift in herd composition. In fact, sheep decreased by 0.4 million heads (~56,000 Livestock Units (Livestock Units (LSU): An indicator that facilitates the aggregation of livestock from various species and ages. (1 sheep = 0.15 LSU and 1 cattle = 1 LSU))) in 20 years and in the same period cattle gained nearly 0.4 million heads (~407,000 Livestock Units) (Figure 1c,d). This transition has been widely associated in the literature with a combination of interacting economic and policy factors, including market conditions and incentives under the Common Agricultural Policy that favored cattle production [19,21,23].

From the 2010s to the 2020s, the emphasis was on intensifying livestock production and expanding permanent pasture (Figure 1b), but sheep showed a slight increase given their adaptability to the low productivity of pastures and reduced need for market supplementation compared to cattle (Figure 1d).
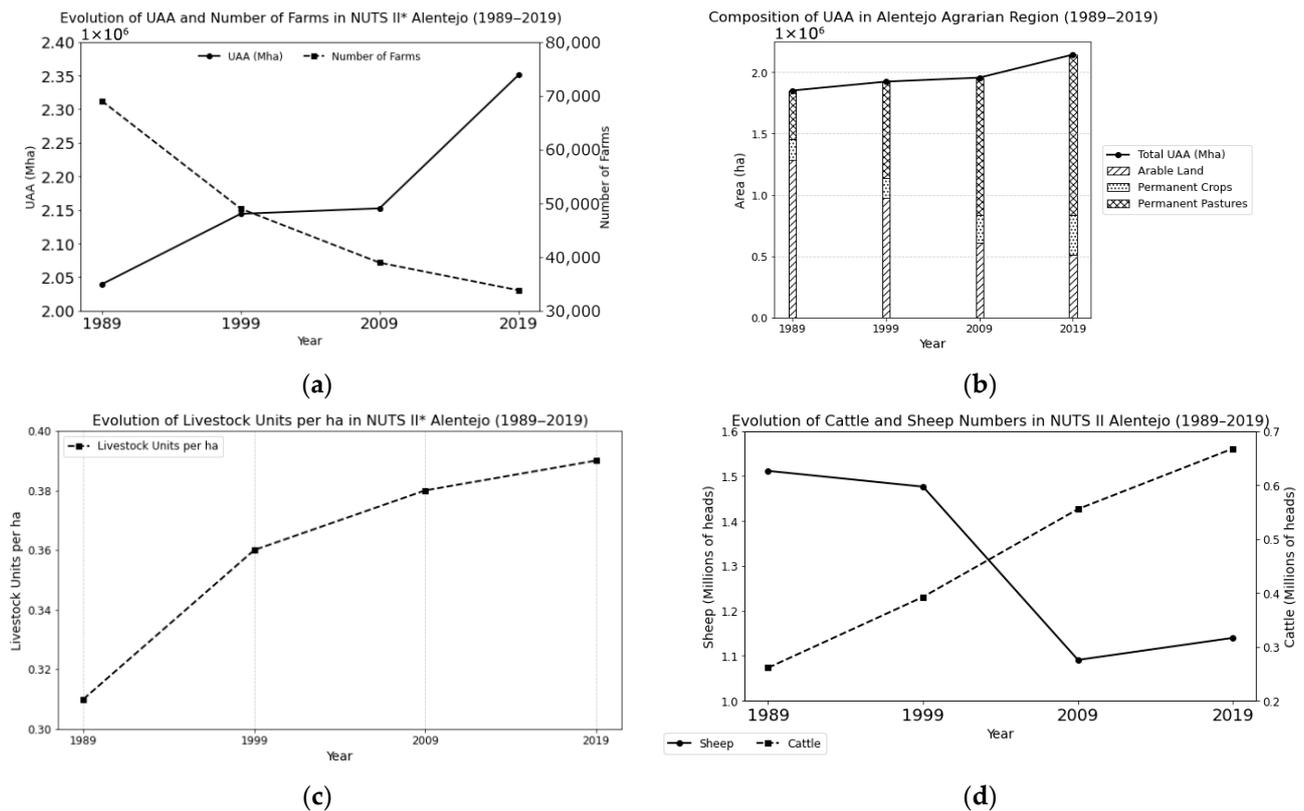
**Figure 1.** (**a**) Evolution of Utilized Agricultural Area (UAA) and number of farms; (**b**) composition of UAA; (**c**) evolution of livestock units per ha; (**d**) evolution of livestock numbers, between 1989 and 2019 (source: author, data from Instituto Nacional de Estatística, Agricultural Censuses of 1989, 1999, 2009, 2019). * NUTS: Nomenclature of Territorial Units for Statistics is developed by Eurostat and employed in both Portugal and the entire European Union for statistical purposes.

### 2.2. Study Approach and Participatory Framework

This study adapts the three-step approach of [37] to assess how selected indicators of Montado farms respond to external pressures. The approach involves: (i) characterizing the baseline situation and main constraints of the system, (ii) identifying key drivers of change, and (iii) assessing the future of the system by analyzing mid-term scenarios of change at the farm level. The framework aims to assess multifunctionality with a focus on economic, environmental, and social indicators.

Figure 2 shows the iterative process employed in the assessment of Montado farms, which is methodologically structured into three distinct phases: pre-modeling, modeling, and post-modeling.

Stakeholders were involved throughout the process. Experts (n = 8) from MED–Mediterranean Institute for Agriculture, Environment and Development acted mainly as knowledge providers and validators. Farmers (n = 10) participated primarily as information providers during the design phase, contributing insights on management challenges and priorities. A cork company contributed sector-specific insights on markets and prices.

### 2.3. System Characterization and Data Collection

Farmers participated in the study at two distinct stages. First, a group of ten farmers (n = 10) contributed as information providers during the design phase, sharing insights on management challenges, priorities, and plausible future developments of Montado systems. These farmers were drawn from different parts of the Alentejo region and reflected a range of management situations corresponding broadly to the diversity captured by the

MAPS typology. Their input informed the framing of scenarios and the identification of key drivers.
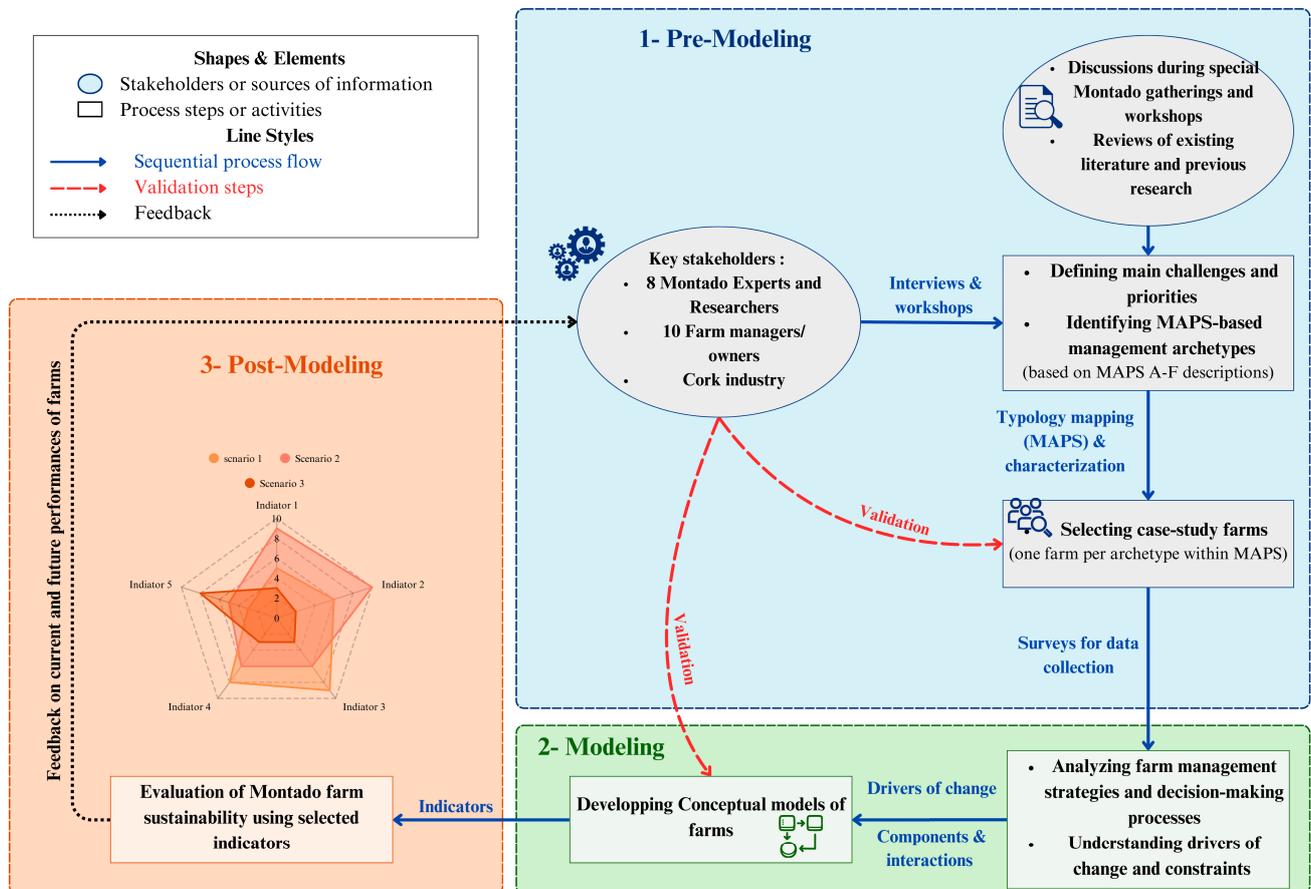


**Figure 2.** Study approach and participatory framework used for assessing Montado farms' sustainability.

From this initial group, three farms were subsequently selected as representative case studies based on the MAPS typology and regional distribution. These three farmers were the only participants providing in-depth farm-specific quantitative and qualitative data through detailed interviews, which formed the empirical basis for the characterization of the farm archetypes and the subsequent scenario assessment.

### 2.3.1. Establishing Criteria and Typology-Based Farm Selection

Farm selection followed a two-step approach that combined: (i) an explicit, literature-based typology of Montado production systems and (ii) stakeholder-informed selection criteria reflecting farm structure, management, and context.

i.    Montado Agro-Forestry Production Systems (MAPS)

Farm selection followed a typology-based approach combining classification based on literature and stakeholder-informed criteria. The Montado Agro-Forestry Production Systems (MAPS) typology (Évora University Unit of Microecology and Conservation cited by Fragoso et al., 2008 [38]) served as the regional reference. MAPS distinguishes six production systems (A–F) based on multivariate clustering of homogeneous spatial units using climate, land use, forest structure, farm size, and livestock activity.

For the purposes of this study, working simultaneously with all six MAPS as separate cases was not feasible because the scenario analysis requires intensive qualitative work and repeated interactions with each farm. Building on the published descriptions of MAPS

A–F in terms of climate, land use, forest structure, farm size, and livestock activity, the six systems were therefore grouped a priori into three management archetypes that correspond to clearly distinct economic and structural configurations of the Montado:

- Livestock-specialized extensive archetype (MAPS A/D): Includes MAPS with very large UAA (Around 800–1366 ha), low-density holm-oak stands, pasture-dominated land use, and extensive livestock grazing in inner or upland dry zones.
- Multifunctional agro-silvopastoral archetype (MAPS B/E/F): Includes MAPS characterized by small to medium UAA (Around 100–450 ha), dense holm and/or cork oak, cereals and pastures under trees, and mixed cattle–sheep systems in inner and inner-littoral zones.
- Forestry-optimized archetype (MAPS C and part of E): Includes MAPS with small UAA (Around 177 ha), high-density cork or mixed oak stands and associated olive/vine systems in wetter littoral or inner-littoral conditions, where high-value tree products dominate farm income.

This aggregation does not modify the original clusters statistically; it organizes them along two theoretically grounded axes: dominant source of income (livestock vs. mixed vs. tree products) and land-use/forest structure (sparse pasture systems vs. mosaics vs. dense forest systems). The aim is to obtain three analytically manageable "ways of farming" of the Montado that remain rooted in the MAPS typology. The resulting archetypes represent dominant configurations within the Montado and may not explicitly represent all intermediate or transitional configurations. Accordingly, scenario outcomes are interpreted at the level of farm archetypes to highlight prevailing patterns and trade-offs.

ii.  Stakeholder-derived selection criteria

Within this typological frame, farm-level selection criteria were defined together with Montado experts and farmers (individual meetings, "Tertúlias do Montado (Tertúlias do Montado: The Montado Talks are an initiative of MED (Mediterranean Institute for Agriculture, Environment and Development) of the University of Évora, which aims to create a regular and structured dialogue between the various players involved in the study, management and use of the Montado)", long-term collaborations). Criteria were chosen to remain consistent with MAPS descriptions and to capture key dimensions of heterogeneity: (i) productive and ecological structure (shares of forest/pasture/crops, tree species composition, main livestock species and indicative stocking intensity); (ii) functional orientation (dominant income source and farm area); (iii) socio economic organization (family vs. hired labor); and (iv) geographical context within Alentejo (north/central/south; inner vs. inner-littoral). These criteria ensured that selected farms were structurally and functionally representative of the main Montado system types and embedded in their context.

iii.  Selection of case-study farms

Using the MAPS-based archetypes and the criteria above, a stratified sampling procedure was implemented:

- Identification of eligible areas: Predominant municipalities for each MAPS group were identified from the published spatial distribution of homogeneous sub-units [38], defining three geographic strata that broadly correspond to: (i) inner dry zones dominated by extensive livestock systems, (ii) the central mixed agro-silvopastoral belt, and (iii) wetter inner-littoral zones with high tree density.
- Compilation of candidate farms: Within these strata, candidate farms were identified through the MED research network and farmer contacts from previous Montado projects. Candidates were pre-screened to ensure that their basic attributes (location,

approximate farm area, dominant tree species, broad land-use pattern, and main activity) matched the profile of the target archetype for that stratum.

- Expert and stakeholder screening: The shortlist of candidates was evaluated by the Montado experts and experienced farmers against the full set of criteria. Farms that diverged from the MAPS-archetype profile (e.g., atypical size, tree composition, or land-use mix for that zone) were excluded.
- Final selection: One farm per archetype was retained, resulting in a set of three case-study farms, each embedded in a different MAPS group and representing one of the three management archetypes (forestry-optimized, multifunctional, and livestock-specialized). Detailed characteristics of these farms, including their locations and quantitative descriptors, are presented in the Results section.

The three farms selected for scenario analysis correspond to distinct archetypes derived from the MAPS typology and are used as illustrative case studies. They are not intended to constitute a statistically representative sample of Montado farms. Rather, they serve to explore contrasting structural configurations, management strategies, and vulnerability profiles, allowing comparative analysis of sustainability trade-offs under alternative future scenarios.

### 2.3.2. Data Collection

Each farm was characterized through structured, face-to-face interviews using a standardized questionnaire (Supplementary Material S1) covering farm structure, tree management, crops, livestock, labor organization, and management practices. Data was collected in 2023 and validated and updated in 2024 through follow-up exchanges with participating farmers.

Interviews were complemented by field observations and participation in Montado-focused events (e.g., Tertúlias do Montado (https://tertuliasdomontado.blogspot.com/ accessed on 6 July 2025), Iberian congress on Dehesas and Montado (https://congresode hesamontado.com/language/en/ accessed on 15 July 2025), which provided additional qualitative insights into decision-making processes, perceived constraints, and adaptation strategies. These data were used to parameterize conceptual models of each farm and to interpret the scenario results.

Structured interviews combined quantitative data organized in spreadsheet format with qualitative insights recorded as structured notes and used narratively to inform conceptual models and scenario interpretation.

### 2.4. Elaboration of the Conceptual Models

The data collected were used to build farm-specific conceptual models following the protocol of [39,40] (Figure 3). These models are developed to represent internal system components, external drivers, and sustainability indicators. This structured approach facilitates a comprehensive understanding of the multifaceted and complex nature of Montado farms, capturing external influences, internal dynamics, and potential influences.

Thus, the conceptual model includes three main parts:

1. Active Environment: Issues and Drivers of Change

Information regarding the challenges and drivers of change was gathered through direct consultations with stakeholders, reviews of existing literature, and detailed farm surveys. The synthesis of these sources identified environmental, economic, political, and social dimensions. For example, climate change can directly impact tree cover and grazing yields, while policy changes, such as those related to the Common Agricultural Policy, can influence the farm manager's decisions and consequently land use and livestock management.

2.    The Agro-Silvopastoral System

The agro-silvo-pastoral system focuses on the internal components and interactions within the farm itself. This includes management practices employed by farmers (such as tree pruning or grazing methods) that influence the other components, like land use (pastures and crops), the tree component, livestock, and soil characteristics.

3.    Passive Environment: Indicators

Finally, the passive environment involves the indicators used to assess the overall sustainability of the Montado farming system. These indicators cover ecological aspects like tree regeneration, economic factors such as farm income and cork production, and social dimensions like employment and preservation of traditional knowledge and landscape. These selected indicators will serve to assess the impact of future scenarios on the sustainability of the Montado farming system.

The conceptual models provided the analytical foundation for the scenario assessment by explicitly mapping key system components (e.g., trees, livestock, crops, labor, and economic drivers) and their interactions. These relationships were used to identify critical leverage points and sensitivities within each farm archetype, thereby guiding expert interpretation of scenario narratives and the evaluation of sustainability indicators. As such, scenario scoring was grounded in the causal structure of the conceptual models rather than in isolated outcomes.
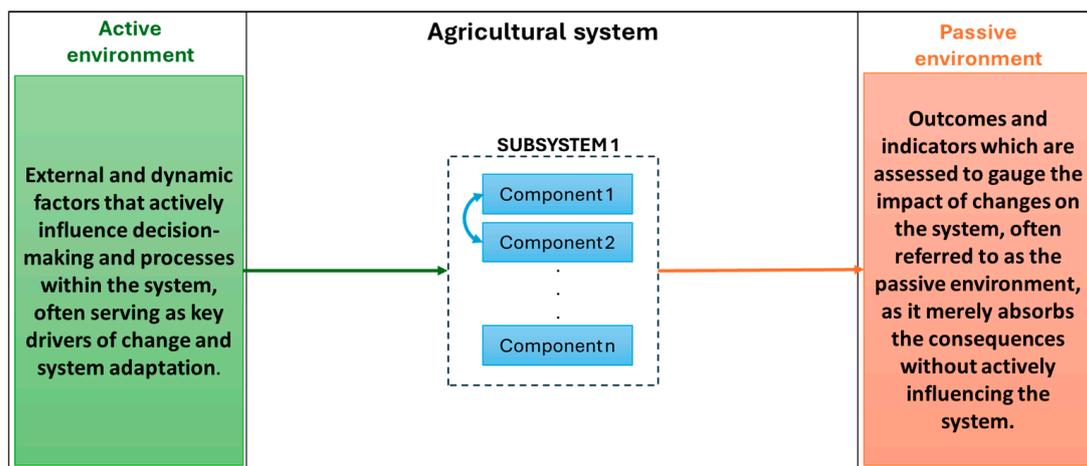


**Figure 3.** Overview of the conceptual model structure of the agricultural system (adapted from Lamanda et al., (2012) [39]). The green arrow represents either a resource, a constraint, or an action, while the orange arrow represents a performance, a service, or an impact.

*2.5. Comparative Assessment: Scenario Analysis*

Building on these conceptual representations, scenario outcomes were evaluated using an expert-based scoring framework to assess how changes in key drivers propagate through each farm system. Stakeholder input informed farm selection and scenario framing, while scenario narratives and indicator scoring were conducted independently by experts. Farm selection relied on the MAPS typology to ensure structural representativeness, while scenario assessment focused on the effects of exogenous drivers rather than on farm-specific preferences.

Exploratory scenarios were developed using the intuitive logics approach, suitable for complex systems with limited quantitative data [33,34]. Scenarios explore plausible futures over a 15–20-year horizon by varying one key driver at a time (climate, market, or labor), while keeping others constant to isolate causal effects. Current farm configurations are used as baseline representations rather than static endpoints. Temporal dynamics,

including changes in management practices, resource availability, and constraints, are explored implicitly through scenario narratives. This design prioritizes analytical clarity over exhaustive interaction effects. Scenario outcomes should therefore be interpreted as stylized representations of dominant pressures rather than fully integrated projections. Interactions between climate, market, policy, and labor drivers are therefore not explicitly modeled but may indirectly influence outcomes through the scenario narratives.

The stages in scenario development followed the process described in [41].

Scenario outcomes were assessed qualitatively using a set of environmental, economic, and social indicators scored on a five-point scale (1 = very low, 2 = low, 3 = moderate, 4 = high, 5 = very high). The details are in Table 1. Four experts were selected from the Mediterranean Institute for Agriculture, Environment and Development (MED) based on their long-term research engagement with Montado systems and complementary expertise. Expert assessments were conducted independently, limiting potential bias and avoiding circularity between stakeholder input and scenario outcomes. Experts assigned scores and confidence levels (moderate (40–69%), high (70–89%), and near certain (90–100%)) for each farm–scenario combination to avoid mutual influence. Individual scores were aggregated using an arithmetic average, while variability in expert judgments was characterized using standard deviation and score ranges (minimum–maximum), reported in Tables S1–S5 (Supplementary Material S2). Confidence levels were also averaged to provide a clear overall indication of expert certainty. This simplification may mask individual differences in judgment, but it was adopted to ensure comparability across scenarios.

Sustainability indicators were selected based on their relevance for assessing farm-level environmental, economic, and social functioning of Montado systems, as identified in the literature and in prior research on these systems. Stakeholder input was used to refine indicator relevance and interpretability at the farm level. No quantitative weighting or ranking was applied, as the analysis focuses on comparative patterns and trade-offs across scenarios.

**Table 1.** Criteria and indicators to assess the different dimensions of Montado farms' dynamics. Scores 2 and 4 are intermediary scores, not represented for simplicity.

| Sub-Criteria | Indicator | Score = 1 (Very Low) | Score = 3 (Moderate) | Score = 5 (Very High) |
|---|---|---|---|---|
| **Social dimension** | | | | |
| Local Identity Preservation | Adoption of traditional practices | No traditional practices retained | Some traditional practices are still in use | Strong reliance on traditional practices |
| | Cultural heritage conservation | No attention to cultural heritage | Some cultural elements are preserved | Active conservation and promotion of cultural heritage |
| | Landscape preservation | Visible degradation, soil erosion | Some conservation efforts | Strong landscape conservation, no visible degradation |
| Labor | Contribution to local employment | No employment generation | Occasional or seasonal local employment | Stable, year-round employment for locals |
| | Work intensity (effort vs. return) | Very high effort, low economic return | Balanced workload & economic return | Efficient workload with good return on investment |
| **Economic dimension** | | | | |
| Farm Revenue | Income stability | Highly fluctuating income | Moderately stable income | Very stable, predictable income |
| | Non-dependence on subsidies | Fully dependent on subsidies | Some alternative revenue sources | Very low dependence on subsidies |
| | Revenue diversification | Single income source | Two or more income sources | Highly diversified income |
| | Market resilience | Highly vulnerable to price changes | Moderate resilience | High adaptability and resistance to market fluctuations |

| Sub-Criteria | Indicator | Score = 1 (Very Low) | Score = 3 (Moderate) | Score = 5 (Very High) |
|---|---|---|---|---|
| Environmental dimension | | | | |
| Tree Regeneration | Effectiveness of seeding practices | No seeding efforts | Some replanting, but inconsistent | Regular and effective replanting |
| | Presence of protective fencing | No fencing, high risk of damage | Partial fencing in key areas | Well-maintained fencing |
| | Grazing management sustainability | Overgrazing, poor rotation | Some rotational grazing | Well-planned rotational grazing system |
| Overgrazing Risk | Stocking rate sustainability | Overstocking, exceeding the carrying capacity | Moderate stocking rate | Stocking rate is well-adapted to land capacity |
| | Livestock species impact | Heavy livestock is causing degradation | Mix of species with moderate impact | Light livestock species minimize damage |

## 3. Results

### 3.1. System Characterization

3.1.1. Representative Montado Farms

This subsection presents the results of the typology-based farm archetype selection, which emerged from the application of the methodological framework described in Section 2. Three Montado case-study farms were selected from the network of farmers based on criteria detailed previously.

The farms chosen are located in different parts of the Alentejo region (Figure 4), which takes into consideration the difference in natural resources and pedoclimatic conditions.
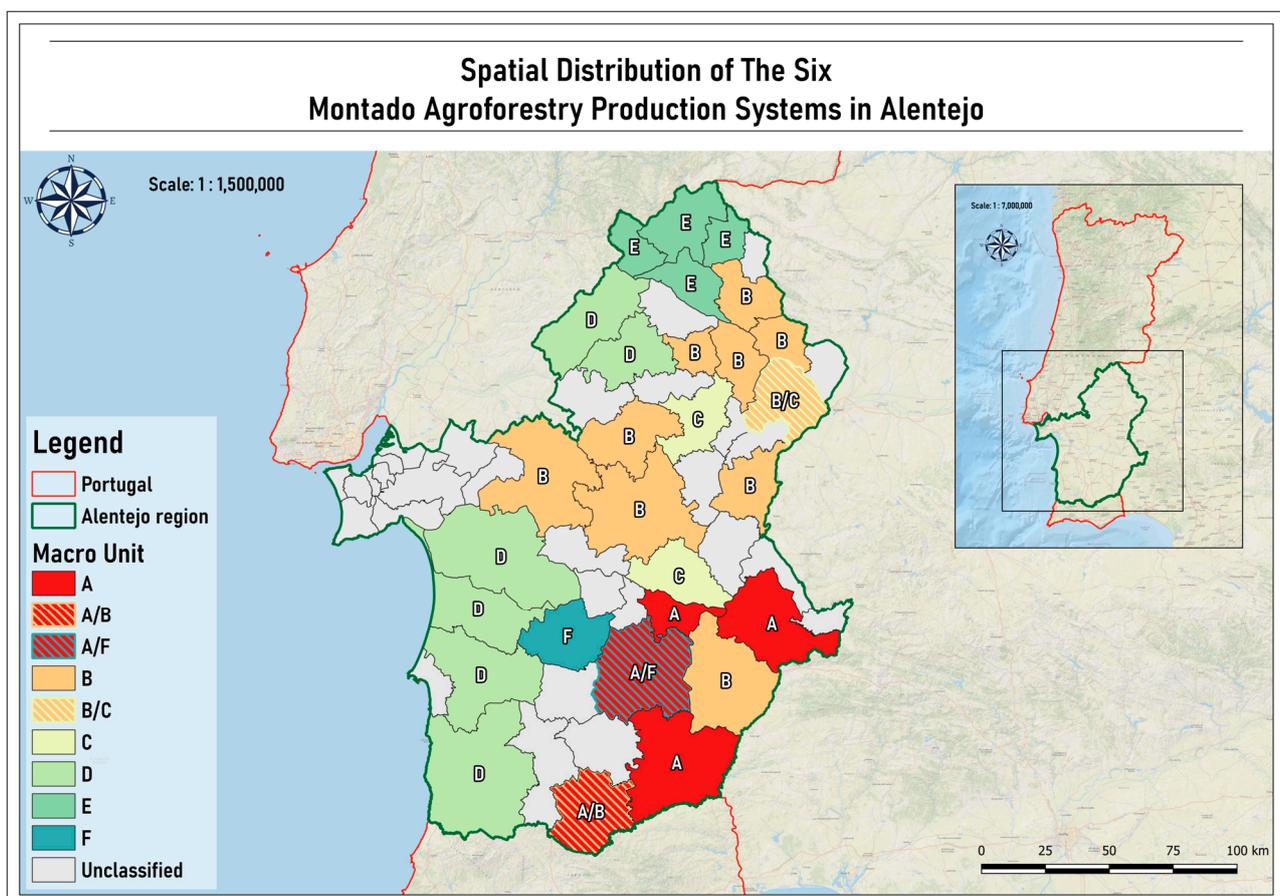


**Figure 4.** Geographical distribution of the Montado Agro-Forestry Production Systems (MAPS) A–F by municipality (map by authors, source of data: [38]).

To keep the anonymity of the farms, the exact location is not represented in the figure. Farm 1 is within MAPS C, but it also represents farms from E. Farm 2 is within the geographical limits of MAPS B, and it also represents E and F. Farm 3 is within C geographically, but also represents part of E.

While the selected farms capture dominant structural configurations of the MAPS typology, they do not encompass all intermediate or atypical situations. Results are therefore intended to illustrate archetype-level patterns within the Alentejo region, rather than to provide exhaustive coverage of all Montado farm configurations or direct extrapolation to other regions.

### 3.1.2. Conceptual Models by Farm

#### Farm Type 1: Montado forest

This type of farm is relatively small (200 ha), focuses on cork oak (Quercus suber) and pine tree (Pinus pinea) production, abandoning traditional livestock integration. The tree density is 40–60 trees per hectare, which falls within the typical range for Montado systems. While this focus on cork oak may appear simplistic, maintaining productive and healthy trees requires multiple management practices as presented in the conceptual model (Figure 5).
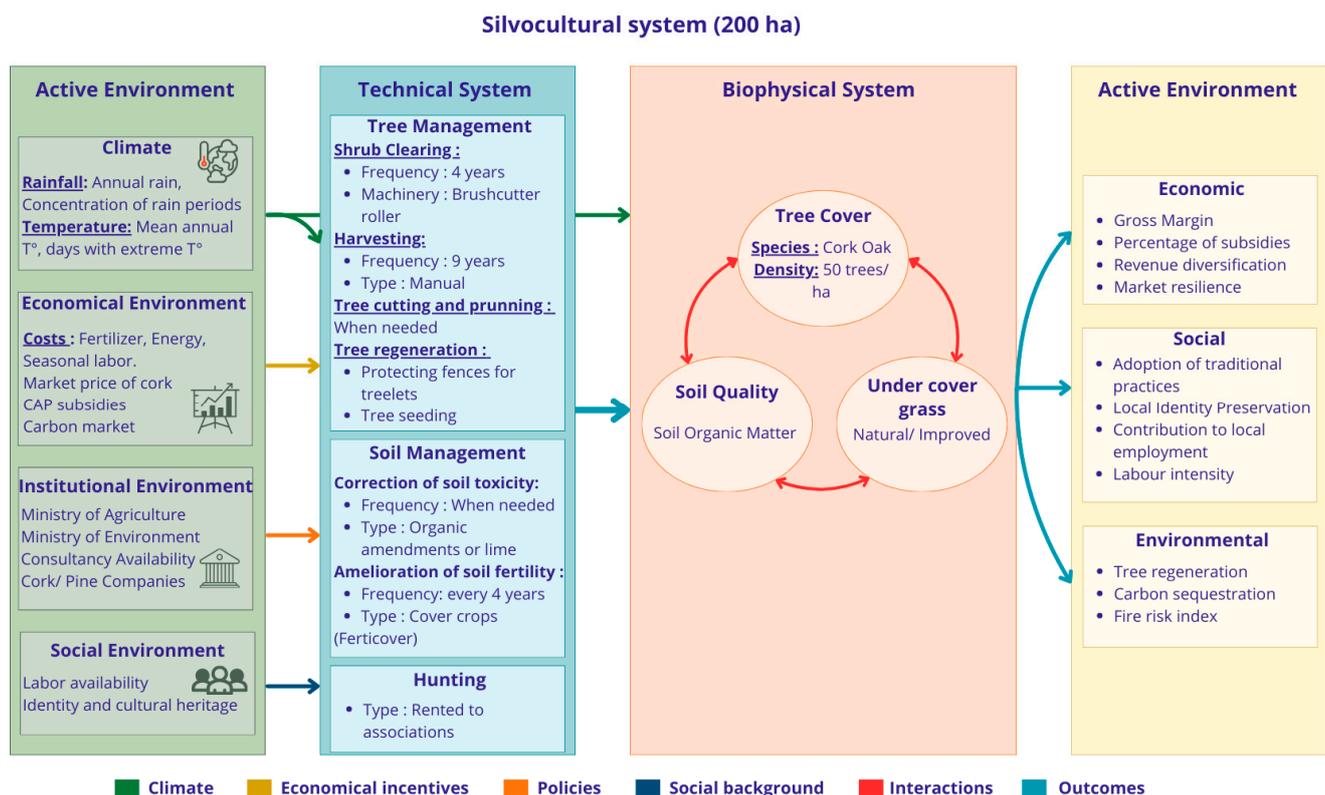


**Figure 5.** Conceptual model of farm 1, representing the silvicultural system, the active environment, and the passive environment.

The technical system is based on the farmer's decisions. The farmer decided to focus on trees and promote natural regeneration by excluding livestock, thereby avoiding grazing pressure and promoting tree health. For example, optimizing cork harvesting schedules to ensure tree health and maximize cork quality. Also, removing diseased or declining trees to prevent the spread of pathogens and maintain tree health and resilience, and pruning to optimize tree growth and productivity. An active reforestation is realized through seeding and tree planting to complement natural regeneration. Then, an investment in

the protection of young trees using fences is made. Finally, implementing vegetation management practices, such as the selective clearing of understory shrubs, can reduce fire risk and support the overall health and resilience of the system.

No-till practices are performed to preserve the soil structure and minimize disturbance, and then the soil fertility is improved using cover crops (e.g., ferticover).

As with all farms in southern Portugal, the climate is a major driver as it impacts the system through the decrease in rainfall, its concentration in shorter but heavier rain periods, and seasons of extreme temperatures impacting both the soil health, soil erosion, and tree vitality.

The farm's income is highly dependent on cork sales; thus, it is impacted by market fluctuations in cork prices. However, emerging carbon markets offer a potential revenue supplement through the sale of carbon credits. Also, the farm benefits from the CAP payments. These include decoupled payments and CAP investment payments for afforestation and reforestation support, as well as agro-environmental subsidies that incentivize sustainable land management practices. To optimize its participation, the farm uses consultancy resources such as those offered by local associations to help identify CAP funding opportunities. In what concerns human resources, this type of farm does not necessitate permanently hired labor, which makes it dependent on the availability of seasonal workers. The current shortages experienced in seasonal labor and the increasing reliance on migrant workers in Portugal make it critical for this farm type. This specialized Montado system involves trade-offs, including the opportunity cost of withdrawing from livestock activity to focus on tree regeneration. However, the management practices, such as no tillage and cover cropping, help maintain diverse understory vegetation and biodiversity.

Farm Type 2: Mixed oak coverage, livestock, and crops

The second Montado farm (Figure 6) is relatively bigger (around 500 ha) and represents a balanced agro-silvopastoral system, integrating cork and holm oak forestry with moderate livestock production. Unlike the specialized tree-focused system of Farm 1, this farm combines multiple land uses and revenue streams, including cork harvesting, livestock sales (mainly sheep and cattle), and short-term land rental (approximately three months per year) for Iberian pig fattening on holm oak acorns. This diversification enhances economic resilience by spreading risk across products and activities, though it also introduces greater operational complexity and uncertainties, particularly regarding input costs and commodity prices.

The farm participates in both pillars of the CAP, leveraging coupled and decoupled/direct payments along with AES to support sustainable management practices across forestry, cropping, and livestock. CAP investment support is also perceived. This multifunctional approach demands daily, full-time management of livestock and cropping activities, as well as silvicultural interventions such as shrub clearing, tree pruning, and harvesting. The workload necessitates permanent labor combined with multiple family members involved in management and decision-making.

This farm typology shows complex trade-offs between productivity and conservation. While its diversified income sources buffer economic risks, intensive livestock activity can increase grazing pressure, soil compaction, and disturbance of tree regeneration if not carefully managed. The integration of AES and targeted CAP subsidies plays a role in keeping the balance between ecological sustainability and economic viability.

Farm Type 3: Holm oak coverage, crops, and livestock-focused production

Farm 3 (Figure 7) is large in terms of area (around 1000 ha), primarily focused on livestock production, characterized by low tree cover (~10%) dominated by holm oak. The

system has a large sheep herd of up to 2000 heads, with a synchronized reproduction schedule featuring three lambing peaks every two years.

Such intensive livestock management is more demanding in terms of labor input, including up to four permanent workers and active decision-making by two family managers. Holistic rotational grazing is practiced across a combination of natural and improved pastures to optimize pasture utilization while maintaining soil and ecosystem health. Strategic supplementation of feed, particularly before and after lambing, supports animal health and productivity but increases dependence on external feed markets, exposing the farm to risks from drought and feed price fluctuations.

Diversification efforts include dedicated land for cereal and permanent crops like carob trees, providing additional revenue streams. The farm participates in both pillars of the CAP, receiving coupled and decoupled payments, AES, and investment support to promote its management framework. While this livestock-centric system maximizes output and economic scale, it faces trade-offs, including vulnerability to climatic extremes and labor availability, along with potential ecological impacts from reduced tree cover and intensive grazing pressure. Careful grazing and reproductive management are essential to balance productivity with long-term sustainability.

The conceptual models enable a thorough understanding of the interconnected components of the system, emphasizing the interactions between tree cover, crops, and livestock. The models clearly illustrate the diverse factors that influence the biophysical system directly or indirectly by impacting farmer decision-making. For the three-farm type, drivers of change are the same categories (i.e., climate, economic environment, institutional environment, and social environment); however, the importance and degree of influence of each element are different. These conceptual models serve as valuable tools for assessing the current and future sustainability of the three farms.
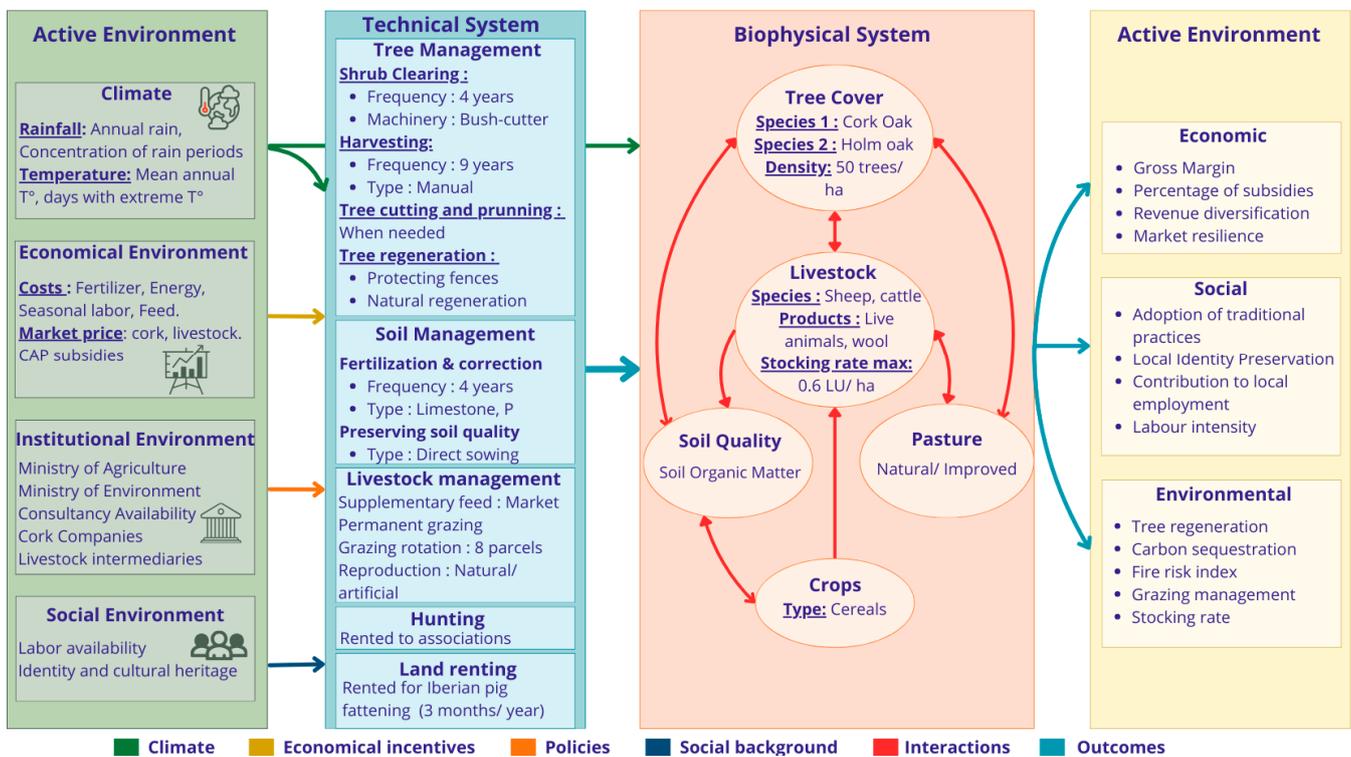


**Figure 6.** Conceptual model of farm 2, representing the agro-silvopastoral system, the active, and the passive environment.
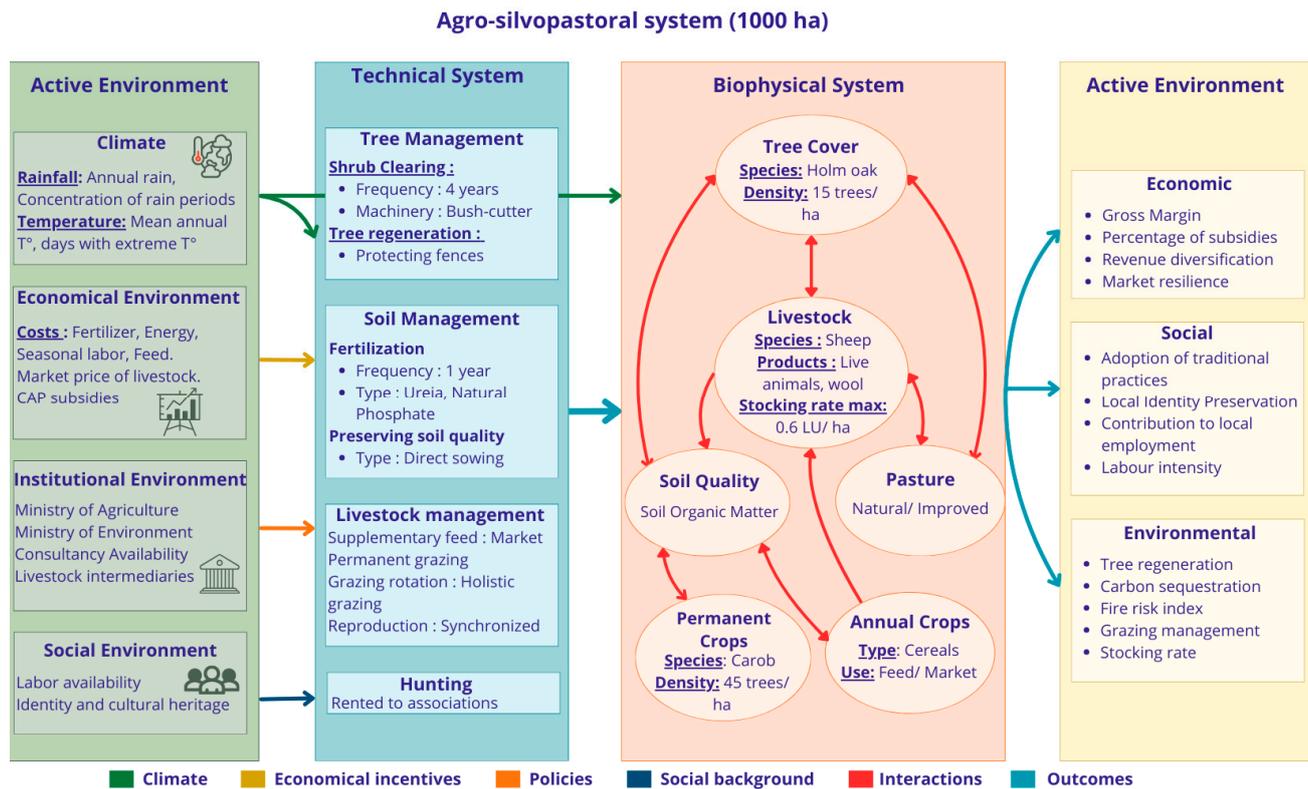
**Figure 7.** Conceptual model of farm 3, representing the agro-silvopastoral system, the active, and the passive environment.

Table 2 provides a descriptive characterization of the three case-study farms based on quantitative farm data and qualitative interview information. These variables support the development of farm-specific conceptual models by detailing farm structure, management practices, and socio-economic organization.

**Table 2.** Summary of the characteristics of the three representative Montado farms.

| Criteria | Variables | Dimension | Farm 1 | Farm 2 | Farm 3 |
|---|---|---|---|---|---|
| Farm Structure | Area (ha) | Structural | 200 | 500 | 1000 |
| | Forest proportion (%) | Environmental | 100 | 35 | 10 |
| | Open pasture proportion (%) | Environmental | 0 | 55 | 75 |
| | Crops proportion (%) | Environmental | 0 | 10 | 15 |
| | Tree density (trees/ha) | Environmental | 50 | 50 | 15 |
| Agricultural Activities | Primary farm activities | Economic | Cork | Cork + livestock | Livestock |
| | Secondary farm activities | Economic | Hunting, beekeeping | Hunting, land renting | Hunting |
| Labor Structure | Type of labor | Social | Family + service companies | Family + permanent livestock labor + service companies | Family + occasional hires + permanent livestock labor |
| | Number of family managers | Social | 1 | 3 | 2 |
| | Permanent labor (AWU *) | Social | 0 | 1.17 | 4.69 |

**Table 2.** *Cont.*

| Criteria | Variables | Dimension | Farm 1 | Farm 2 | Farm 3 |
|---|---|---|---|---|---|
| Farm Productivity | Type of products | Economic | Cork | Cork, meat, crops | Meat, crops |
| | Net Farm Income ** (€/ha) | Economic | 450 | 415 | 411 |
| | Subsidies (% NFI) | Economic | 19% | 25% | 40% |
| Regeneration Strategy | Tree regeneration practices | Environmental | Protection fences for treelets, no livestock, seeding | Grazing management, protection fences for treelets | Grazing management, fences for rotational grazing |
| Degree of Intensification | Stocking rate (LSU/ha) | Environmental | 0 | 0.5 | 0.4 |
| | Fertilizer rate (kg/ha) | Environmental | 30 | 38 | 15.3 |
| | Part of purchased feed (%) | Economic | NA | 5% | 6% |

\* Annual Work Units (AWU) follow the Portuguese/EU statistical standard (INE, Eurostat), where 1 AWU corresponds to 1800 h of work per year. Permanent labor is calculated on this basis. \*\* Net farm income is calculated as total farm revenues minus variable and fixed production costs, plus subsidies.

### 3.2. Comparative Sustainability Analysis

#### 3.2.1. System Constraints

As stated in the conceptual models above (Figures 5–7), the drivers of change in the system are linked mainly to climate and land use change, the latter being a direct consequence of management practices (farmers' decisions) that are shaped by a confluence of economic, institutional, and social factors.

Climate Change: Climate change poses a major threat, with predictions of increased temperatures and reduced rainfall exacerbating desertification and land degradation [17]. Droughts are recurrent in this climate, but their frequency and severity are increasing. In the Alentejo region, it is common to have several days with temperatures above 40 °C in summer and minimum temperatures below 0 °C in winter (IPMA (https://www.ipma.pt/en/oclima/normais.clima/1981-2010/#535 accessed 27 May 2025)). Data from the district of Évora show the average maximum temperature has increased from 19.6 °C between 1971 and 2007 to 20.6 °C between 2000 and 2007, showing the effects of climate change in the region (IPMA (https://www.ipma.pt/en/oclima/normais.clima/1981-2010/#535 accessed 27 May 2025) [42]). At the farm level, higher maximum temperatures increase water stress on pastures and trees, reduce forage availability during critical periods, and exacerbate heat stress for livestock, with implications for grazing management and tree regeneration. Average annual rainfall typically ranges between 500 and 700 mm, but its inter-annual variability is a key characteristic, with a dry season from June to September and a wet season from October to May. The rainfall can fluctuate significantly, as evidenced by the period between 2015 and 2020, which saw accumulated rainfall varying from 313 mm in 2018/2019 to 683 mm in 2017/2018 [43].

Market Conditions: Market conditions also present challenges. The cost of essential inputs, particularly feed for livestock, can fluctuate significantly due to factors like weather patterns, global market trends, and geopolitical events. These fluctuations make it difficult for farmers and can threaten profitability, especially in years with poor pastures when supplemental feed is necessary. For instance, Producer Price Indices (the Producer Price Index (PPI) measures the average change over time in the selling prices received by domestic producers for their output) (PPI) for forage plants and cereals in Portugal have shown a significant upward trend since 2021, with forage PPI rising from 125.10 in 2021 (the base 100 year is 2015) to 446.74 in 2023 (Instituto Nacional

de Estatísitca, (https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_indicadores&indOcorrCod=0009868&xlang=en&contexto=bd&selTab=tab2 accessed 16 May 2025) [44]). This quadrupling of forage prices in just two years reveals a high degree of volatility. Cereals, although more stable, also experienced a spike in 2022, peaking at 182.09 before decreasing to 149.67 in 2023. For farms relying on purchased feed, such price volatility increases production costs and income uncertainty, with direct implications for stocking decisions and farm risk management.

Policy Constraints: The CAP shapes management practices and land-use decisions in the Montado since the accession of Portugal to the EU in 1986. Initial CAP initiatives, based on production-oriented subsidies, incentivized cattle and cereal cultivation, at the expense of small ruminants and integrated silvo-pastoral systems. The 1992 MacSharry reform shifted price guarantees to direct payments; however, these payments remained largely coupled with production. This reform also introduced the first agro-environmental measures and rural development concerns (Agenda 2000, the 2003 mid-term review, which initiated the move towards decoupled payments, and the 2013 reform), incorporated and expanded rural development objectives (European Council, (https://www.consilium.europa.eu/en/policies/the-common-agricultural-policy-explained/timeline-history-of-cap/ accessed 27 May 2025)). While some conservation practices received support, many payments remained linked to old land-use patterns, misaligning with current ecological objectives [20,21]. The 2023–2027 reform aims for a more equitable, ecological, and results-oriented approach through eco-schemes and rural development instruments, while also giving member states more flexibility to tailor their strategic plans to national and regional specificities.

Labor Shortages: Labor shortages, particularly for tasks requiring specialized skills, pose a significant threat to the maintenance of traditional management practices within the Montado system. The ongoing rural exodus and demographic aging in regions like Alentejo have greatly reduced the pool of experienced workers [45,46]. As a result, the decline in skilled labor availability can lead to the abandonment of practices such as pruning and appropriate cork harvesting, which are essential for the long-term health and productivity of cork oak trees.

These labor constraints are not modeled quantitatively but are considered qualitatively in the scenario narratives and expert assessment, particularly for farm archetypes with high dependence on seasonal or skilled labor.

The relative sensitivity of each farm archetype to different constraints is inferred from expert judgment, based on their in-depth knowledge of the selected farms and on the comparative changes observed across indicators under the different scenarios.

### 3.2.2. Performance of the Farms and Projected Sustainability

The scenarios developed (Table 3) explore different trajectories in the evolution of drivers and their implications for Montado sustainability:

We evaluated the sustainability of Montado systems by applying the study's exploratory scenarios to the three farms, using the established conceptual models as a framework. This allowed for a structured comparison of potential sustainability shifts across different farm types.

Figure 8 summarizes the performance scores for key indicators under the Baseline and selected future scenarios. Scores range from 1 (very low) to 5 (very high) based on expert assessment (see Table 1 and Supplementary Material S2). Assessments for environmental and social indicators (e.g., local identity, regeneration) carry high confidence, whereas socio-economic indicators (labor, revenue) are assigned moderate confidence. For visual clarity, the diagrams display only the Baseline, the average external pressure scenario

(Scenario 3), and the result-based policy (Scenario 4) to highlight the contrast between continued trends, systemic stress, and targeted intervention.
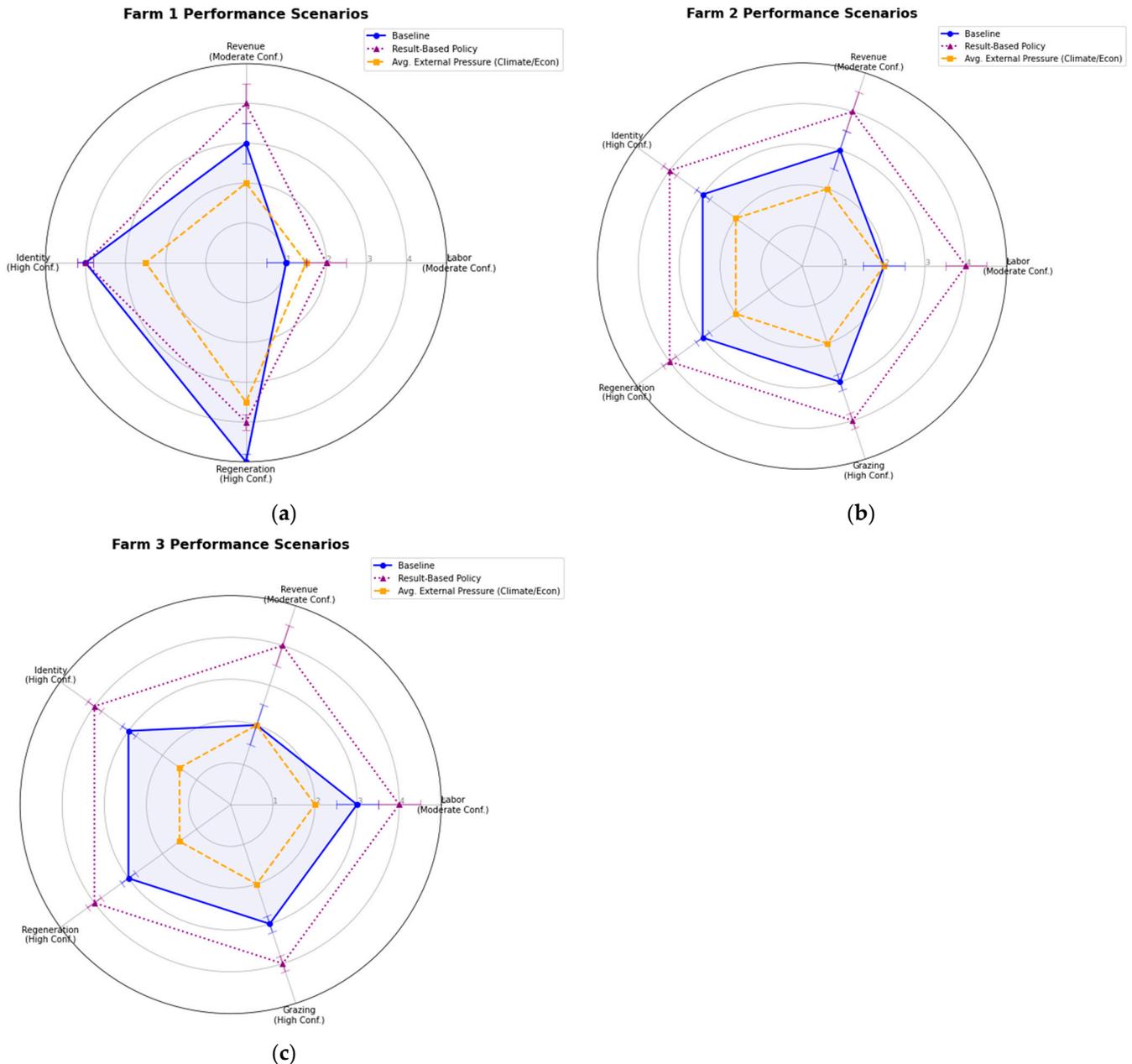


**Figure 8.** Comparative assessment of sustainability indicators across three Montado farms. (**a**) Farm 1; (**b**) Farm 2, and (**c**) Farm 3. Values represent expert assessment scores (1–5). Error bars indicate confidence levels (high vs. moderate).

The radar diagrams (Figure 8) reveal clearly differentiated sustainability trajectories across the three Montado farm types. Under the baseline scenario, Farm 1 exhibits a strongly specialized profile, characterized by high performance in local identity preservation and tree regeneration, reflecting a conservation-oriented management logic. However, this specialization is accompanied by weaker socio-economic performance, particularly in labor contribution and revenue stability. Farms 2 and 3 display more balanced baseline profiles, with moderate scores across most dimensions, indicating greater functional diversification but less pronounced cultural or ecological specialization.

**Table 3.** Identification of four scenarios to analyze the sustainability of Montado farms.

| Scenario | Description | Main Driver of Change |
|---|---|---|
| Baseline scenario | Reference scenario in which climate, market, labor, and policy conditions continue to evolve similarly to current trends, with no major disruptions. | Continuity of current trends |
| Scenario 1: Climate stress | Increasingly severe droughts, declining water availability, and higher tree mortality rates. | Continuity of current trends + climate |
| Scenario 2: Economic instability | Cork and feed prices have become increasingly volatile. | Continuity of current trends + market |
| Scenario 3: Average external pressure scenario | Climate and economic drivers shift simultaneously: climate stress intensifies, market volatility grows. | Continuity of current trends + climate + market |
| Scenario 4: Result-based policy | New CAP emphasizes measurable environmental outcomes. Support is tied to performance indicators, increasing opportunities, but also complexity. | Baseline + policy (performance-based implementation) |

In contrast, the result-based policy scenario consistently improves sustainability outcomes across all farms. Farms 2 and 3 approach high performance levels across social, economic, and environmental dimensions, reflecting improvements in labor stability, grazing management, and regeneration capacity. For Farm 1, the policy induces a partial rebalancing of the system: while environmental performance remains high, economic indicators improve substantially, highlighting the potential of result-based mechanisms to transform conservation outcomes into stable and predictable income streams.

## 4. Discussion

The Montado exemplifies the challenge of maintaining multifunctionality in Mediterranean agro-silvopastoral landscapes faced with intensifying market and policy pressures. Other similar systems, like Dehesa in Spain, and the agro-forestry systems in North Africa (Morocco, Algeria, Tunisia), are facing a similar reality, where climate change is intensifying drought stress, variability, and pressure on tree-based and extensive livestock systems. The long-term maintenance of the agro-silvopastoral farms is bound by a core set of trade-offs that divide ecological, economic, and social functions. The ecosystem's capacity to provide biodiversity, climate regulation, and landscape identity is now confronted by the dual forces of economic productivity and system conservation, as subsidies and markets drive farm trajectories in contrasting directions [26,47].

### 4.1. Economic Productivity and Socio-Ecological Sustainability Trade-Offs

Our scenario analysis extends prior insights by showing how productivity gains, particularly in livestock-specialized systems, are associated with higher sensitivity to market and climate variability. Under baseline and economic stress conditions, livestock-oriented farms achieve relatively satisfying economic returns but suffer marked declines in ecological indicators like tree regeneration and cultural landscape identity. This supports well-established findings that intensification in Mediterranean silvo-pastoral systems often compromises long-term ecosystem functionality [48,49]. Furthermore, equally worrying, it compromises the capacity of the farm business models to incorporate payments for ecosystem services provided, now and in the future, as these services will be strongly hampered.

Conversely, conservation-oriented systems maintain environmental and cultural benefits but depend heavily on subsidies and face labor constraints in terms of qualification and availability of seasonal workers. These results underscore that the way CAP policies are structured pushes farms to make choices between being environmentally balanced and socially and economically viable. Pillar I of the CAP (favoring productivity) and Pillar II of

the CAP (incentivizing environmental stewardship) often promote hybrid management that lacks coherence and fails to optimize either goal [50]. Policy design should consider the high labor intensity required for conservation-oriented systems, where maintaining tree health and ecological functions demands continuous and skilled management, yet often yields limited immediate economic return.

The multifunctionality shows a comparatively resilient model under all scenarios, showing balance across labor, revenue, and environmental indicators. In the literature on Mediterranean agro-silvopastoral systems, resilience is closely linked to multifunctionality, structural diversity, and management flexibility. These characteristics enable systems to buffer climatic, market, and policy disturbances. Our results are consistent with this perspective, showing that resilience emerges from the combination of diversified activities and long-term ecological structures, rather than from productivity gains alone. By analyzing these dynamics explicitly at the farm level, this study complements existing landscape and process-oriented assessments of resilience and aligns with evidence that diverse, mixed systems buffer shocks better and maintain adaptive flexibility [20]. However, achieving such diversity is not easily attainable in systems like Montado, where timeframes and structural constraints limit transformation. Cork trees may require up to 30 years to produce their first yield, and high mortality rates, particularly under grazing pressure, make natural regeneration difficult. As such, transitioning back from a livestock-dominated system towards a more balanced or conservation-oriented model is highly constrained and impossible in the short to medium term.

Overall, scenario results indicate differentiated sensitivities across archetypes: forestry-oriented systems are most sensitive to climate stress, multifunctional farms are most shaped by market and policy conditions, and livestock-specialized farms exhibit the strongest overall vulnerability under stress scenarios, notably in labor and ecological performance indicators.

### 4.2. Implications for Governance

Addressing these trade-offs requires a paradigm shift in policy and farm management: one-size-fits-all incentives should give way to locally tailored strategies that integrate environmental, economic, and social objectives.

The observed trade-offs across the three farm archetypes can also be interpreted, in broad conceptual terms, through the lens of the land sparing versus land sharing debate [51,52]. Forestry-focused Montado systems are closer to a land sparing logic, in which ecological functions and tree regeneration are prioritized, while mixed agro-silvopastoral systems reflect a land-sharing strategy that integrates production and ecological functions within the same land unit. Livestock-specialized systems, although primarily oriented toward production, continue to deliver certain environmental functions through extensive grazing and landscape maintenance, but face greater challenges in sustaining tree regeneration and cultural landscape attributes. Importantly, the results do not point to the superiority of one strategy over another. Rather, they highlight how current policy frameworks interact with structurally different farm systems in uneven ways, sometimes reinforcing existing tensions between production, conservation, and labor requirements. From this perspective, the issue is the lack of clear alignment between policy incentives and the long-term sustainability pathways of different farm types, underscoring the importance of policy coherence that is sensitive to structural diversity.

In Mediterranean heterogeneous landscapes such as the Montado, uniform application of policy instruments that were designed without local consultation reduces effectiveness. As seen in similar Mediterranean systems, generic incentives risk reinforcing unsustainable trajectories or deepening dependence on subsidies [14,53]. Moreover, the lack of coherence

between EU policies (e.g., CAP) exacerbates trade-offs. Mixed systems face conflicting signals, required to intensify for viability yet penalized for ecological degradation.

The recent CAP reform gives greater flexibility for Member States to tailor agri-environmental measures to national and regional contexts, encouraging the adoption of performance or results-based payments for the delivery of targeted and measurable environmental outcomes [54]. Currently, one pilot project in the Montado is putting this model into practice by co-designing and testing field-level indicators and management strategies suited to the system's multifunctional character and HNV [54,55]. This scheme is applied to Natura 2000 farms, with 176 farmers having signed the contract for 2023-27. Nonetheless, it remains to be seen (a) the effectiveness of these payments in improving the Montado condition, and (b) the possibility for upscaling to a much larger share of the Montado area.

*4.3. Possible Futures for Montado Farms*

The Montado's resilience since the 18th century stems from its diversity, which buffers it against social, economic, and environmental shocks. Revitalizing this diversity seems to be the goal to preserve the overall system, even if it is with slight adaptation in the business model. In already degraded systems with not many trees left, reversing this trend requires a very considerable investment in soil regeneration and improvement of the tree cover, with new plantations and effective protection of the young shoots. However, some farms are adopting strategic integration of livestock or cash crops such as olive orchards and vineyards as promising income alternatives, especially while slow-growing oak trees mature and begin producing. These additional crops can provide vital short-term to mid-term revenue without forcing a full shift toward irrigated monocultures. Well-managed agroforestry and mixed cropping systems can create transitional income sources that support farmers and safeguard the landscape's multifunctionality. Targeted and system-tailored policies also play a renewed role in sustaining the farms in their re-diversification process, including results-based incentives.

*4.4. Discussion Summary*

Taken together, the discussion shows that sustainability outcomes in Montado systems are strongly differentiated across farm archetypes. Livestock-specialized systems achieve short-term economic performance but are highly vulnerable to combined climatic, market, and policy pressures, particularly in ecological and labor dimensions. Forestry-oriented systems preserve key ecological functions but remain sensitive to climate stress and policy incentives, while multifunctional systems display greater resilience through balanced performance across economic, environmental, and social indicators. These findings underline that sustainability trade-offs are structurally embedded and that effective governance responses must be tailored to farm-type-specific configurations.

*4.5. Study Limitations*

Several limitations are to be acknowledged. First, the analysis is based on a limited number of archetypal case-study farms, selected for analytical rather than statistical representativeness. While this constrains direct quantitative generalization, the objective is to capture contrasting farm structures and management strategies identified through the regional typology, enabling in-depth exploration of differentiated sustainability trajectories. Second, the scenario analysis relies on assumptions regarding future climatic, market, and policy conditions and simplifies complex and uncertain dynamics. The results should therefore be interpreted as plausible pathways rather than predictions. Third, although the participatory process enhances contextual relevance and grounding in farmer experience, it may also reflect the perspectives of the participating actors. Despite these limitations, the

integrated typology-based, participatory, and farm-level modeling approach provides a robust framework to analyze trade-offs and sustainability patterns in complex Mediterranean agro-silvo-pastoral systems such as the Montado.

## 5. Conclusions

This study demonstrates the value of a farm-level, typology-based, and scenario-oriented approach for assessing the sustainability of the Montado system under combined pressures. The results show that sustainability trajectories differ markedly across farm archetypes, indicating that responses to external drivers cannot be inferred from a single representative system.

Linking a regional typology with participatory inputs helps bridge the gap between plot-scale process studies and landscape-level assessments, capturing trade-offs and decision-making constraints at the scale where management choices are made. The findings also highlight the complex role of the Common Agricultural Policy, which can support short-term economic viability while constraining long-term ecological resilience when incentives are not aligned with the system's structural diversity. From a policy perspective, these results underline the need for more differentiated and coherent policy instruments that are tailored to farm-type-specific structures and sustainability objectives.

Future research could complement the qualitative, expert-based scenario assessment adopted here with quantitative modeling approaches, enabling a numerical evaluation of scenario impacts and trade-offs at the farm level.

Future pathways for agro-silvopastoral systems depend on preserving multifunctionality, maintaining the Montado's woodland structure, and strategically integrating diversification options to buffer income during oak maturation. Holistic management approaches and responsive policy frameworks are essential to support this balance and to secure the ecological, economic, and cultural value.

**Institutional Review Board Statement:** Formal ethical review and approval were not required for this study under the institutional framework of the University of Évora, as the research involved voluntary, non-invasive interviews with adult farm managers regarding agricultural practices and did not involve human biological material. The research was conducted in accordance with the Code

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| AES | Agri-Environmental Schemes |
| AWU | Annual Work Unit(s) |
| CAP | Common Agricultural Policy |
| EU | European Union |
| HNV | High Nature Value |
| INE | Instituto Nacional de Estatística (Portugal) |
| IPMA | Instituto Português do Mar e da Atmosfera |
| LSU | Livestock Unit(s) |
| MAPS | Montado Agro-Forestry Production Systems |
| NFI | Net Farm Income |
| NUTS | Nomenclature of Territorial Units for Statistics |
| PPI | Producer Price Index |
| UAA | Utilized Agricultural Area |

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