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VAL MED ALM

Deliverable 4.2

Report of the Environmental, Economic and Social Indicators

VALMEDALM: Valorization of **Med**iterranean **Alm**ond orchards through the use of intercropping integrated strategies

Index

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1. Executive Summary

This work is part of Work Package 4 of the PRIMA–VALMEDALM project, dedicated to assessing the economic, social, and environmental impacts of intercropping practices and technologies applied to Mediterranean almond cultivation. In particular, it addresses the objectives of Task 4.3 – Integration of environmental, economic, and social sustainability results, which involves the use of Multi-Criteria Decision Analysis (MCDA) tools to integrate sustainability results derived from previous activities of economic analysis, indicator selection, and technical-environmental assessment.

The need for an integrated approach stems from the complexity of the almond-intercrop systems observed across the 5 VALMEDALM demosites. Intercropping practices can indeed generate productive, economic, and environmental benefits, but these effects depend heavily on the soil and climate conditions, the intercropped species, water availability, farm organization, and market conditions. The evidence gathered during the project activities shows that intercropping can offer real advantages only when crop combinations are properly adapted to local conditions, avoiding excessive competition and leveraging potential synergies between the main and intercropped crops. Therefore, the evaluation of alternatives cannot be based exclusively on a single indicator, such as almond yield or net farm income. On the contrary, it is necessary to consider the economic, environmental, social, and agronomic dimensions simultaneously to capture the trade-offs among profitability, economic stability, soil conservation, fertility, biodiversity, production quality, resilience, and farm viability.

In light of the above, this deliverable proposes a multi-criteria framework that integrates the Analytic Hierarchy Process (AHP) with regime analysis. The AHP allows estimation of the relative weights of criteria and subcriteria based on the preferences expressed by a panel of stakeholders and experts, while Regime Analysis enables comparison of alternatives in terms of relative dominance, taking into account the ordinal or semi-quantitative nature of much of the available information. This approach allows for the transformation of experimental data, economic information, evidence from literature, and expert judgments into a structured decision-making framework.

The practices observed at the demosites were then categorized into four representative management archetypes: almond cultivation with intercropping of medicinal and aromatic plants (MAPs), almond cultivation with intercropping of grain legumes, organic almond cultivation with intercropping of forage legumes, and conventional non-intercropped management. The objective of this work is not to identify a universally valid solution for all Mediterranean contexts, but to provide a transparent and replicable procedure for comparing alternatives and for identifying the most balanced archetypes with respect to the various dimensions of sustainability.

In this context, Deliverable 4.2 serves as an evaluative synthesis within WP4: Assessment of the economic, social and environmental impacts of tested practices and technologies.

2. Methodology

The multi-criteria analysis was structured within a sequential MCDA framework based on the AHP to define weights, verify consistency, and subsequently aggregate the alternatives. In an initial phase, the management options observed at the VALMEDALM project demosites were harmonized and reduced to a limited set of representative archetypes, each described in standardized technical data sheets detailing production, economic, and structural characteristics. For the present application, four archetypes were considered: (A1) almond cultivation with intercropping of medicinal and aromatic plants (MAPs); (A2) almond cultivation with intercropping of grain legumes; (A3) organic almond cultivation with intercropping of forage legumes; (A4) almond cultivation with conventional management practices (Table 1). However, the archetypes should not be interpreted as statistically representative of the entire Mediterranean almond-growing sector, but rather as summary profiles constructed from the evidence available at the VALMEDALM demosites and designed to facilitate a multi-criteria comparison of the main management trajectories.

Table 1. Technical, productive, and economic profile of the four management archetypes considered in the multi-criteria analysis, with reference to economic, productive, and soil indicators observed at the VALMEDALM demosites.

Item	A1	A2	A3	A4
Average gross sales, €/ha	20,684[1]	1,572[1]	7,611[1]	3,163[1]
Average operating costs, €/ha	9,234[1]	1,058[1]	2,375[1]	1,001[1]
Average net income, €/ha	9,812[1]	-395[1]	4,001[1]	1,118[1]
Maximum-minimum range among the observed financial statements, €/ha	52,862[2]	2,716[2]	2,090[2]	4,713[2]
Almond yield, kg/ha	724 ± 154[2]	216.5 ± 39.9[2]	295.8 ± 41.2[2]	246.3 ± 69.7[2]
Soil organic matter at the end of the trial, g/kg	18.44 ± 5.03[1]	24.50 ± 0.70[3]	21.17 ± 6.43[1]	23.33 ± 5.77[1]
Total soil nitrogen, g/kg	0.30 ± 0.05[1]	0.62 ± 0.03[3]	0.80 ± 0.13[1]	0.57 ± 0.15[1]
D Total soil nitrogen vs. control (A4), %	−46.5[2]	+8.8[2]	+19.3[2]	-
Note: [1] data observed from farm records or laboratory analyses; [2] value calculated from available data; [3] proxy reconstructed from the literature.				

2.1. Definition of the hierarchy of criteria and subcategories

In a second phase, the decision-making hierarchy of the multi-criteria model was defined, structured into four macro-categories of evaluation -economic, environmental, social, and agronomic- each subdivided into three operational subcategories, for a total of 12 dimensions of analysis (Table 2). The selection of the macro-categories and their sub-categories was based on integrating two complementary information sources. On the one hand, quantitative data provided by the project partners were considered, relating to gross marketable production, operating costs, net income, and key soil indicators; on the other hand, a targeted review of the scientific literature was conducted, aimed at including dimensions not directly observable at the demosites but relevant for the comparative evaluation of the archetypes, in particular functional biodiversity, product and supply chain differentiation, social acceptability, operational safety, and resilience of the cropping system.

The final structure of the evaluation framework thus combined directly measurable criteria with criteria derived from the literature and expert elicitation, in order to ensure empirical robustness and interpretive completeness. The decision to structure the model along four main dimensions reflects the inherently multifunctional nature of Mediterranean almond farming, in which the performance of a cropping system cannot be evaluated solely on the basis of yield or short-term economic results. In Mediterranean contexts, in fact, the sustainability of farms is strongly influenced by the ability to balance profitability, economic stability, the conservation of natural resources, social resilience, and adaptation to soil and climate conditions.

In this context, the economic dimension plays a central role, as the adoption of innovative intercropping systems depends on their ability to generate income, reduce risk exposure, and maintain management levels compatible with available farm resources. At the same time, in Mediterranean tree-based systems, economic viability alone is insufficient to describe the true sustainability of these practices, especially in areas characterized by high interannual variability in yields, low profit margins, and increasing climate uncertainty (Table 2).

The environmental macro-category has been included due to its particular relevance to Mediterranean almond cultivation, which is often located in semi-arid or sub-humid areas prone to water stress, soil degradation, loss of organic matter, and erosion. In these contexts, soil conservation, fertility maintenance, and increased organic carbon are essential conditions for medium- to long-term production stability. Similarly, functional biodiversity and impact reduction are central aspects, as strengthening the farm's ecological components can improve ecosystem services and the overall resilience of the agroecosystem (Table 2).

The social dimension was considered because the adoption of agroecological practices and mixed cropping systems depends not only on their technical effectiveness but also on their feasibility at the farm level. In Mediterranean contexts, often characterized by small or medium-sized farms and a strong link between production, the local area, and local supply chains, ease of adoption, compatibility with work organization, the potential to create local value, and the quality of operating conditions take on particular importance. Considering these aspects enables a more realistic assessment of the archetypes' transferability (Table 2).

The agronomic macro-category was retained as an independent axis of evaluation because it is directly linked to the cropping system's functionality and its ability to sustain almond tree productivity under water and nutrient limitations. In Mediterranean systems, in fact, practices that are favorable from an environmental or social perspective may prove difficult to implement if they compromise yield, production quality, or the competitive balance between the main crop and companion species. The joint consideration of yield, quality, and resilience therefore allows for a more accurate assessment of the trade-offs between ecological intensification and productive stability (Table 2).

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Overall, the combined inclusion of economic, environmental, social, and agronomic criteria reflects the need to evaluate the archetypes from a multidimensional perspective, comprehensively synthesizing the main factors that guide the choice between different management options (Table 2).

Table 2. Hierarchical structure of the AHP framework adopted for the evaluation of the archetypes, structured into macro-categories, sub-criteria, operational definitions, and main reference indicators.

Macro-category	Code	Sub-criterion	Operational definition	Main indicators
Economic	ECO1	System profitability	Ability of the almond + intercrop system to generate a positive economic result per hectare	Gross margin, net profit, gross marketable production, farm net income
Economic	ECO2	Economic stability and resilience	Ability of the system to ensure less variable results and lower exposure to price, yield, or market uncertainty	Margin variability, price/yield sensitivity, break-even point, revenue stability
Economic	ECO3	Costs and management complexity	Level of additional operating costs, labour requirements, and organisational complexity	Additional operating costs, labour hours/ha, mechanisation requirements, management complexity
Environmental	ENV1	Soil conservation	Ability of the system to protect the soil from erosion, loss of cover, and structural degradation	Soil cover, infiltration, bulk density, erosion proxy
Environmental	ENV2	Soil fertility and carbon	Ability of the system to improve organic matter, nutrient availability, and soil quality	Organic matter, SOC, root biomass, nutrient availability
Environmental	ENV3	Biodiversity and impact reduction	Ability of the system to support beneficial organisms and reduce inputs or environmental impacts	Pollinators, beneficial arthropods, pesticide reduction, N inputs, energy
Social	SOC1	Acceptability and adoption	Ease with which the practice can be introduced and integrated into ordinary farm management	Survey on ease of adoption, compatibility with routines/machinery, intention to adopt
Social	SOC2	Local socio-economic benefits	Contribution to the valorisation of the territory, local supply chains, and rural economies	Local income opportunities, diversification, creation of territorial value
Social	SOC3	Safety, health, and employment	Effects on working conditions, risks for operators, and support for local employment	Reduced exposure to pesticides, operational risk, seasonal/permanent employment
Agronomic	AGR1	Almond yield	Ability of the system to maintain or improve yield	Kernel yield, productive efficiency, yield stability
Agronomic	AGR2	Production quality and health	Effects on market quality and phytosanitary status of production	Size, defects, market quality, incidence of pathogens/pests
Agronomic	AGR3	Resilience and competition	Ability of the system to support almond trees under stress conditions and limit competition for resources	Water stress, production stability, mortality/decline, competition for water and nutrients

2.2. Design of the AHP questionnaire and collection of preferences

In the third phase, preferences were collected using an AHP questionnaire administered via Google Forms to a purposively selected sample of 25 industry professionals with technical, scientific, or operational expertise relevant to the study's focus. The survey was distributed through the heads of research units in the five countries participating in the VALMEDALM project — Italy, Portugal, Morocco, Croatia, and Israel — each of which involved a group of participants representing the main stakeholder profiles relevant to the assessment, in line with the AHP approach, which prioritizes the quality and relevance of judgment over sample size: researchers/faculty, farmers, technicians/agronomists, and representatives of trade associations or public agencies.

The questionnaire was designed using a pairwise comparison approach and structured across two decision-making levels: a first level concerning the four macro-categories and a second level concerning the three sub-categories within each macro-category. For each pair of criteria, the survey was structured in two distinct phases: in the first phase, respondents were asked to indicate which of the two criteria they considered more important or, in the event of equivalence, to select both; in a second, immediately following phase, they were asked to quantify the intensity of their preference by assigning a value on the Saaty scale from 1 to 9, where 1 corresponds to equal importance and 9 to extreme importance. The odd numbers (1, 3, 5, 7, 9) represent the main levels of intensity, while the even numbers (2, 4, 6, 8) were provided as intermediate options. The collected responses were exported into tabular format, subjected to a preliminary check to verify their completeness and syntactic consistency, and subsequently entered into the AHP-OS calculator (Goepel, 2018) for the processing described in the following section.

2.3. Construction of Comparison Matrices and Weight Estimation

For each respondent, the AHP-OS calculator constructed a 4×4 matrix relating to the macro- categories and four 3×3 matrices relating to the sub-categories within each macro-category, automatically applying the principle of reciprocity: given a generic element a_{ij}, the corresponding symmetric element was defined as its reciprocal, while the diagonal elements were set equal to 1. From each matrix, the vector of individual weights was derived using the eigenvalue method implemented in AHP-OS (Goepel, 2018), which solves the dominant right eigenvector problem $A \cdot w = \lambda max \cdot w$. The consistency ratio (CR) was calculated according to Saaty (1980) and used as a diagnostic indicator of the internal coherence of respondents' judgments. The values obtained show variability across the matrices and among respondents, reflecting both the panel's heterogeneity and the complexity of the required comparisons. The questionnaire involved an international and multidisciplinary group of experts and stakeholders, who were asked to evaluate the economic, environmental, social, and agronomic dimensions simultaneously, often characterized by trade-offs and priorities that are not immediately comparable.

Table 3. Diagnostic summary of the consistency indices of the AHP matrices.

AHP matrix	No. of responses	Mean CR	Median CR	Responses with CR ≤ 0.10
Macro-categories	25	0.6049	0.3802	2
Economic criteria	25	0.4026	0.2633	7
Environmental criteria	25	0.6718	0.3301	7
Social criteria	25	0.5174	0.3301	3
Agronomic criteria	25	0.4338	0.3756	7

The diagnostic results reported in Table 3 therefore help qualify the interpretation of the AHP weights by showing the degree of coherence of the matrices without reducing the evaluation process to a mechanical filter for accepting or excluding responses. This choice is consistent with the applied and exploratory nature of the analysis, which was designed to integrate technical knowledge, operational experience, and expert preferences from the different Mediterranean contexts involved in the project.

The normalized individual weights were subsequently aggregated using the arithmetic mean of the weight vectors, yielding the average weights of the four macro-categories and the local average weights of the three sub-categories within each macro-category. Aggregation using the arithmetic mean of the individual weight vectors was preferred over the geometric mean of the ratings due to the heterogeneity of the panel, composed of professionals with different educational backgrounds, experience, and evaluative perspectives—a situation in which the literature suggests preserving individual variability rather than aggregating ratings upstream (Forman & Peniwati, 1998).

The overall weights of the 12 sub-criteria were finally derived by multiplying the average weight of the macro-category by the average local weight of the corresponding sub-category:

$$\boldsymbol{W_{global,i} = W_{macro,k} \times W_{local,i|k}}$$

where *Wmacro,k* represents the weight of macro-category k and *Wlocal,i|k* the local weight of sub- category ii belonging to the same macro-category. This step determined the final set of overall weights used in the subsequent phase of evaluating the alternatives.

2.4. Application of Regime Analysis

Once the weight assignment phase using AHP was completed, the comparative evaluation of the archetypes was conducted using regime analysis, following the approach outlined in the adopted methodological reference (Hinloopen & Nijkamp, 1990). In this phase, we did not proceed with a simple linear aggregation of standardized scores; instead, we constructed a sequence of matrices to compare the alternatives on a criterion-by-criterion basis using a relative dominance criterion.

First, the effects matrix was constructed, organized by placing the archetypes in the rows and the 12 sub-criteria in the columns. For each archetype, an ordinal performance rating on a 1–5 scale was then assigned for each sub-category, where 1 indicates very low performance, 2 low, 3 moderate, 4 high, and 5 very high. Scores were collected using a dedicated expert scoring form created in Google Forms and shared with participants at the final meeting of the VALMEDALM project, held on May 18, 2026, in Bragança, Portugal, at the Brigantia Ecopark building MORECoLAB (Collaborative Laboratory Montanhas de Investigação).

During the meeting, the link to the questionnaire and the corresponding QR code were displayed during the session dedicated to Task 4.3, allowing participants to complete the multi-criteria evaluation grid directly. Before completing the form, participants were briefed on the transition from AHP weights to archetype scoring, the evaluation scale adopted, and the reference data available for each archetype. Each respondent was asked to evaluate the relative performance of the four archetypes with respect to each sub-criterion, maintaining consistency of judgment within each row of the grid—that is, by comparing all archetypes simultaneously before moving on to the next sub-criterion. The assignment of ordinal scores was therefore carried out by integrating three complementary sources of information: data observed at the demosites, available technical and scientific evidence, and expert judgment gathered through the scoring survey administered during the meeting. In this way, the effects matrix was intended as a tool for the comparative synthesis of the archetypes' relative performance, not as a direct experimental measurement of all the sub-criteria considered. Starting with the effects matrix, the ranking matrix was subsequently developed, in which each alternative was compared with every other alternative for each criterion. This step transformed the matrix of ordinal evaluations into a structure for direct comparison between pairs of archetypes, thereby making the direction of preference explicit for each evaluation element.

In a subsequent phase, the weighted regime matrix was constructed by assigning to each comparison the weight of the corresponding sub-criterion derived from the AHP. In this way, the dominance among alternatives was not considered in purely ordinal terms but weighted according to the relative importance attributed by respondents to the various evaluation criteria. The algebraic sum of the values in the weighted regime matrix made it possible to obtain, for each comparison between two archetypes, a partial preference index that expresses the relative desirability of one alternative over the other.

In the final phase of the analysis, the aggregate regime index (Ci) was determined for each alternative, allowing the results of the comparisons with all other alternatives to be synthesized and the final hierarchy of design options to be identified. The index is given by the ratio of the sum of the values obtained by alternative i in comparison with the other alternatives to the total number of alternatives considered, net of the unit:

$$\boldsymbol{C_i = \frac{\sum C_{ij}}{n-1}}$$

where cij expresses the preference of alternative i over alternative j, while n represents the total number of alternatives. In this way, for each alternative, a summary value is obtained that summarizes its overall performance relative to the set of options considered. The final ranking was then constructed by ordering the alternatives in descending order of the C_i values.

3. Results

3.1. Sample characteristics

The AHP survey collected 25 valid responses from an international panel of opinion leaders evaluating criteria relevant to the multi-criteria analysis of intercropping archetypes in Mediterranean almond cultivation. The sample includes respondents from the five countries involved in the VALMEDALM project, with a geographic distribution representative of all the project partners' regions.

From a professional standpoint, the panel consisted primarily of researchers and academics, alongside technicians, agronomists, farmers, and representatives of public institutions or policymakers (Fig. 1). This composition reflects the survey's design, which aimed to gather expert opinions from individuals with scientific, technical, and operational expertise relevant to the evaluation topic.

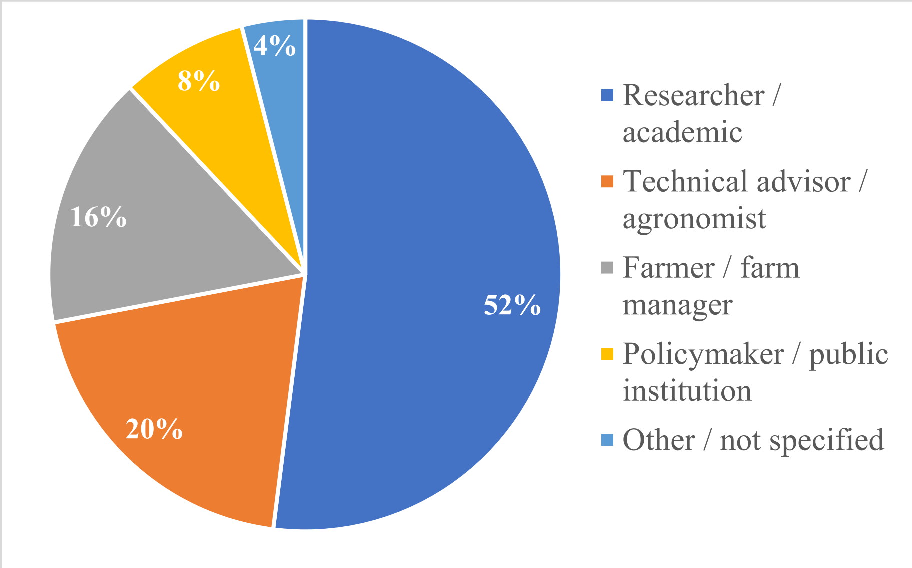

Figure 1. Percentage distribution of respondents to the AHP questionnaire by professional profile, with a prevalence of researchers/academics, followed by technical advisors/agronomists, farmers or farm managers, policymakers/public institutions, and other or unspecified profiles.

Regarding the production context with the most experience, eight respondents reported having experience in both irrigated and dryland/rainfed systems (Table 4). A portion of the sample, however, indicated a primary specialization in irrigated or rainfed almond orchards, while some respondents reported experience not directly related to almond cultivation but nonetheless similar to the management of Mediterranean tree systems.

Table 4. Distribution of respondents according to their main production context of experience, expressed as absolute values and percentages of the total sample.

Experience context	Number of respondents	Share of the sample
Both irrigated and rainfed almond orchards	8	32.0%
Other / not applicable	8	32.0%
Irrigated almond orchard	4	16.0%
Rainfed almond orchard	3	12.0%
Other tree crop systems	2	8.0%
Total	**25**	**100.0%**

As for the purely technical aspects of the questionnaire, the overall clarity of the proposed categories and subcategories was rated positively. On a scale of 1 to 5, most respondents gave scores of 4 or 5, while only two gave a score of 2. Finally, in response to the question regarding the possible underrepresentation of one of the four macro-categories in the evaluation framework, seven respondents indicated that the categories are balanced, while eighteen reported a possible underrepresentation of at least one dimension (Table 5). The category most frequently cited as underrepresented is the social category.

Table 5. Respondents' perception of the possible underrepresentation of macro-categories within the AHP evaluation framework.

Response	Number of respondents	Share of the sample
Social category underestimated	8	32.0%
The four categories are balanced	7	28.0%
Environmental/ecological category underestimated	5	20.0%
Economic category underestimated	4	16.0%
Agronomic category underestimated	1	4.0%
Total	**25**	**100.0%**

3.2. AHP Weights

The pairwise comparisons collected via the AHP questionnaire were processed by considering all available responses. For each respondent, weight vectors were derived for the first level of the hierarchy—consisting of the four macro-categories—and for the second level—consisting of the three sub-criteria within each macro-category. The individual weights were subsequently aggregated using the arithmetic mean to preserve the variability of preferences expressed by a panel that was heterogeneous in terms of professional profile, gender, and sectoral experience. This approach is consistent with the methodological framework already established in the study, in which individual judgments are aggregated downstream, and the overall weights of the sub-criteria are obtained by multiplying the weight of the macro-category by the local weight of the corresponding sub-criterion.

At the macro-category level, the agronomic dimension had the highest average weight, accounting for 33.78% of the total. This is followed by the economic dimension at 28.37% and the environmental dimension at 28.28%, which have nearly equivalent values. The social dimension, on the other hand, has less weight, at 9.57%. Overall, the distribution of weights reveals a preference structure concentrated primarily on agronomic, economic, and environmental aspects, while social aspects play a secondary role in the aggregated AHP weighting (Tab. 6).

Table 6. Average weights assigned to the four macro-categories of the AHP analysis, expressed as normalised values and as percentage shares of the total weight.

Rank	Macro-category	Average weight	Percentage weight
1°	Agronomic criteria	0.3378	33.78%
2°	Economic criteria	0.2837	28.37%
3°	Environmental criteria	0.2828	28.28%
4°	Social criteria	0.0957	9.57%
Total		**1.000**	**100.00%**

Calculating the overall weights of the sub-criteria allows for a more detailed examination of which factors had the greatest impact on the overall decision-making structure (Tab. 7). The sub- criterion with the highest overall weight is AGR1 – Almond tree yield, at 13.49%. This is followed by ECO2 – Economic stability and resilience at 12.63%, ECO1 – System profitability at 11.78%, and AGR2 – Production quality and safety at 11.41%. ENV3 – Biodiversity and impact reduction also has a high weight, at 11.22%, placing it among the top five sub-criteria in the ranking.

In the middle group are ENV2 – Soil fertility and carbon, at 9.99%, AGR3 – Resilience and competitiveness, at 8.88%, and ENV1 – Soil conservation, at 7.07%. The lowest weights, on the other hand, are associated with the social sub-criteria and the economic criterion related to costs and management complexity. Specifically, SOC2 – Local socio-economic benefits reach 4.86%, while ECO3 – Costs and management complexity, SOC1 – Acceptability and adoption, and SOC3 – Safety, health, and employment are below 4%.

Table 7. Global weights of the twelve sub-criteria derived from the combination of the macro-category weight and the local weight of the corresponding sub-criterion.

Rank	Code	Sub-criterion	Macro-category	Global weight	Weight
1°	AGR1	Almond tree yield	Agronomic	0.1349	13.49%
2°	ECO2	Economic stability and resilience	Economic	0.1263	12.63%
3°	ECO1	System profitability	Economic	0.1178	11.78%
4°	AGR2	Production quality and health	Agronomic	0.1141	11.41%
5°	ENV3	Biodiversity and impact reduction	Environmental	0.1122	11.22%
6°	ENV2	Soil fertility and carbon	Environmental	0.0999	9.99%
7°	AGR3	Resilience and competition	Agronomic	0.0888	8.88%
8°	ENV1	Soil conservation	Environmental	0.0707	7.07%
9°	SOC2	Local socio-economic benefits	Social	0.0486	4.86%
10°	ECO3	Costs and management complexity	Economic	0.0396	3.96%
11°	SOC1	Acceptability and adoption	Social	0.0241	2.41%
12°	SOC3	Safety, health, and employment	Social	0.0229	2.29%
Total				**1.000**	**100.00%**

For each comparison matrix, the consistency index was calculated and used as a diagnostic indicator of the ratings' internal consistency. At this stage, however, responses with consistency values exceeding the conventional threshold of 0.10 were not excluded from the calculation of the average weights. Operationally, therefore, the set of weights presented in Tables 6 and 7 represents the result of aggregating the full sample, including responses with CR above the threshold. Individual judgments were retained in their original form throughout the aggregation process, in order to preserve the preferences expressed by respondents and avoid introducing additional assumptions during data processing. The CR values were therefore used as diagnostic information to contextualize the interpretation of the AHP weights and to describe the degree of consistency of the comparison matrices.

The consistency indices calculated for the AHP matrices show variability across the hierarchy's levels and among respondents. This variability is consistent with the nature of the panel, composed of diverse professional and geographic profiles, and with the complexity of the comparisons required, which involved the simultaneous evaluation of economic, environmental, social, and agronomic dimensions. In accordance with the adopted methodological approach, the consistency values were used as diagnostic information rather than as an exclusion criterion.

3.3. Ranking of archetypes

The final phase of the MCDA involved constructing the final ranking of management archetypes for Mediterranean almond cultivation. To this end, the overall weights of the twelve sub-criteria derived from the AHP were combined with the performance scores assigned to the four archetypes by a group of 10 opinion leaders. The scores were expressed on an ordinal scale from 1 to 5, where 1 indicates a very low propensity and 5 a very high propensity of the archetype with respect to the sub-criterion in question.

First, the individual evaluations were aggregated using the arithmetic mean, yielding an average effects matrix (Tab. 8). This matrix serves as the informational basis for the subsequent application of regime analysis, according to the methodological workflow adopted in this study, which involves moving from the effects matrix to the regime matrix, to the weighted regime matrix, and finally to the calculation of the aggregate regime index for each alternative.

Table 8. Average Effects Matrix of the archetypes with respect to the twelve sub-criteria, obtained by aggregating the ordinal evaluations expressed by opinion leaders on a 1–5 scale.

Code	Sub-criterion	A1	A2	A3	A4
ECO1	System profitability	3.80	3.00	3.20	2.80
ECO2	Economic stability and resilience	3.60	3.20	3.40	2.67
ECO3	Costs and management complexity	3.50	3.40	3.30	2.30
ENV1	Soil conservation	3.80	4.20	4.40	2.00
ENV2	Soil fertility and carbon	3.40	4.00	4.20	2.20
ENV3	Biodiversity and impact reduction	4.20	3.80	3.90	1.70
SOC1	Acceptability and adoption	2.80	3.30	3.40	3.90
SOC2	Local socio-economic benefits	3.60	3.60	3.70	2.20
SOC3	Safety, health, and employment	3.80	3.70	3.70	2.80
AGR1	Almond tree yield	3.50	3.40	3.60	3.30
AGR2	Production quality and health	3.50	3.80	3.70	2.30
AGR3	Resilience and competition	3.90	3.67	3.60	2.60
Note: Values are expressed as average scores on a 1–5 scale. In two sub-criterion/archetype combinations, the number of valid observations is 9 instead of 10: ECO2–A4 and AGR3–A2.					

Starting with the average effects matrix, the archetypes were compared in pairs for each sub-criterion. For each binary comparison, a positive sign was assigned to the archetype with the higher average score, a negative sign to the archetype with the lower score, and a zero value in cases of a tie (Tab. 9). Subsequently, each dominance sign was weighted using the corresponding sub- criterion’s overall AHP weight. The algebraic sum of the weighted values yielded a partial preference index for each comparison between archetypes.

Table 9. Summary of pairwise comparisons between archetypes using weighted regime analysis, with indication of the partial preference index and the prevailing archetype in each comparison.

Pairwise comparison	Partial preference index	Prevailing archetype
A1 vs A2	*0.3337*	A1
A1 vs A3	*0.0153*	A1
A1 vs A4	*0.9517*	A1
A2 vs A3	*-0.4920*	A3
A2 vs A4	*0.9517*	A2
A3 vs A4	*0.9517*	A3

The summary of the pairwise comparisons shows that the three archetypes based on consociational systems prevail over the conventional archetype. In direct comparison with A4, A1, A2, and A3 all have a positive index of 0.9517, due to the same dominance structure across criteria. In all three comparisons, the intercropping archetypes outperform A4 on eleven out of twelve sub-criteria and are outperformed only on SOC1 – Acceptability and adoption. Since regime analysis is based on the direction of dominance rather than on the magnitude of score differences, the resulting weighted preference index is identical across these comparisons. Among the consociational archetypes, the comparison between A1 and A3 is particularly close, with a partial preference index of 0.0153 in favor of A1, while A3 prevails over A2 with an index of 0.4920.

Finally, the aggregate regime index was calculated for each archetype by synthesizing the values obtained in comparisons with all other alternatives. The final ranking was determined by ordering the archetypes in descending order of the aggregate index (Tab. 10).

Table 10. Final ranking of management archetypes according to the aggregate regime index, calculated on the basis of AHP weights and the ordinal performance scores of the archetypes.

Rank	Code	Archetype	Aggregate regime index
1st	A3	Almond + Forage Legumes	0.4761
2nd	A1	Almond + MAPs	0.4336
3rd	A2	Almond + Grain Legumes	0.0420
4th	A4	Conventional farming	-0.9517

The final ranking identifies A3 – Almond + Forage Legumes as the archetype with the highest value of the aggregate regime index, followed by A1 – Almond + MAPs. A2 – Almond + Grain Legumes ranks third, with a positive index but close to zero, while A4 – Conventional farming records a negative value and occupies the last position in the ranking.

Therefore, the final ranking of the regime analysis weighted with AHP weights is as follows:

A3 > A1 > A2 > A4

4. Robustness analysis: W5 winsorization of AHP matrices and stability of the MCDA ranking

4.1. Rationale of the robustness analysis

The original AHP analysis was based on pairwise comparisons provided by 25 stakeholders with different professional, geographical and operational backgrounds. The questionnaire was structured on two hierarchical levels: a first level concerning the four macro-categories of sustainability, and a second level concerning the three sub-criteria within each macro-category. The judgments were expressed according to the Saaty scale from 1 to 9, where 1 indicates equal importance and 9 indicates extreme importance.

The diagnostic analysis of the original AHP matrices showed relatively high consistency ratio values across all levels of the hierarchy. In particular, the mean CR exceeded the conventional threshold of 0.10 in all matrices. However, adopting the threshold CR ≤ 0.10 as a strict exclusion rule would have led to the removal of a large share of the stakeholder judgments, thereby reducing the representativeness and heterogeneity of the expert panel. For this reason, in the baseline scenario, hereafter referred to as S0, the CR was used as a diagnostic indicator rather than as a mechanical exclusion criterion.

To assess whether the final MCDA ranking was affected by highly intense and potentially inconsistent judgments, a robustness analysis was conducted by applying a W5 winsorization procedure to the original AHP pairwise comparison matrices. This procedure was designed to attenuate extreme preference intensities while preserving the direction of each stakeholder's judgment.

4.2. W5 winsorization procedure

The W5 scenario was obtained by capping all pairwise comparison intensities greater than 5 at the value 5. Therefore, values from 1 to 5 were left unchanged, while values 6, 7, 8 and 9 were replaced by 5. The direction of the preference was not modified. As a result, the procedure did not reverse any stakeholder judgment but only reduced the maximum admissible preference intensity.

The transformation applied to each direct pairwise comparison was:

$$a_{ij}^{W5} = min(a_{ij}^{S0}, 5)$$

where a_ij^S0 is the original pairwise-comparison intensity in the baseline scenario, and a_ij^W5 is the corresponding winsorized intensity in the W5 robustness scenario. The reciprocal property of the AHP matrix was preserved as follows:

$$a_{ji}^{W5} = \frac{1}{a_{ij}^{W5}}$$

and the diagonal elements were kept equal to unity (e.g., a_ji^W5=1). Thus, for each respondent, the W5 transformation produced a revised reciprocal comparison matrix:

$$A^{W5} = \begin{bmatrix} 1 & \cdots & a_{1n}^{W5} \\ \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}^{W5}} & \cdots & 1 \end{bmatrix}$$

This correction was applied before recalculating the AHP weights and consistency ratios. The W5 scenario therefore represents a conservative robustness treatment of the original judgments, aimed at reducing the influence of extreme comparisons without altering the qualitative preference structure expressed by stakeholders.

4.3. Recalculation of AHP weights under W5

After applying the W5 transformation, the priority vector was recalculated for each individual matrix using the eigenvector method. The AHP priority vector was obtained from the dominant right eigenvector of the comparison matrix:

$$A^{W5} \cdot w^{W5} = \lambda_{max}^{W5} \cdot w^{W5}$$

where A^W5is the winsorized comparison matrix, w^W5 is the vector of AHP priorities, and λ_max^W5 is the maximum eigenvalue of the matrix.

For each matrix, the consistency index was recalculated as:

$$CI^{W5} = (\lambda_{max}^{W5} - n) \,/\, (n - 1)$$

where (n) is the order of the comparison matrix. The consistency ratio was obtained by normalizing over the random index associated with a matrix of order n:

$$CR^{W5} = \frac{CI^{W5}}{RI_n}$$

where 〖RI〗 _nis the random index associated with a matrix of order n. The individual W5 weights were subsequently aggregated using the arithmetic mean, consistently with the aggregation procedure adopted in the baseline scenario:

$$\overline{w}_C^{W5} = 1/m \cdot \sum_{r=1}^{m} w_{r,c}^{W5}$$

where w ̅_C^W5 is the average W5 weight of criterion c, and w_(r,c)^W5 is the W5 weight assigned by respondent r, and m is the number of respondents.
Finally, the global W5 weight of each sub-criterion was obtained by multiplying the W5 weight of the corresponding macro-category by the W5 local weight of the sub-criterion:

$$W_i^{W5} = W_{macro,k}^{W5} \cdot W_{i|k,local}^{W5}$$

where W_(macro,k)^W5 is the W5 weight of macro-category k, and W_(i|k,local)^W5 is the W5 local weight of sub-criterion i within macro-category k.

4.4. Effect of W5 on consistency ratios

The W5 procedure reduced the mean CR values in all AHP matrices. The largest absolute reductions were observed for the environmental matrix, the macro-category matrix and the social matrix. Although the W5 transformation did not bring all mean CR values below the conventional threshold of 0.10, it substantially attenuated inconsistency while maintaining the full set of stakeholder judgments.

Table 11. Mean and median consistency ratios under the baseline scenario (S0) and the W5 winsorized scenario, with absolute and relative reductions across AHP matrices.

AHP matrix	No. responses	Mean CR S0	Mean CR W5	Absolute reduction	Reduction %	Median CR S0	Median CR W5
Macro-categories	25	0.6225	0.4057	0.2168	34.83%	0.3803	0.2531
Economic criteria	25	0.4059	0.2729	0.1331	32.78%	0.2633	0.2541
Environmental criteria	25	0.6718	0.4415	0.2303	34.28%	0.3301	0.2541
Social criteria	25	0.5174	0.3201	0.1972	38.12%	0.3301	0.2541
Agronomic criteria	25	0.4338	0.3342	0.0995	22.94%	0.3756	0.2541

The results indicate that W5 acts as a consistency-improving robustness treatment. The reduction is particularly relevant because it is obtained without deleting respondents and without forcing artificial consistency into the matrices. Instead, the procedure only limits the influence of very high preference intensities, which are often responsible for strong transitivity violations in AHP pairwise comparisons.

The comparison between S0 and W5 shows that the overall structure of macro-category weights remains substantially stable. The agronomic dimension remains the most important macro-category, followed by the economic and environmental dimensions. The social dimension increases under W5, suggesting that part of its relatively low weight in the baseline scenario was influenced by stronger preference intensities assigned to other dimensions.

Table 12. Comparison of macro-category weights between the baseline scenario (S0) and the W5 scenario, including absolute and relative changes.

Macro-category	S0 weight	W5 weight	Delta W5-S0	Delta %
Economic	0.2838	0.2742	-0.0096	-3.39%
Environmental	0.2789	0.2797	0.0008	0.29%
Social	0.0889	0.1045	0.0156	17.53%
Agronomic	0.3484	0.3416	-0.0068	-1.95%

The main effect of W5 is therefore not a radical reconfiguration of the hierarchy, but a moderate redistribution of weights. Economic and agronomic dimensions slightly decrease, the environmental dimension remains almost unchanged, and the social dimension increases while still remaining the least weighted macro-category.

4.5. Effect of W5 on global sub-criterion weights

The W5 global weights confirm the relevance of agronomic, economic and environmental aspects in the evaluation framework. Almond tree yield remains the highest-weighted sub-criterion, followed by economic stability and resilience, production quality and health, system profitability, and biodiversity and impact reduction.

Table 11. Global weights of the 12 sub-criteria under the baseline scenario (S0) and the W5 scenario, with rank positions and weight changes.

Rank W5	Code	Sub-criterion	Macro-category	S0 global weight	W5 global weight	Delta W5-S0	Delta %
1	AGR1	Almond tree yield	Agronomic	0.1391	0.1344	-0.0047	-3.38%
2	ECO2	Economic stability and resilience	Economic	0.1245	0.1175	-0.0071	-5.67%
3	AGR2	Production quality and health	Agronomic	0.1177	0.1148	-0.0029	-2.46%
4	ECO1	System profitability	Economic	0.1197	0.1132	-0.0065	-5.44%
5	ENV3	Biodiversity and impact reduction	Environmental	0.1107	0.1087	-0.0020	-1.77%
6	ENV2	Soil fertility and carbon	Environmental	0.0985	0.0989	0.0004	0.41%
7	AGR3	Resilience and competition	Agronomic	0.0916	0.0924	0.0008	0.90%
8	ENV1	Soil conservation	Environmental	0.0698	0.0721	0.0024	3.40%
9	SOC2	Local socio-economic benefits	Social	0.0452	0.0506	0.0054	11.90%
10	ECO3	Costs and management complexity	Economic	0.0395	0.0435	0.0040	9.99%
11	SOC1	Acceptability and adoption	Social	0.0224	0.0280	0.0056	24.89%
12	SOC3	Safety, health and employment	Social	0.0213	0.0259	0.0046	21.72%

The most relevant increases are observed for the social sub-criteria, particularly acceptability and adoption, safety, health and employment, and local socio-economic benefits. However, these increases are not large enough to change the overall dominance structure of the model. The top-ranking criteria remain linked to productive performance, economic stability, profitability, biodiversity, soil fertility and agronomic resilience.

4.6. Effect matrix used for regime analysis

The revised W5 weights were then combined with the same effects matrix used in the baseline regime analysis. The effects matrix was obtained by aggregating the scores assigned by the opinion leaders to the four management archetypes. Scores were expressed on a 1–5 ordinal scale, where 1 indicates very low performance and 5 indicates very high performance.

Table 12. Average performance scores of the four archetypes across the 12 sub-criteria used in the effects matrix.

Code	Sub-criterion	A1 Almond + MAPs	A2 Almond + Grain Legumes	A3 Almond + Forage Legumes	A4 Conventional farming	Min valid n
ECO1	System profitability	3.80	3.00	3.20	2.80	10
ECO2	Economic stability and resilience	3.60	3.20	3.40	2.67	9
ECO3	Costs and management complexity	3.50	3.40	3.30	2.30	10
ENV1	Soil conservation	3.80	4.20	4.40	2.00	10
ENV2	Soil fertility and carbon	3.40	4.00	4.20	2.20	10
ENV3	Biodiversity and impact reduction	4.20	3.80	3.90	1.70	10
SOC1	Acceptability and adoption	2.80	3.30	3.40	3.90	10
SOC2	Local socio-economic benefits	3.60	3.60	3.70	2.20	10
SOC3	Safety, health and employment	3.80	3.70	3.70	2.80	10
AGR1	Almond tree yield	3.50	3.40	3.60	3.30	10
AGR2	Production quality and health	3.50	3.80	3.70	2.30	10
AGR3	Resilience and competition	3.90	3.67	3.60	2.60	9

The W5 robustness analysis therefore isolates the effect of changing the AHP weighting structure while keeping the performance assessment of the archetypes constant. This allows the sensitivity of the final ranking to the treatment of stakeholder preferences to be directly assessed.

4.7. Weighted regime analysis under WP5

After recalculating the global weights of the twelve sub-criteria under the W5 scenario, these weights were combined with the average performance scores assigned by the opinion leaders to the four archetypes.

The regime analysis was carried out through a pairwise comparison of the archetypes. This means that each archetype was compared with every other archetype, criterion by criterion. For each sub-criterion, the archetype with the higher performance score was considered to prevail over the other one. If the two archetypes had the same score, no advantage was assigned to either of them.

In practical terms, the procedure worked as follows:

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- if archetype A1 had a higher score than archetype A2 for a given sub-criterion, A1 received the W5 weight of that sub-criterion as a positive contribution;
- if A1 had a lower score than A2, the same W5 weight was assigned as a negative contribution;
- if A1 and A2 had the same score, the contribution was equal to zero.

This operation was repeated for all twelve sub-criteria. The positive and negative contributions were then summed to obtain the partial preference index for each pairwise comparison. A positive partial preference index indicates that the first archetype prevails over the second one. A negative value indicates that the second archetype prevails over the first one. A value close to zero indicates that the two archetypes have a very similar overall profile.

Once all pairwise comparisons were completed, the aggregate regime index was calculated for each archetype by averaging its preference indices against all the other archetypes. Since four archetypes were considered in the analysis, each archetype was compared with the other three alternatives.

The final ranking was obtained by ordering the archetypes according to their aggregate regime index. The higher the aggregate regime index, the better the position of the archetype in the final ranking.

Under the W5 scenario, the weighted regime analysis therefore allowed the effect of the winsorized AHP weights to be tested directly on the final ranking, while keeping unchanged the opinion leaders' performance scores assigned to the archetypes.

4.8. Pairwise dominance results

The pairwise regime analysis confirms that A1 prevails over A2, A3 and A4; A3 prevails over A2 and A4; and A2 prevails over A4. The direct comparison between A1 and A3 remains extremely close, with a W5 partial preference index equal to 0.0025 in favour of A1. This confirms that the two leading archetypes have very similar overall profiles.

Table 13. Pairwise regime comparison results under S0 and W5, showing partial preference indices and the prevailing archetype in each comparison.

Pairwise comparison	Partial preference index S0	Partial preference index W5	Delta W5-S0	Prevailing archetype W5
A1 vs A2	0.3382	0.3219	-0.0163	A1
A1 vs A3	0.0147	0.0025	-0.0123	A1
A1 vs A4	0.9552	0.9441	-0.0112	A1
A2 vs A3	-0.4811	-0.4727	0.0084	A3
A2 vs A4	0.9552	0.9441	-0.0112	A2
A3 vs A4	0.9552	0.9441	-0.0112	A3

The comparison between A1 and A3 is the most sensitive pairwise relationship in the model. Under W5, A1 still slightly prevails over A3 in the direct pairwise comparison, but the margin is almost negligible. However, when all pairwise comparisons are aggregated into the final regime index, A3 remains the best-performing archetype. This is due to its strong relative position against A2 and A4 and to its balanced performance across environmental and agronomic sub-criteria.

4.9. Final ranking under W5

The final aggregate regime indices confirm the same ranking obtained in the baseline scenario. A3 remains the first-ranked archetype, followed by A1, A2 and A4.

Table 14. Aggregate regime indices and final ranking of the four archetypes under the baseline scenario (S0) and the W5 scenario.

Rank W5	Code	Archetype	Aggregate regime index S0	Aggregate regime index W5	Delta W5-S0	Ranking stability
1	A3	Almond + Forage Legumes	0.4739	0.4714	-0.0024	Confirmed
2	A1	Almond + MAPs/Herbs	0.4360	0.4228	-0.0132	Confirmed
3	A2	Almond + Grain Legumes	0.0453	0.0498	0.0045	Confirmed
4	A4	Conventional farming	-0.9552	-0.9441	0.0112	Confirmed

The final ranking under W5 is therefore:

A3 > A1 > A2 > A4

This result confirms the robustness of the baseline ranking. The attenuation of extreme AHP judgments does not alter the order of the management archetypes. The first two alternatives remain very close, but A3 retains the highest aggregate regime index. The figure below presents the comparative performance profile of the two archetypes across the twelve sub-criteria considered in the robustness analysis.

4.10. Interpretation of ranking robustness

The W5 robustness analysis provides three main insights. First, the consistency of the AHP matrices improves under W5. The reduction in mean CR values confirms that highly intense judgments contributed to part of the inconsistency observed in the baseline matrices. However, since W5 does not force consistency mechanically and does not remove respondents, the revised scenario preserves the diversity of the stakeholder panel. Second, the weighting structure remains substantially stable. The agronomic dimension remains the most important macro-category, while economic and environmental dimensions retain similar levels of relevance. The social dimension increases under W5, especially through acceptability and adoption, local socio-economic benefits, and safety, health and employment. Nevertheless, this increase does not change the overall MCDA ranking.

Third, the dominance of intercropping-based archetypes over conventional farming is confirmed. A4 receives a favourable score only for acceptability and adoption, but this advantage is insufficient to compensate for weaker performance on most environmental, agronomic and socio-economic criteria.

As a result, A4 remains clearly separated from the three intercropping systems under both S0 and W5. The comparison between A3 and A1 deserves specific attention. A1 performs particularly well in system profitability, costs and management complexity, biodiversity and impact reduction, safety, health and employment, and agronomic resilience. A3, on the other hand, shows a more balanced profile across soil conservation, soil fertility and carbon, local socio-economic benefits, almond yield, and production quality. The W5 results suggest that the leading position of A3 is not an artefact of extreme AHP judgments, but is supported by its broad and balanced performance across several highly weighted criteria.

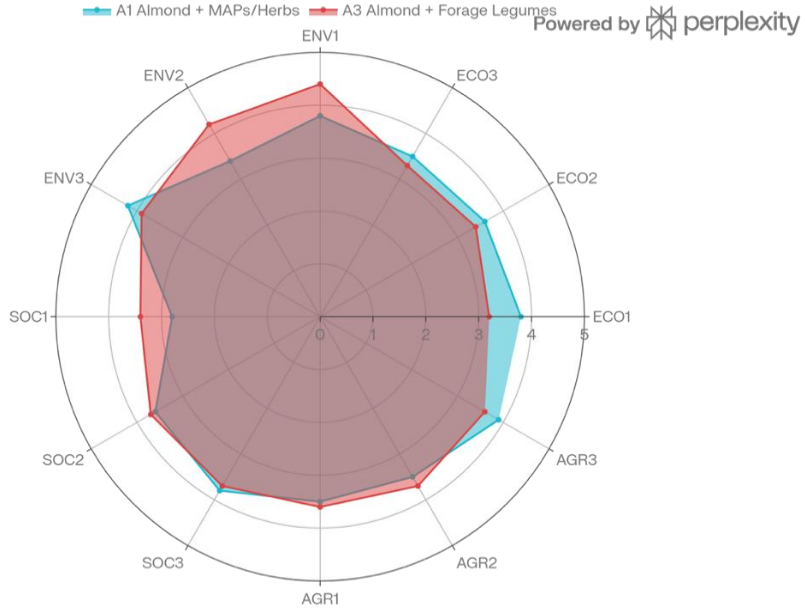

Figure 2. Comparative radar plot of A1 (Almond + MAPs) and A3 (Almond + Forage Legumes) across 12 sub-criteria, grouped into environmental, economic, social, and agronomic dimensions. Scores are normalized on a common scale to highlight relative strengths, weaknesses, and trade-offs between the two systems.

Overall, the W5 robustness analysis strengthens the reliability of the MCDA results. It demonstrates that the final ranking is stable even when extreme stakeholder preference intensities are conservatively bounded. The main conclusion of the analysis is therefore confirmed: diversified almond-based intercropping systems outperform conventional almond management, with A3 – Almond + Forage Legumes and A1 – Almond + MAPs emerging as the two most promising archetypes.

5. Discussion

The integration of AHP and regime analysis highlights the stronger overall competitiveness of mixed-cropping archetypes compared with conventional almond farming. The final ranking identifies A3 – Almond + Forage Legumes as the alternative with the highest aggregate regime index value, followed very closely by A1 – Almond + MAPs. The two archetypes should therefore be interpreted as a group of highly competitive alternatives rather than as clearly separated options. A2 – Almond + Grain Legumes occupies an intermediate position, while A4 – Conventional farming ranks last.

This result is consistent with the multidimensional nature of the framework, which evaluates the archetypes not only in terms of profitability or yield, but also in relation to environmental, social, and agronomic functions.

This interpretation is further strengthened by the post-hoc robustness analysis conducted on the AHP judgments to assess the sensitivity of the results to the internal consistency of respondents' pairwise comparisons. In the baseline scenario, the consistency ratio values were above the conventional threshold in several matrices, reflecting the difficulty for respondents to compare heterogeneous sustainability dimensions such as profitability, biodiversity, adoption, and agronomic resilience. However, rather than excluding a large share of the panel on the basis of a mechanical CR threshold, the study retained all valid responses in the main analysis and treated consistency as a diagnostic indicator. This choice is coherent with the exploratory and expert-based nature of the study, in which the objective was not to reproduce the preferences of a homogeneous decision-making body, but to synthesize the perspectives of stakeholders with different professional, geographical, and operational backgrounds.
To test whether the final MCDA ranking was driven by highly intense and potentially inconsistent judgments, a W5 winsorization procedure was applied to the original AHP matrices. This procedure capped all pairwise comparison intensities above 5 while preserving the direction of each judgment. In other words, no respondent's preference was reversed; only the maximum intensity of strong preferences was attenuated. The recalculation of AHP weights under W5 reduced the mean consistency ratio in all matrices, especially for the macro-category, environmental, and social matrices. Although the procedure did not bring all consistency ratios below the conventional threshold, it substantially reduced inconsistency without deleting respondents or artificially imposing coherence. The robustness analysis therefore provides a more conservative test of the baseline results while preserving the informational heterogeneity of the panel.

The results of the W5 scenario confirm the stability of the weighting structure. The agronomic dimension remains the most important macro-category, followed by the economic and environmental dimensions, while the social dimension remains the least weighted. However, the social dimension increases under W5, suggesting that its relatively low weight in the baseline scenario was partly influenced by stronger preference intensities assigned to other dimensions. This increase is particularly visible for acceptability and adoption, local socio-economic benefits, and safety, health and employment. Nevertheless, these changes are not large enough to alter the overall structure of the model. The highest-weighted sub-criteria remain almond tree yield, economic stability and resilience, production quality and health, system profitability, biodiversity and impact reduction, soil fertility and carbon, and agronomic resilience. This confirms that the evaluation framework is primarily driven by productive compatibility, economic stability, environmental performance, and agronomic resilience.
The top position of A3 – Almond + Forage Legumes appears consistent with the literature on Mediterranean tree systems, which attributes a significant role to cover crops and legumes in improving soil fertility, nitrogen cycling, and the agroecological quality of the system. In Mediterranean almond orchards, the use of cover crops has been associated

with increases in organic carbon, soil nitrogen, and soil functionality, especially in low-input systems and under semi-arid conditions (Repullo-Ruibérriz de Torres et al. 2021; Fernández-Soler et al. 2024). Similarly, the combination of crop diversification and conservation practices, such as reduced tillage, can improve key soil quality parameters without necessarily compromising almond yield (Almagro et al. 2023).

The result obtained for A3 can therefore be interpreted as the effect of an overall balanced profile. The forage legume archetype does not stand out because it maximizes a single criterion, but because it performs well across several highly weighted dimensions: soil conservation, soil fertility and carbon, almond tree yield, production quality and health, local socio-economic benefits, and agronomic resilience. This feature is particularly relevant in regime analysis, where the final ranking derives from pairwise dominance comparisons between alternatives rather than from a fully compensatory additive aggregation of scores. The W5 robustness analysis confirms that the leading position of A3 is not an artefact of extreme AHP judgments, but is supported by its broad and balanced performance across multiple criteria.

A1 – Almond + MAPs ranks second, with an aggregate regime index very close to that of A3. This result can be linked to the potential of aromatic and medicinal plants in Mediterranean systems, both as tools for production diversification and as components that strengthen farm multifunctionality. MAPs have been identified as crops particularly suited to intercropping strategies in the Mediterranean basin, thanks to their potential to diversify income, enhance local supply chains, and support complementary ecological functions (Marotti et al. 2023). A1's strong ranking therefore appears consistent with its favorable profile in terms of profitability, biodiversity, local benefits, safety and health, and agronomic resilience. The positive assessment of A1 regarding biodiversity and impact reduction can also be linked to the literature on ecological infrastructure and flower strips. The presence of herbaceous or aromatic species with diverse blooms can help support pollinators, beneficial arthropods, and ecosystem services, although the effects on yield and biological control depend heavily on the context, floristic composition, and farm management (Albrecht et al. 2020; Mockford et al. 2023; Sorribas et al. 2025).

The comparison between A1 and A3 deserves specific attention. The W5 pairwise regime analysis shows that the direct comparison between the two leading archetypes is extremely close, with only a negligible margin in favour of A1 in the pairwise comparison. However, when all pairwise comparisons are aggregated into the final regime index, A3 remains the first-ranked archetype. This apparent tension is not contradictory. It indicates that A1 and A3 have very similar overall profiles, but that A3 performs more consistently across the full set of comparisons, especially against A2 and A4. A1 appears particularly strong in system profitability, management complexity, biodiversity and impact reduction, safety, health and employment, and agronomic resilience. A3, by contrast, shows a more balanced profile across soil conservation, soil fertility and carbon, local socio-economic benefits, almond yield, and production quality. The final ranking should therefore be read as identifying A3 as the most balanced option overall, while recognizing A1 as an almost equally competitive archetype with high multifunctional potential.

A2 – Almond + Grain Legumes occupies an intermediate position. While showing positive performance across various environmental and agronomic criteria, it does not reach the dominance level of A3 and A1 in the regime analysis. This result can be explained by the fact that grain legumes offer potential functional benefits, particularly in nitrogen provision and crop diversification, but may be more exposed to economic, production, and management constraints than forage legumes or aromatic plants. The literature highlights that the success of intercropping in tree-based systems depends on the compatibility between the main crop and the intercrop, competition for water and nutrients, the commercial value of the secondary crop, and its integration into farm management (Martinelli et al. 2022; Vasconcelos et al. 2021; Moreira et al. 2024). The robustness analysis confirms that A2 remains clearly above conventional farming but below the two most competitive intercropping archetypes.

The final position of A4 – Conventional farming confirms that non-intercropped management is less competitive when evaluated through a multidimensional framework. This does not imply that conventional management lacks specific advantages. It may be simpler to adopt, more familiar to farmers, and less complex from an organizational standpoint. Indeed, A4 receives its most favorable relative performance for acceptability and adoption, reflecting the lower perceived complexity of established practices. However, this advantage is not sufficient to compensate for weaker performance in biodiversity, soil fertility, soil conservation, local socio-economic benefits, and impact reduction. The robustness analysis confirms that A4 remains clearly separated from the three intercropping systems under both the baseline and W5 scenarios. This supports the conclusion that conventional almond management is disadvantaged when environmental, agronomic, economic, and social criteria are considered simultaneously.

A central element of the results concerns the weight assigned to the AHP criteria. The agronomic dimension is the most significant, followed by the economic and environmental dimensions, while the social dimension receives a lower weight. This ranking suggests that opinion leaders evaluated intercropping primarily in terms of productive compatibility, system stability, and agroecological benefits. The centrality of almond tree yield confirms that the adoption of agroecological practices in permanent tree systems remains conditioned by the need not to compromise the productivity of the main crop. This point is particularly relevant in Mediterranean contexts, where water stress, climate variability, and soil fragility make it more complex to balance ecological intensification with productive stability.

The high weight assigned to economic stability and resilience is also consistent with the literature on Mediterranean agricultural systems, in which economic sustainability depends not only on average profitability but also on the ability to reduce outcome variability, diversify income sources, and mitigate production and market risks. From this perspective, mixed-farming systems can contribute to farm resilience not only through secondary production but also through improved soil fertility, reduced inputs, and functional diversification of the system (Alcon et al. 2020; Di Vita et al. 2023; Marotti et al. 2023).

The relatively low weight of the social dimension calls for a cautious interpretation. On the one hand, the AHP results indicate that, in pairwise comparisons, respondents assigned lower priority to aspects such as acceptability, local socio-economic benefits, health, safety, and employment. On the other hand, contextual responses show that part of the panel perceived the social dimension as potentially underestimated. The W5 robustness analysis reinforces this interpretation: when extreme preference intensities are attenuated, the weight of the social dimension increases, although it remains the least influential macro-category. This suggests that social aspects were not irrelevant to respondents, but tended to be dominated by agronomic, economic, and environmental concerns when strong comparative judgments were allowed. The discrepancy can therefore be interpreted as a difference between conceptual relevance and comparative priority. Social aspects are recognized as important for the transferability of intercropping practices, but they are less dominant when directly compared with productive stability, economic viability, and agroecological performance.

This point is particularly important because the literature on the adoption of agroecological innovations emphasizes that technical sustainability is not sufficient to ensure the spread of practices if they are not compatible with farm resources, available knowledge, work organization, and farmers' expectations (Alcon et al. 2020; Moreira et al. 2024). This interpretation is also supported by a complementary study developed within Task 4.3, in which Q-methodology was applied to investigate the subjective viewpoints of 100 stakeholders across the five VALMEDALM partner countries on the adoption of intercropping in Mediterranean almond cultivation. The analysis identified five distinct perspectives, ranging from an ecological efficiency orientation to a productivity skepticism viewpoint, revealing that resistance to intercropping adoption is not simply a matter of technical unfamiliarity, but reflects heterogeneous combinations of economic concerns, perceived operational complexity, and compatibility with local farming identities. Notably, even the most skeptical perspective expressed support for policy incentives, suggesting that differentiated policy instruments, rather than normative prescriptions, are better suited to the plurality of motivations identified across Mediterranean contexts. These findings are consistent with the present analysis: intercropping archetypes are preferred when they combine agroecological benefits and production stability, but their transferability depends on the ability to reduce perceived uncertainty, implementation costs, and potential competition with the main crop (Mirabella et al., manuscript in preparation).

From a methodological standpoint, the combination of AHP and regime analysis enabled the structuring of expert preferences through pairwise comparisons and the derivation of relative weights for criteria and sub-criteria (Saaty 1980; Goepel 2018). Regime analysis proved particularly appropriate because the performance of alternatives was expressed on ordinal or semi-quantitative scales. By comparing alternatives through criterion-by-criterion dominance relations, regime analysis avoids assuming full compensation among criteria and is therefore suitable for sustainability assessments in which trade-offs among environmental, economic, social, and agronomic dimensions cannot be reduced to a simple additive logic (Hinloopen et al. 1983; Hinloopen et al. 2004).

The choice to aggregate individual priorities while maintaining the full set of valid responses is also supported by the methodological literature on group AHP. Forman and

Peniwati distinguish between aggregating individual judgments and aggregating individual priorities, noting that the choice depends on the nature of the decision-making group and on the meaning attributed to the expressed preferences (Forman and Peniwati 1998). In the present study, the aggregation of individual priorities is consistent with the heterogeneous composition of the panel, which included respondents with different professional, geographic, and cultural backgrounds. The aim was not to simulate a single homogeneous collective decision-maker, but to synthesize a plurality of expert perspectives.

The consistency diagnostics of AHP judgments provide an additional element for interpreting the results. In decision-making processes based on pairwise comparisons, internal consistency is an important methodological requirement, as it allows the logical stability of respondents' expressed preferences to be assessed (Saaty 1980; Pant et al. 2022). However, in this study, high CR values should not be interpreted only as a weakness of the dataset. They also reflect the complexity of the trade-offs presented to respondents, especially when comparisons involved dimensions that are conceptually different and difficult to reduce to a common scale. For this reason, the baseline analysis retained all valid responses and avoided using consistency as a rigid exclusion criterion. The W5 robustness analysis complements this choice by showing that, even when extreme preference intensities are conservatively bounded and consistency improves, the final ranking remains unchanged. This confirms that the main results are not dependent on the most intense or least consistent judgments.

Overall, the results support the utility of an integrated AHP–regime analysis framework for evaluating intercropping systems in Mediterranean almond cultivation. Within the adopted multi-criteria framework, intercropped archetypes show a better comparative position than conventional management when agronomic, economic, environmental, and social criteria are considered simultaneously. In particular, forage legumes emerge as the most balanced option overall, while aromatic and medicinal plants are highly competitive, especially for production diversification, biodiversity, profitability, and multifunctional potential. The robustness analysis strengthens this conclusion by demonstrating that the ranking A3 > A1 > A2 > A4 remains stable under a conservative W5 scenario designed to reduce the influence of extreme AHP judgments.

These findings must nevertheless be interpreted with certain caveats. The AHP panel was not designed to ensure statistical representativeness in a strictly probabilistic sense, although it is adequate for the exploratory and expert-based aims of the study. The panel combines international coverage with a predominance of technical-scientific profiles, thereby supporting the elicitation of informed, domain-specific insights (Melillo & Pecchia, 2016; Schmidt et al., 2015; Darko et al., 2019). Moreover, evidence from expert-panel and Delphi-based methodologies suggests that panels of 20–30 participants per stakeholder group may be sufficient to yield stable and replicable judgments in well-defined domains (Akins et al., 2005; Manyara et al., 2024).

Furthermore, the performance matrix derives from a separate expert elicitation phase conducted with 10 opinion leaders, supplemented, where necessary, by demosite data, literature proxies, and expert judgment, particularly for dimensions that are not directly measurable. The archetypes also derive from the harmonization of demosites that are heterogeneous in terms of soil and climate conditions, associated species, water availability, and available data. For these reasons, the final ranking should not be interpreted as an absolute or definitive measure of technical superiority. Rather, it should be understood as the outcome of a structured decision-making procedure that integrates expert preferences, ordinal performance assessments, and multi-criteria weights.

From this perspective, the ranking constitutes a comparative synthesis useful for identifying promising intercropping options and supporting subsequent site-specific validation across Mediterranean almond-growing contexts. The post-hoc robustness analysis increases confidence in the stability of the results: diversified almond-based intercropping systems consistently outperform conventional almond management, and A3 – Almond + Forage Legumes and A1 – Almond + MAPs emerge as the two most promising archetypes, with A3 showing the most balanced overall profile.

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