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Territorial Embeddedness or Technological Dependence? Rethinking Agroecological Resilience Through Traditional Mountain Farming Systems in Semi-Arid Morocco

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Abstract

Agroecology is increasingly considered a potential pathway for addressing the interconnected challenges of climate adaptation, food security, biodiversity conservation, and rural sustainability. However, how agroecological practices coexist with technological and external-input-based management remains insufficiently documented in semi-arid smallholder farming systems. This study assessed agroecological practice integration and management heterogeneity in Skoura M'Daz (SMDZ), a semi-arid mountain region of the Middle Atlas, Morocco. Structured surveys were conducted with 70 farmers across 22 villages and complemented by field observations. A six-component Agroecological Practice Intensity Index (AEPI; range 0–6) was developed to quantify the integration of selected agroecological practices, together with an Input Intensity Score (IIS) describing reliance on selected external-input and technology-mediated practices. The mean AEPI was 3.94/6 (65.7% of the maximum possible score), and 87% of farms implemented at least three of the six AEPI components. Agroforestry (71.4%), crop rotation (74.3%), and organic or mixed fertilization (91.4%) were widely represented among surveyed farms. Rural farms had a higher mean AEPI than urban/peri-urban farms (4.23 vs. 3.66); the difference reached the conventional significance threshold with Welch's t-test ($p = 0.0417$) but not with the complementary Mann–Whitney test ($p = 0.0664$), indicating suggestive rather than unequivocal evidence of a territorial contrast. Rural location remained positively associated with the AEPI in multivariable analysis, including after adjustment for formal education in a sensitivity model. The full AEPI was negatively correlated with IIS (Spearman $\rho = -0.252$, $p = 0.0354$); however, leave-one-component-out analysis showed that this relationship was sensitive to index construction and partly reflected structural overlap between the two indices. An a priori AEPI–IIS classification identified four management configurations, with Agroecological Custodians representing the largest group. Farmers reported multiple perceived benefits associated with agroecological practices, particularly for soil fertility, crop yield stability, water availability, production costs, and drought response, while also identifying constraints related to water access, technical assistance, financial support, and extension services. Because this study is cross-sectional and observational, the reported relationships represent statistical associations rather than causal effects, and neither the

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AEPI nor farmers' perceptions provide direct measurements of ecological performance or resilience. Overall, the findings document substantial agroecological practice integration and heterogeneous combinations of ecological and technology-mediated management within SMDZ, providing a context-specific basis for future longitudinal and biophysical research on the sustainability and resilience of semi-arid mountain farming systems.

Keywords: agroecology; agroecological practice integration; territorial embeddedness; smallholder farming; external-input dependence; semi-arid agriculture; Morocco

1. Introduction

Agriculture in Mediterranean and semi-arid regions is entering a period of profound instability driven by the combined effects of climate change, recurrent droughts, water scarcity, soil degradation, biodiversity loss, and increasing socio-economic vulnerability [1]. Among these regions, Morocco has become one of the clearest examples of how hydro-climatic stress is progressively reshaping agricultural sustainability, rural livelihoods, and territorial resilience. Recent studies increasingly identify Morocco as a climate change hotspot where water scarcity is no longer a secondary environmental issue, but the principal structural constraint affecting agricultural systems and food security [1–3].

In response to these pressures, agroecology has emerged as one of the most promising frameworks for rethinking agricultural development. International organizations such as the Food and Agriculture Organization (FAO), the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the European Union increasingly present agroecology as a pathway capable of reconciling food production, biodiversity conservation, climate adaptation, and social resilience [4–6]. Recent evidence further indicates that agroecological management can contribute to soil protection, resource conservation, and the restoration of ecosystem functions, reinforcing the need to evaluate agricultural sustainability through ecological and socio-institutional dimensions in addition to conventional productivity indicators [7–9]. Yet despite its growing visibility, agroecology remains deeply debated. One of the main controversies concerns whether agricultural resilience should rely primarily on technological intensification—including precision irrigation, digital agriculture, and optimized inputs—or on territorially embedded ecological knowledge, diversification, and collective resource management [10,11].

These tensions reflect deeper conceptual divergences regarding resilience, sustainability, innovation, and agricultural transformation under semi-arid conditions. Rather than opposing traditional and technological pathways, emerging debates increasingly focus on the capacity of different innovations to strengthen territorially embedded ecological regulation mechanisms while avoiding excessive dependence on external inputs, capital-intensive investments, and centralized infrastructures. As synthesized in Table 1, conventional modernization paradigms tend to frame resilience as a function of technological optimization, productivity enhancement, and resource use efficiency. By contrast, the agroecological perspective emerging from this study emphasizes ecological diversification, local knowledge systems, collective action, and adaptive governance as key mechanisms for long-term socio-ecological stability. From this perspective, the critical question is not whether innovation should be adopted, but which forms of innovation reinforce ecological processes, farmer autonomy, and territorial resilience. Consequently, innovations such as participatory knowledge networks, locally adapted water management systems, agroecological advisory services, digital tools supporting ecological decision-making, and low-external-input technologies may be more compatible with resilient transition pathways than technologies that

increase structural dependence on external resources. This suggests that the sustainability of future agricultural transformations may depend less on technological sophistication itself than on the extent to which innovation remains aligned with ecological functioning, local capacities, and the adaptive dynamics of socio-ecological systems.

Table 1. Main conceptual controversies addressed in article.

Controversy	Dominant Modernization Narrative	Agroecological Interpretation Proposed in This Study
Agricultural modernization	Technological intensification improves resilience	Resilience also depends on ecological diversification and local governance
Water management	Efficiency depends on technological irrigation	Collective gravity irrigation may enhance socio-ecological stability
Productivity	Specialization increases productivity	Diversification stabilizes production under climatic uncertainty
Sustainability	Sustainability equals input optimization	Sustainability also includes territorial embeddedness and adaptive flexibility
Innovation	Innovation is primarily technological	Innovation can emerge from hybridization between traditional knowledge and selective technologies

Building on these debates, the analytical framework proposed in Figure 1 illustrates how climate stressors, agroecological practices, territorial embeddedness, and external-input dependence interact to shape resilience trajectories in semi-arid mountain agroecosystems, conceptualizing traditional ecological practices not as isolated technical options, but as interconnected mechanisms stabilizing agricultural systems under hydro-climatic uncertainty.

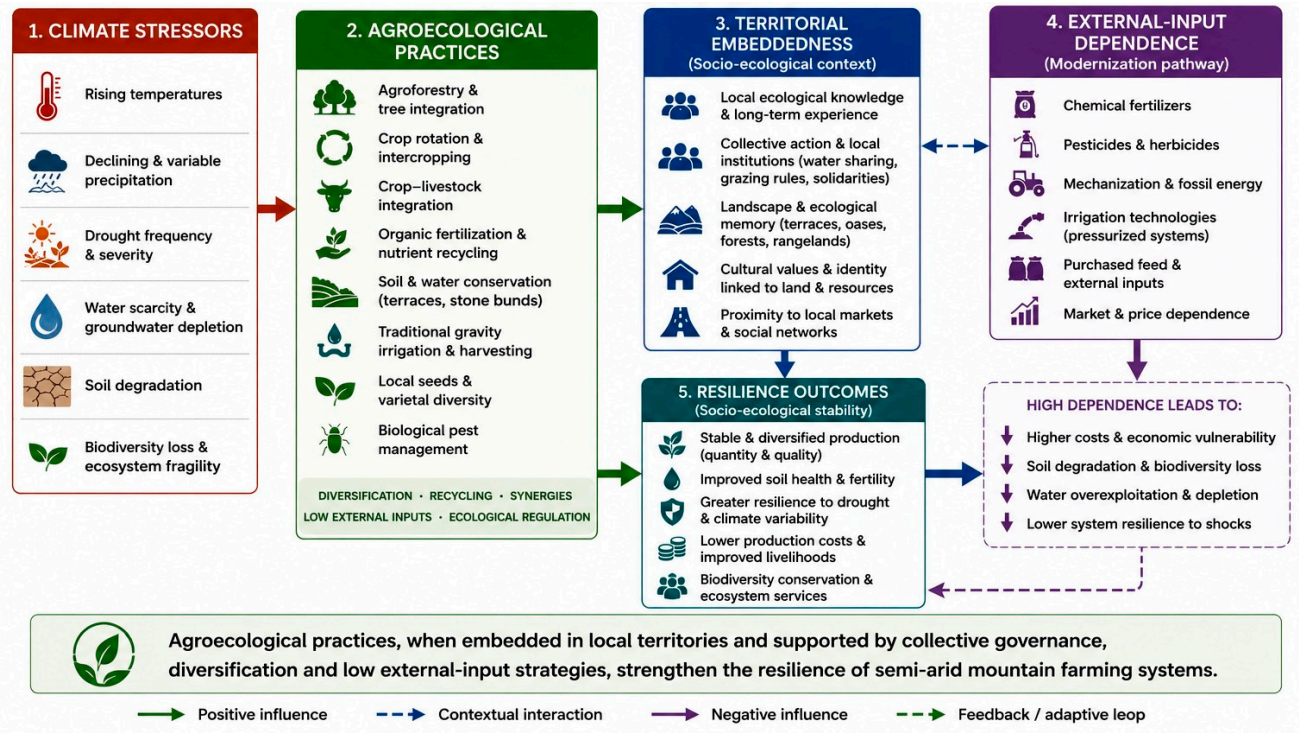


Figure 1. A conceptual framework linking climate stressors, agroecological practices, territorial embeddedness, external-input dependence, and resilience outcomes in semi-arid mountain agroecosystems. The framework illustrates how recurrent drought, water scarcity, soil degradation, and

biodiversity erosion interact with farming systems under semi-arid Mediterranean conditions. Agroecological practices—including agroforestry, crop diversification, crop–livestock integration, organic nutrient recycling, soil and water conservation, and traditional irrigation systems—are presented as interconnected mechanisms capable of enhancing ecological regulation and reducing dependence on external inputs. The figure further emphasizes the role of territorial embeddedness through local ecological knowledge, collective governance, landscape memory, and social networks in strengthening adaptive capacity. In contrast, increasing dependence on external inputs and modernization-oriented pathways may amplify socio-ecological vulnerability through groundwater depletion, biodiversity loss, economic fragility, and reduced resilience to climatic shocks. Overall, the framework conceptualizes traditional mountain agroecosystems not as residual agricultural systems, but as territorially embedded resilience architectures capable of stabilizing production and sustaining ecological functions under accelerating hydro-climatic stress.

This debate is particularly relevant in Morocco, which simultaneously faces increasing climatic stress and hosts a remarkable diversity of traditional farming systems that historically evolved under water scarcity and ecological uncertainty. Mountain and oasis agroecosystems have long relied on crop diversification, agroforestry, gravity irrigation, crop–livestock integration, terracing, and organic nutrient recycling—designed not to maximize short-term productivity, but to stabilize production and maintain ecological balance under highly constrained environments [1].

However, dominant modernization narratives continue to portray many traditional systems as economically marginal or technologically outdated, even as highly intensified agricultural models increasingly reveal their ecological fragility through groundwater depletion, soil degradation, biodiversity decline, and growing dependence on external inputs [12,13]. This creates a major paradox: the regions where agroecology is most necessary are often those where the socio-economic conditions for transition remain weakest. Recent literature describes this contradiction as a "Hydro-Agroecological Transition Trap," where worsening water stress simultaneously increases the need for agroecological redesign while reducing the capacity of farms and institutions to implement it.

Importantly, Morocco is not an agroecological blank slate. Across rainfed cereal systems, mountain mosaics, oasis territories, and mixed crop–livestock systems, many agroecological practices already exist, including crop rotations, intercropping, agroforestry, biological regulation, and organic fertilization [1,3,14–17]. Yet most previous studies have focused on isolated practices or local initiatives without fully explaining why these practices remain weakly connected, poorly scaled, and insufficiently institutionalized under Moroccan conditions.

This study builds upon these debates through an integrated agroecological assessment conducted in Skoura M'Daz (SMDZ), in the Middle Atlas Mountains of Morocco. Rather than viewing traditional mountain agriculture as a residual system inherited from the past, this article explores whether these farming systems may instead represent territorially embedded resilience architectures capable of supporting adaptation under accelerating climatic instability.

To address this question, the study combines field surveys, statistical analysis, and a reproducible Agroecological Practice Intensity Index (AEPI) designed to quantify agroecological coherence under real smallholder conditions. This paper investigates four aspects of agricultural systems in SMDZ. First, it characterizes local farmers and describes the structure of traditional agricultural systems across the surveyed villages. Second, it applies to the AEPI to quantify the coherence of ecological practices independently of technological intensification. Third, it analyzes the extent to which agroecological intensity is shaped by territorial embeddedness, particularly rural location and participation in local socio-

professional networks. Fourth, it examines whether increasing dependence on external agricultural inputs and technologies is associated with a weakening of ecological coherence. The study zone is characterized by pronounced hydro-climatic constraints, rainfed and irrigated smallholder farming, and long-standing collective water management through traditional canals, making it particularly suited to testing whether territorially embedded, low-input systems retain the diversified structure historically associated with adaptive capacity under climatic uncertainty. Beyond the Moroccan case, the article contributes to broader debates on agroecology, resilience, and agricultural modernization by questioning a central assumption of contemporary agricultural policy: does technological intensification necessarily increase resilience in semi-arid environments, or can diversified ecological systems offer more durable adaptive capacities under long-term climate uncertainty?

In this study, resilience is not treated as a directly measured farm-level outcome. Rather, the analysis examines agroecological practice configurations and perceived multifunctional benefits that correspond to attributes commonly associated with adaptive capacity in socio-ecological systems. The results are therefore interpreted as evidence of potential resilience-enhancing attributes rather than direct proof of resilience.

2. Materials and Methods

2.1. Study Area

The study was conducted in Skoura M'Daz (SMDZ), located in the province of Boulemane (Fès-Meknès region), within the Middle Atlas Mountains of Morocco (Figure 2). SMDZ represents a typical semi-arid mountain agroecosystem characterized by strong hydro-climatic constraints, steep topography, fragmented smallholder farming systems, and high dependence on traditional gravity irrigation and rainfed agriculture. The region is situated within a highly heterogeneous mountainous landscape where elevation gradients, rugged terrain, and irregular rainfall patterns strongly shape agricultural practices, water availability, and land use organization. As illustrated in Figure 2, The study area is embedded within a mountainous environment characterized by rugged topography, narrow valleys, seasonal watercourses, and terrace-based agricultural systems that have historically evolved under conditions of climatic uncertainty and limited water availability.

The territory is surrounded by three major mountain ranges Tichoukt (2000 m) to the southeast, Jbel Taboujebert (1900 m) to the southwest, and Ich Irhanimone (1000 m) to the north—which strongly influence its hydrological dynamics and agricultural potential. The area extends to a total useful agricultural area (UAA) of 9580 ha, including 5330 ha of irrigated land and 4250 ha of rainfed land, distributed among 2546 farming units. The agrarian structure is highly fragmented, with 92% of farms covering less than 2 ha, a characteristic feature of mountain farming systems. Water resources depend on a diversified hydrographic network consisting of 39 springs (aïoun) irrigating approximately 2300 ha, three main watercourses—notably the Oued Guigou and the Tallet—and 35 traditional wells. Irrigation is predominantly conducted through gravity-fed canal systems, reflecting a centuries-old tradition of collective water management. From a pedological perspective, the dominant soils are calcareous-clay soils with surface organic matter contents ranging from 2 to 4%, total calcium carbonate contents between 30 and 60%, a balanced texture (20% fine sand and 20% clay), and a water retention capacity of approximately 40% [18]. Despite these relatively favourable agronomic characteristics, soil productivity remains strongly constrained by irregular and increasingly insufficient water availability, highlighting the close interaction between soil properties and the broader hydro-climatic challenges affecting the region.

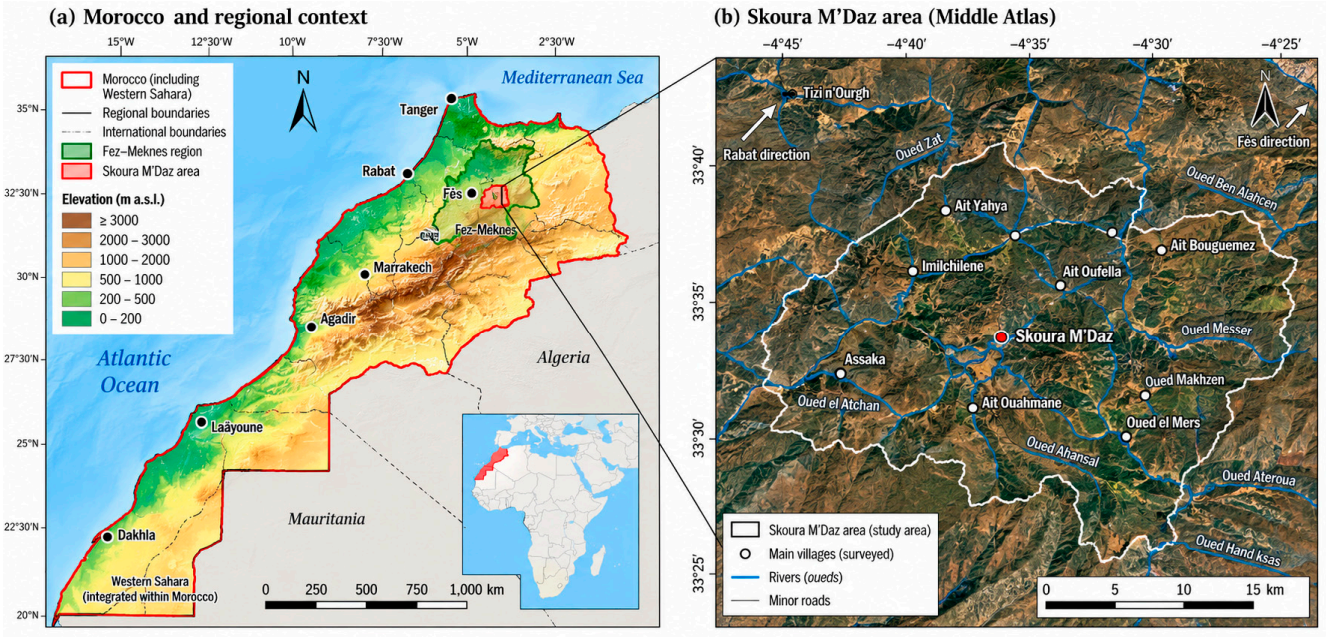


Figure 2. The study area of Skoura M'Daz (SMDZ) in the Middle Atlas Mountains of Morocco. The figure illustrates the geographical location, elevation gradients, hydrographic network, and mountainous configuration of the SMDZ agroecosystem. The region is characterized by steep topography, semi-arid climatic conditions, fragmented agricultural landscapes, and strong dependence on traditional irrigation systems and terrace-based agriculture. The spatial configuration highlights the close interaction between environmental constraints, territorial organization, and agroecological adaptation strategies in semi-arid mountain systems.

The climate of SMDZ is of the semi-arid mountain type, as evidenced by the analysis of meteorological records covering the 2008–2025 period [18]. Mean annual rainfall averages 350 mm, distributed in a markedly irregular pattern across the year, with a pronounced spring peak reaching approximately 82 mm in April and 75 mm in May, followed by a sharp summer dry season during which monthly precipitation drops to as low as 13 mm in July. This bimodal seasonal pattern—wet spring, dry summer—is characteristic of the semi-arid Mediterranean mountain regime and generates a critical mismatch between crop water demand and rainfall availability during the summer growing season. Thermal conditions are equally constraining, with mean monthly temperatures ranging from approximately 7 °C in January to 25 °C in July–August [18]. Maximum temperatures peak at around 32 °C in summer, while minimum temperatures approach 0 °C in winter, with recurrent snowfall episodes that further restrict the agricultural calendar. The combination of a low and seasonally concentrated rainfall regime, extreme thermal amplitudes, and a marked summer aridity expose cropping systems to dual hydric and thermal stress throughout the year. Beyond this structural seasonal pattern, interannual precipitation variability has increased considerably over the study period, with drought sequences becoming more frequent and severe—most critically during the 2022 agricultural season, when a pronounced winter rainfall deficit severely compromised all rainfed crops. Taken together, these climatic characteristics confirm that SMDZ constitutes a semi-arid mountain agroecosystem subject to strong and intensifying hydro-climatic constraints, providing the essential biophysical context for understanding local farmers' adaptation strategies.

The climate of SMDZ is characterized by marked interannual rainfall variability, recurrent drought episodes, hot dry summers, and increasing hydro-climatic instability associated with regional climate change. Such environmental conditions have historically constrained agricultural intensification while simultaneously favouring the persistence of diversified low-input farming systems integrating agroforestry, crop diversification,

livestock integration, terracing, and traditional ecological knowledge. Unlike highly intensified agricultural plains in Morocco, where modernization processes have profoundly transformed socio-ecological structures, SMDZ remains relatively less mechanized and less dependent on external agricultural inputs. Consequently, many traditional agroecological practices remain operational and continue to structure local adaptive strategies.

This territorial configuration makes SMDZ particularly relevant for agroecological research because it provides a living socio-ecological laboratory where traditional ecological knowledge, collective resource management, and low-input diversified systems remain deeply embedded within local agricultural landscapes (Table 2). The region therefore offers a unique opportunity to investigate whether traditional mountain agriculture may function not as a residual production system inherited from the past, but rather as a territorially embedded resilience architecture capable of supporting adaptation under accelerating hydro-climatic stress.

Table 2. Main environmental and agroecological characteristics of SMDZ study area.

Variable	Characteristics
Geographic location	Middle Atlas Mountains, Boulemane Province, Morocco
Agroecological context	Semi-arid mountain agroecosystem
Dominant farming structure	Fragmented smallholder systems
Climate characteristics	Semi-arid climate with irregular rainfall and recurrent droughts
Topography	Steep slopes, mountainous terrain, narrow valleys
Elevation range	Predominantly 1500–2500+ m a.s.l.
Main water management system	Traditional gravity irrigation and seasonal water harvesting
Dominant farming practices	Agroforestry, crop rotation, crop–livestock integration, terracing
Degree of mechanization	Relatively low compared with intensified agricultural plains
External-input dependence	Generally moderate to low
Main climatic constraints	Water scarcity, drought frequency, rainfall variability
Agroecological relevance	Persistence of territorially embedded traditional ecological practices
Research significance	Natural laboratory for studying resilience under hydro-climatic stress

2.2. Sampling Method

A multi-stage stratified random sampling approach was employed to select the surveyed farms. In the first stage, the study area was stratified according to its administrative divisions, and the province of Boulemane was retained for investigation. In the second stage, the commune of Skoura M'Daz was selected as the focal study site due to its representative mountainous agroecosystems and traditional agricultural practices. In the third stage, 22 villages within the commune were identified and selected to ensure adequate spatial coverage of the study area. Subsequently, 4–6 farms were randomly selected within each village using a simple random sampling procedure, regardless of farm size, production orientation, or geographical location. This sampling strategy was designed to capture the diversity of farming systems and management practices present across the study area while minimizing selection bias [19,20].

A total of 70 farms distributed across 22 villages were included in the final survey. Farms were selected within the surveyed localities independently of farm size and production orientation to capture the diversity of farming systems occurring across SMDZ. The original survey design was therefore hierarchically structured, with individual farms nested within villages. However, because the anonymized analytical dataset did not retain

all 22 original village identifiers in a sufficiently standardized form to reconstruct the complete clustering structure unambiguously, village-level clustering was not retrospectively imposed on the inferential models. This limitation was explicitly considered when interpreting territorial comparisons and is acknowledged in the limitations of the study.

2.3. Survey Design and Data Collection

A structured field survey was conducted with 70 farmers distributed across 22 villages in Skoura M'Daz to capture both the socio-economic organization of farming systems and the ecological logic underlying traditional agricultural practices. The questionnaire was designed to document farm structure, land fragmentation, topography, irrigation systems, agroforestry, crop rotation, fertilization strategies, external-input use, livestock integration, water management, terracing systems, and locally transmitted ecological knowledge. Rather than treating farmers' responses as purely declarative information, the survey was systematically complemented by field observations, allowing reported practices to be cross-checked against visible land use patterns, irrigation infrastructures, tree–crop associations, soil and water conservation structures, and terrace-based farming arrangements. This mixed approach strengthened the reliability of the dataset by linking farmers' knowledge, observed practices, and landscape evidence, thereby providing a robust empirical basis for assessing agroecological coherence under real smallholder conditions.

2.4. Development of the Agroecological Practice Intensity Index (AEPI)

To move beyond a purely descriptive inventory of farming practices, we developed the Agroecological Practice Intensity Index (AEPI) aimed at quantifying the degree of agroecological practice integration within smallholder farming systems. The index was designed as an operational and reproducible tool for assessing whether agroecological practices occur as isolated management options or as interconnected components of broader agroecological strategies.

The AEPI incorporates six components: agroforestry, crop rotation, intercropping, organic or mixed fertilization, absence of chemical inputs, and crop–livestock integration. These practices were selected because they represent complementary dimensions of agroecological management repeatedly emphasized in the agroecological literature, including biodiversity enhancement, ecological interactions, nutrient cycling, reduction in synthetic-input dependence, and crop–livestock diversification.

For farm i, the AEPI was calculated as $AEPI_i = \sum_{j=1}^{6} x_{ij}$, where $x_{ij} = 1$ when agroecological practice j was present on farm i, and $x_{ij} = 0$ otherwise. The AEPI therefore ranged from 0 to 6.

Binary coding was adopted because the survey consistently documented the presence or absence of these practices but did not provide sufficiently standardized measurements of their intensity, spatial extent, duration, management quality, or ecological effectiveness. Binary scoring therefore minimized unsupported assumptions while maintaining comparability across heterogeneous smallholder farms.

Equal weighting was adopted because no empirical evidence or context-specific theoretical basis was available to justify assigning greater ecological importance to any single component. Equal weighting was therefore considered the most transparent and parsimonious specification for an exploratory index of practice integration.

The AEPI should not be interpreted as a direct measure of ecological performance, productivity, environmental impact, adaptive capacity, or resilience. It measures the degree of integration of multiple agroecological practices within individual farming systems. Consequently, higher AEPI values indicate broader agroecological practice integration but do not, by themselves, demonstrate superior ecological functioning or resilience outcomes.

2.5. External-Input Intensity and Agroecological–Input Integration

To complement the Agroecological Practice Intensity Index (AEPI), an Input Intensity Score (IIS) was constructed to characterize the relative reliance of surveyed farms on selected external-input and technology-mediated management practices. The purpose of this indicator was not to classify technologies or external inputs as inherently beneficial or detrimental, nor to treat technological intensification as the inverse of sustainability. Rather, the IIS was designed as a descriptive measure of a distinct management dimension that could be examined alongside agroecological practice integration.

The IIS was calculated as the unweighted sum of four binary indicators: chemical-input use, mineral-only fertilization, mechanized labour, and drip irrigation use. Each component was coded as 1 when the corresponding practice was present and 0 otherwise, such that

$$IIS_i = C_i + M_i + L_i + D_i$$

where C_i denotes chemical-input use, M_i mineral-only fertilization, L_i mechanized labour, and D_i drip-irrigation use for farm i. The resulting score ranged theoretically from 0 to 4, with higher values indicating greater reliance on the selected external-input and technology-mediated management practices. Importantly, higher IIS values should not be interpreted as lower sustainability per se. For example, drip irrigation or mechanization may contribute to resource use efficiency or reduced labour constraints under specific conditions; their inclusion in the IIS reflects their role as technology-mediated management practices rather than an assumption of adverse environmental performance.

To examine the relative configuration of agroecological practice integration and input intensity within individual farms, the Agroecological–Input Integration Index (AITI) was subsequently derived. Because AEPI and IIS have different theoretical ranges (0–6 and 0–4, respectively), both indices were normalized to their respective theoretical maxima before integration. The AITI for farm i was calculated as

$$AITI_i = (AEPI_i/6) - (IIS_i/4).$$

The resulting index has a theoretical range from −1 to +1. Positive values indicate that normalized agroecological practice integration exceeds normalized input intensity, values close to zero indicate comparable normalized levels of the two dimensions, and negative values indicate that normalized input intensity exceeds normalized agroecological practice integration. The AITI is therefore interpreted as a descriptive balance between two management dimensions and not as a direct measure of sustainability, ecological performance, adaptive capacity, or resilience.

The AEPI and IIS were additionally examined as separate dimensions rather than relying exclusively on their integration into AITI. This distinction was important because farms may simultaneously exhibit high levels of agroecological practice integration and high levels of technology-mediated or external-input use. Accordingly, the analytical framework does not assume that agroecological management and technological innovation constitute mutually exclusive pathways. Instead, the joint distribution of the AEPI and IIS was used descriptively to characterize heterogeneous management configurations among surveyed farms.

A further methodological consideration concerns the partial structural overlap between the two indices. Specifically, the AEPI includes the absence of chemical inputs and organic or mixed fertilization as positive components, whereas the IIS includes chemical-input use and mineral-only fertilization. Consequently, the two indices are not fully independent, and an inverse association between AEPI and IIS may partly arise from their mathematical construction. For this reason, associations between the two indices were

interpreted cautiously and evaluated through the leave-one-component-out sensitivity analysis described in Section 2.4. The AITI should likewise be regarded as a descriptive positioning metric rather than as independent evidence of a trade-off between agroecological management and technological or external-input use.

2.6. Statistical Analyses

All statistical analyses were conducted in R version 4.4.1 [21] using a reproducible analytical workflow. The analytical strategy combined descriptive statistics, between-group comparisons, rank-based association tests, multivariable regression, sensitivity analyses, and a priori descriptive classification of farming systems. The objective was to characterize patterns of agroecological practice integration, territorial variation, external-input intensity, and management configurations among the surveyed SMDZ farms. Given the cross-sectional and observational nature of the study, the analyses were not designed to establish causal relationships or to directly measure ecological performance, adaptive capacity, or resilience.

Descriptive statistics were first used to characterize the socio-economic, structural, and management attributes of the surveyed farms. Continuous variables were summarized using means, medians, standard deviations, and relevant distributional measures, whereas categorical variables were described using frequencies and percentages. The characteristics examined included farm size, farmer age and agricultural experience, topography, irrigation system, livestock integration, agroforestry, intercropping, crop rotation, fertilization strategy, chemical-input use, labour type, and participation in professional organizations. The Agroecological Practice Intensity Index (AEPI), Input Intensity Score (IIS), and Agroecological–Input Integration Index (AITI) were calculated as described in Sections 2.4 and 2.5.

Given the relatively small sample size (n = 70) and the heterogeneity of the surveyed farming systems, bootstrap resampling was used to estimate confidence intervals for selected descriptive indicators, including the mean AEPI. Differences in the AEPI between rural and urban/peri-urban farms were assessed using Welch's two-sample t-test, which does not assume equal group variances. A Mann–Whitney test was additionally performed as a complementary non-parametric sensitivity analysis. Because these tests rely on different assumptions and evaluate different aspects of the group distributions, agreement between their p-values was not considered a prerequisite for interpreting the territorial comparison. Both results were therefore reported to provide a transparent assessment of the robustness of the observed contrast. The magnitude of the between-group difference was additionally summarized using Hedges' g.

The relationship between AEPI and IIS was examined using Spearman's rank correlation coefficient. Particular caution was required in interpreting this association because the two indices contain partially inverse components. For example, chemical-input use contributes positively to IIS, whereas the absence of chemical inputs contributes positively to the AEPI; similarly, mineral-only fertilization contributes to IIS, whereas organic or mixed fertilization contributes to the AEPI. The observed correlation was therefore not assumed to represent an entirely independent relationship between agroecological practice integration and external-input or technology-mediated management. Its sensitivity to index composition was examined using the leave-one-component-out procedure described in Section 2.4.

Multivariable associations with the AEPI were examined using ordinary least-squares regression with heteroskedasticity-consistent HC3 standard errors. The primary model included rural location, IIS, topography, membership in a professional organization, farmer age, and log-transformed farm area [log (area + 1)] as explanatory variables. Regression

coefficients were interpreted as conditional associations rather than causal effects. Model fit was assessed using R^2 and adjusted R^2, while multicollinearity was examined using variance inflation factors (VIFs). Additional diagnostic procedures were used to evaluate residual behaviour, heteroskedasticity, and potentially influential observations.

To examine potential socio-demographic confounding, an additional sensitivity model included formal education as a binary covariate distinguishing respondents with any formal education from those reporting no formal education. This binary specification was used because the available survey categories did not provide sufficiently precise information on completed years of schooling to support a defensible continuous measure of educational duration. Results from this expanded model are reported in Table S7.

The original sampling design included farms distributed across 22 villages. However, the anonymized analytical dataset available for the present analyses did not retain sufficiently standardized village identifiers to reconstruct all original village-level clusters unambiguously. Village-clustered standard errors were therefore not estimated, as reconstructing or imposing cluster assignments would have required unverifiable assumptions. Potential residual dependence among observations originating from the same villages is consequently acknowledged as a limitation of the inferential analysis.

The farming system typology was constructed as a priori two-dimensional descriptive classification based on the AEPI and IIS rather than through an unsupervised clustering procedure. Farms were assigned to four mutually exclusive management configurations according to their positions in the AEPI–IIS space: Agroecological Custodians (higher-category AEPI/lower-category IIS), Hybrid Agroecological Intensifiers (higher-category AEPI/higher-category IIS), Input-Dependent Systems (lower-category AEPI/higher-category IIS), and Low-Intensity Traditional Systems (lower-category AEPI/lower-category IIS).

The thresholds used to define these categories were established as transparent operational cut-offs on the discrete score ranges rather than as statistically optimized or externally validated ecological thresholds. The AEPI ranges from 0 to 6 and represents the sum of six binary agroecological-practice components. A score of AEPI ≥ 4 was therefore used to define the higher category because it indicates the presence of at least four of the six practices included in the index, corresponding to at least two-thirds of its components. Scores of AEPI ≤ 3 formed the complementary lower category. Similarly, IIS ranges from 0 to 4 and summarizes four binary external-input or technology-mediated indicators. IIS ≥ 2 was used to define the higher-input category, indicating the presence of at least two of the four IIS components, whereas IIS ≤ 1 defined the complementary lower-input category. Because both indices are integer-valued, these cut-offs generate exhaustive and mutually exclusive categories without intermediate or unclassified values.

These thresholds were selected to provide a simple, interpretable, and reproducible partition of the AEPI–IIS management space. They were not derived from data-driven optimization, cluster separation, outcome maximization, or empirically identified ecological breakpoints. Accordingly, an AEPI score of 4 should not be interpreted as a threshold above which a farm becomes agroecologically sustainable or resilient, nor should an IIS of 2 be interpreted as a threshold of excessive input dependence or environmental pressure. The resulting four configurations are therefore best understood as descriptive management profiles defined a priori for comparative purposes, rather than as naturally occurring clusters, statistically optimized farm types, or externally validated categories of sustainability, vulnerability, or resilience.

Co-occurrence among agroecological practices was examined descriptively as the frequency with which pairs of practices were simultaneously present within the same farm. These values represent joint adoption frequencies and were not treated as statistical

measures of dependence, association strength, ecological synergy, or functional interaction. No causal or ecological relationship among practices was inferred solely from their co-occurrence.

Graphical representations were generated in R to support interpretation of the analyses, including AEPI distributions, territorial comparisons, AEPI–IIS relationships, regression coefficient plots, and the two-dimensional farming system classification. Statistical significance was evaluated using two-sided tests with $\alpha = 0.05$. However, exact p-values, confidence intervals, effect sizes, model estimates, and sensitivity analyses were considered jointly rather than interpreting results solely through a dichotomous significance threshold. Throughout the analysis, statistical relationships are interpreted as associations within the surveyed farms. They should not be regarded as evidence of causality, ecological effectiveness, adaptive capacity, or resilience outcomes.

3. Results

3.1. Structural Characteristics of Farming Systems

The surveyed farming systems in Skoura M'Daz (SMDZ) were overwhelmingly dominated by smallholder agriculture characterized by strong land fragmentation, limited mechanization, and high dependence on locally embedded ecological management strategies (Figure 3). As illustrated in Figure 3, nearly 63% of farms cultivated less than 5 ha, while the median farm size reached only 3.0 ha, confirming the predominance of structurally constrained family-based production systems. The socio-economic profile of farmers further revealed an ageing agricultural population, with a mean age of 52.2 years and an average farming experience of 17.7 years, indicating the persistence of intergenerational ecological knowledge despite relatively low formal education levels. Illiteracy exceeded 52%, highlighting the strong contrast between institutional educational marginalization and the high operational complexity of local agroecological management systems. Figure 3 further demonstrates that these farms rarely function as specialized monocultures. Instead, most systems combine agroforestry, crop rotation, crop–livestock integration, gravity irrigation, and organic or mixed fertilization into highly diversified production portfolios. Agroforestry practices were reported by 71.4% of farmers surveyed, crop rotation by 74.3%, and traditional gravity irrigation by 72.9%, while organic or mixed fertilization reached exceptionally high levels (91.4%). Such diversification patterns contrast sharply with dominant modernization-oriented agricultural models based on specialization, mechanization, and external-input intensification. Rather than representing isolated management practices, these results show that traditional mountain farming systems in SMDZ frequently combine multiple agroecological practices within diversified management portfolios.

3.2. Agroecological Practice Integration Across Surveyed Farms

The surveyed farms showed substantial agroecological practice integration. The mean Agroecological Practice Intensity Index (AEPI) reached 3.94 out of 6, corresponding to 65.7% of the maximum possible AEPI score, with a bootstrap 95% confidence interval ranging from 3.67 to 4.23 (Table 3). As shown in Figure 3, nearly 87% of farmers implemented at least three major agroecological practices simultaneously, while more than one-quarter of surveyed systems belonged to the "high agroecological intensity" category. This result is scientifically important because it emerges within highly constrained socio-ecological environments characterized by recurrent droughts, irregular rainfall, steep topography, fragmented landholdings, limited financial resources, and relatively low mechanization levels. These results indicate that multiple agroecological practices remain jointly implemented across many surveyed farms despite the structural and environmental constraints characterizing the study area. Figure 4 further demonstrates that SMDZ farmers display higher frequencies

of agroforestry, crop rotation, organic fertilization, and traditional water management practices than national Moroccan averages, Mediterranean Basin averages, and global smallholder averages. Particularly notable is the prevalence of organic or mixed fertilization, which reached 91.4% in SMDZ compared with only 59.6% at Mediterranean scale and 36.8% at global smallholder scale. Similarly, traditional water harvesting and gravity irrigation systems remained highly prevalent, reinforcing the importance of territorially embedded water management strategies in semi-arid resilience. Collectively, these results indicate that agroecological practices in SMDZ frequently occur in combination rather than exclusively as isolated management options. However, the AEPI quantifies practice integration and does not directly measure the ecological effectiveness, adaptive capacity, or resilience generated by these configurations.

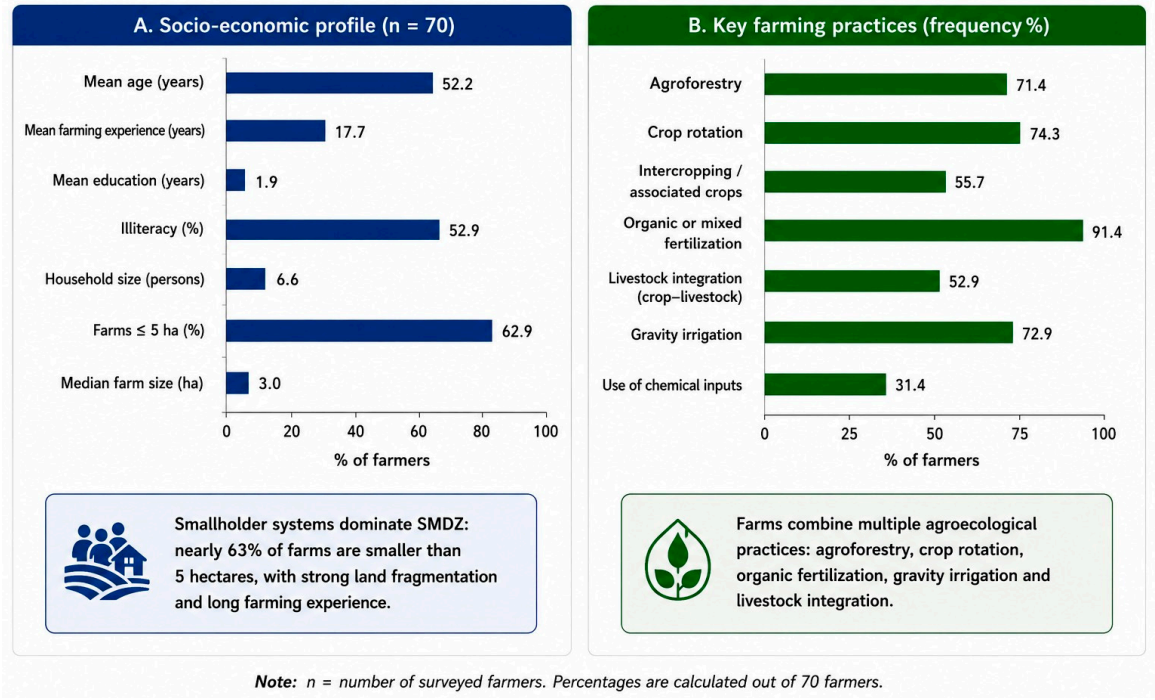


Figure 3. Structural characteristics and dominant agroecological practices of surveyed farming systems in Skoura M'Daz (SMDZ), Morocco (n = 70). The figure summarizes the socio-economic profile and ecological organization of surveyed smallholder farming systems distributed across 22 villages in the Middle Atlas Mountains. (**A**) illustrates the structural characteristics of the farming population, highlighting strong land fragmentation, low formal education levels, and long farming experience under semi-arid mountain conditions. Nearly 63% of farms cultivate less than 5 ha, while the median farm size remains limited to 3.0 ha, reflecting the predominance of family-based smallholder systems. (**B**) presents the prevalence of key agroecological practices, showing high frequencies of agroforestry, crop rotation, organic or mixed fertilization, traditional gravity irrigation, and crop–livestock integration. The coexistence of multiple ecological practices within the same farming systems indicates that agroecological management in SMDZ functions as an integrated diversification strategy rather than a collection of isolated techniques. Collectively, the results reveal the persistence of territorially embedded low-input agroecosystems capable of maintaining ecological coherence despite hydro-climatic stress, fragmented landholdings, and limited mechanization.

The leave-one-component-out sensitivity analysis indicated high rank-order stability of the AEPI. Spearman correlations between the full six-component AEPI and the reduced five-component specifications ranged from ρ = 0.893 to 0.971 (all $p < 0.001$; Table S6), indicating that the overall ranking of farms was not disproportionately determined by a single component. Nevertheless, the territorial contrast showed some sensitivity to index specification, with Welch p-values ranging from 0.021 to 0.133 across reduced specifications

(Table S6). These results support the internal stability of the composite AEPI while also indicating that some inferential relationships depend on their precise composition.

Table 3. Advanced statistical indicators of agroecological intensity.

Indicator	Value
Mean AEPI (/6)	3.943
AEPI percentage of theoretical maximum	65.71%
Bootstrap 95% CI lower	3.671
Bootstrap 95% CI upper	4.229
Farmers with intermediate AEPI (%)	60.0
Farmers with high AEPI (%)	27.1
Mean Input Intensity Score (/4)	1.014
Mean Agroecological–Input Integration Index (AITI)	0.404

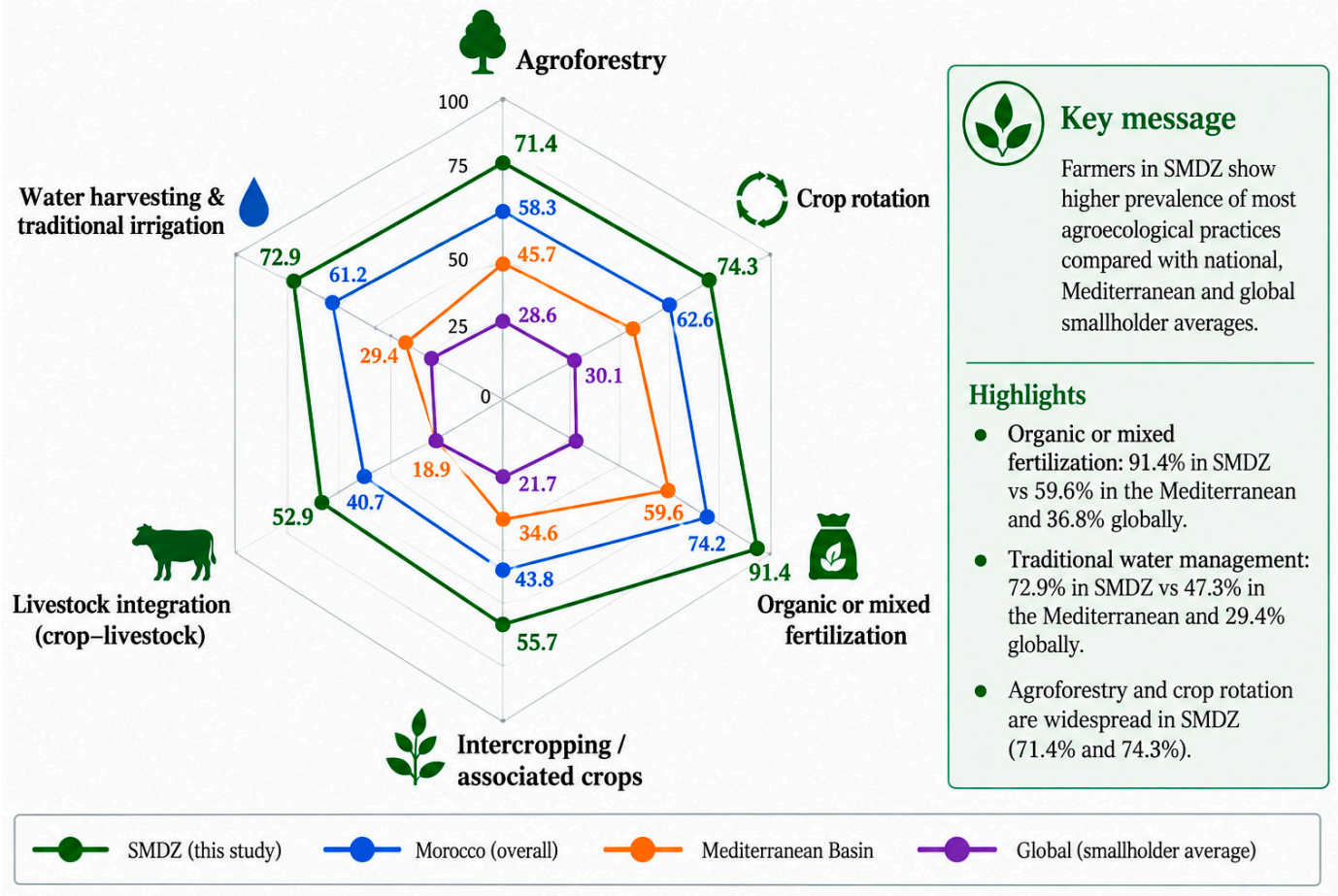


Figure 4. Comparative prevalence of agroecological and traditional practices in the SMDZ agroecosystem relative to Moroccan, Mediterranean, and global smallholder systems. The radar diagram compares the prevalence of six major agroecological and traditional practices among surveyed farmers in Skoura M'Daz (SMDZ, n = 70) with reference values reported at Moroccan national scale, across the Mediterranean Basin, and within global smallholder farming systems. SMDZ consistently exhibits higher levels of agroforestry, crop rotation, organic or mixed fertilization, crop diversification, crop–livestock integration, and traditional water management practices. Particularly strong differences are observed for organic or mixed fertilization and gravity-based water harvesting systems, highlighting the persistence of low input.

3.3. Territorial Differences in Agroecological Practice Integration

Rural farms displayed higher mean AEPI values than urban/peri-urban farms (4.23 versus 3.66; Figure 5a; Table S2). The mean difference of 0.57 AEPI units reached the conventional significance threshold under Welch's *t*-test (p = 0.0417), with a moderate standardized effect size (Hedges' g = 0.491). However, the complementary Mann–Whitney test did not reach the conventional 0.05 significance threshold (p = 0.0664; Table S2). The unadjusted evidence for a territorial difference should therefore be regarded as suggestive rather than unequivocal. In the multivariable model, rural location remained positively associated with the AEPI after adjustment for input intensity, topography, professional-organization membership, age, and farm area (β = 0.631, 95% CI: 0.035 to 1.227, p = 0.0379; Figure 6; Table 4). An additional sensitivity model including formal education yielded a comparable positive coefficient for rural location (β = 0.654, 95% CI: 0.071 to 1.238, p = 0.028; Table S7). Taken together, these analyses indicate a positive association between rural location and agroecological practice integration, while the inconsistency between the two unadjusted tests warrants caution regarding the strength of the territorial contrast. Rural location is treated here as a contextual variable and should not be interpreted as a direct measure of territorial embeddedness or as evidence of a causal territorial effect.

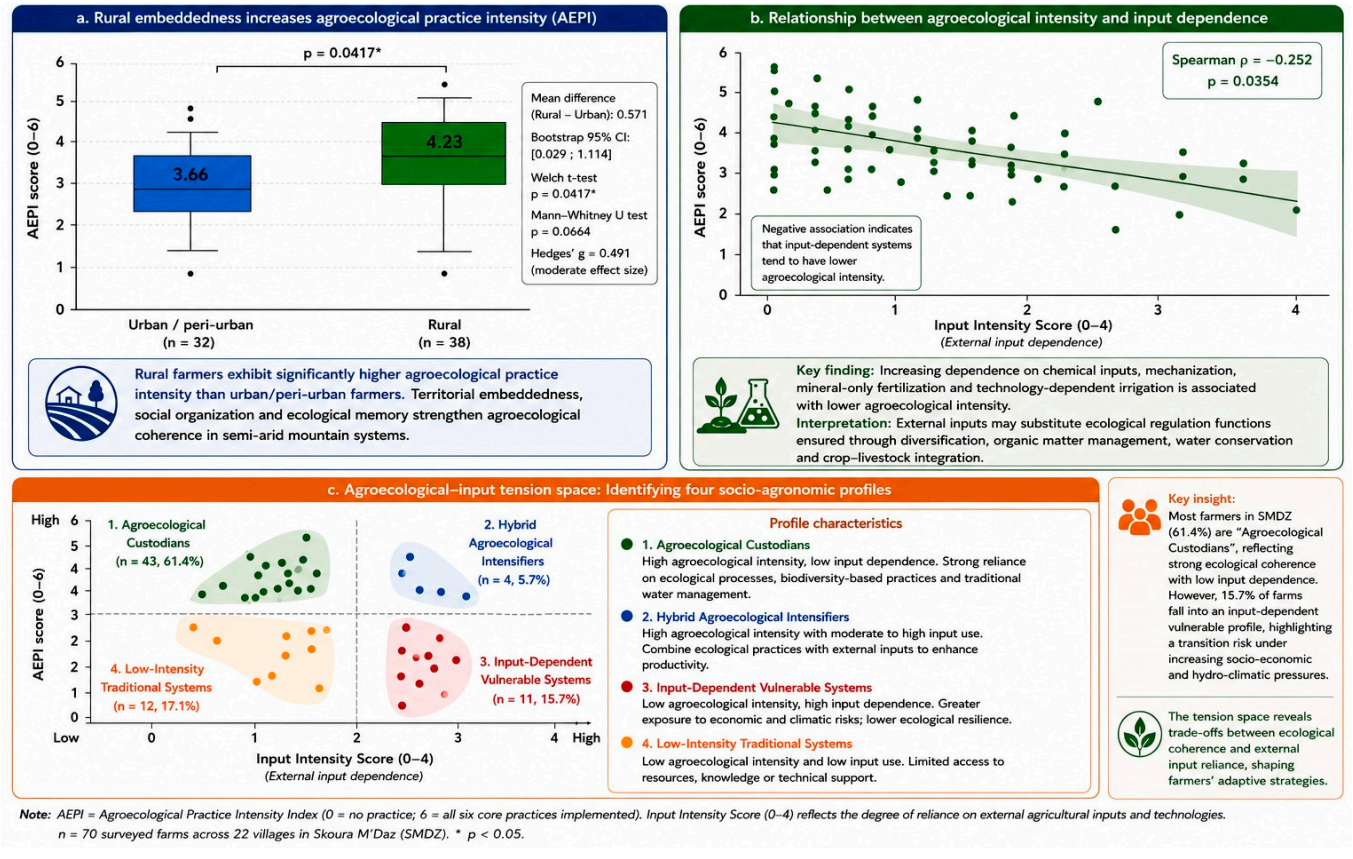


Figure 5. Territorial effects, agroecological–input trade-offs, and typological differentiation of farming systems in Skoura M'Daz (SMDZ), Morocco. (**a**) Comparison of AEPI values between rural and urban/peri-urban farms. Rural farms showed a higher mean AEPI (4.23) than urban/peri-urban farms (3.66). The difference reached the conventional significance threshold using Welch's *t*-test (p = 0.0417), whereas the complementary Mann–Whitney test yielded p = 0.0664. The territorial contrast is therefore interpreted cautiously as suggestive evidence of a difference in agroecological practice integration (**b**) Bivariate relationship between the AEPI and the Input Intensity Score. The full AEPI showed a weak negative correlation with input intensity (Spearman ρ = −0.252, p = 0.0354). Because sensitivity analysis indicated that this relationship was strongly influenced by overlapping chemical-input components in the construction of the two indices (Table S6), the association is interpreted

descriptively rather than as evidence of a causal trade-off. (**c**) presents the agroecological–input tension space and identifies four major farming profiles: Agroecological Custodians, Hybrid Agroecological Intensifiers, Input-Dependent Vulnerable Systems, and Low-Intensity Traditional Systems. Most surveyed farms belong to the Agroecological Custodian profile, characterized by high ecological coherence and low input dependence, whereas a smaller group exhibits increasing vulnerability associated with stronger external-input reliance. Collectively, the figure demonstrates that resilience trajectories in SMDZ are shaped by a dynamic interaction between territorial embeddedness, ecological diversification, and modernization pressures, rather than by technological intensification alone.

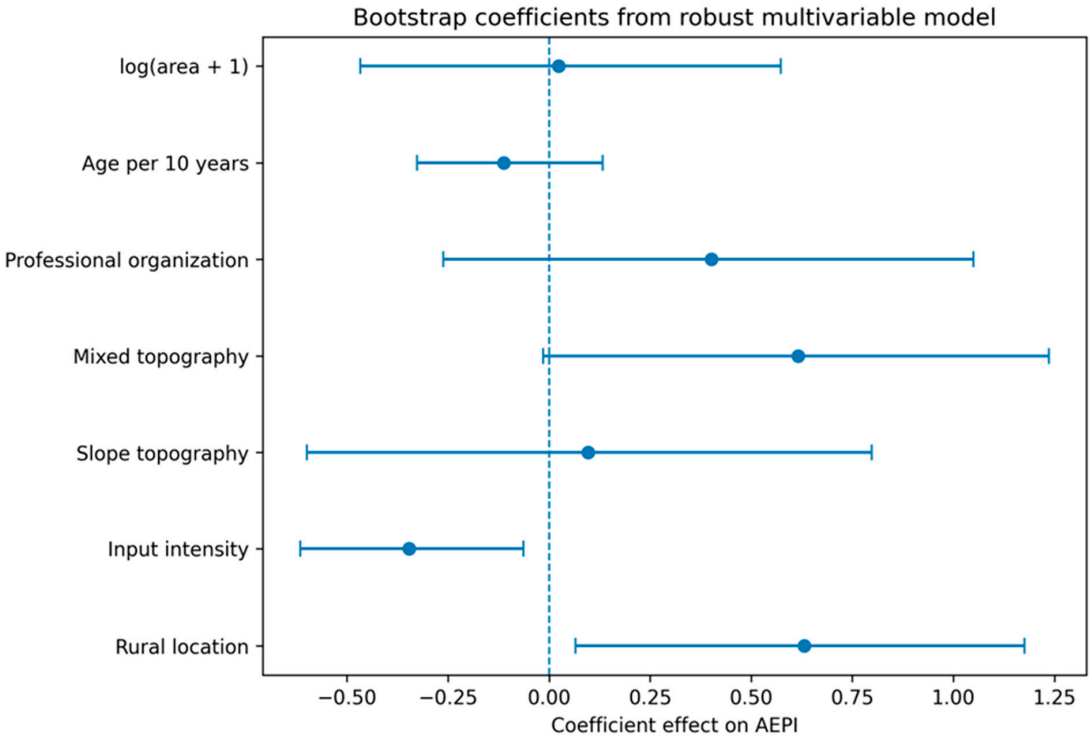


Figure 6. Bootstrap-derived coefficients from the robust multivariable model explaining agroecological practice intensity (AEPI) in the semi-arid mountain systems of SMDZ Bootstrap coefficient estimates derived from the robust multivariable regression model evaluating the determinants of agroecological practice intensity (AEPI) across surveyed farms in the semi-arid mountain region of Skoura M'Daz (SMDZ). Points represent estimated standardized regression coefficients, while horizontal bars indicate bootstrap-derived 95% confidence intervals. The vertical dashed line corresponds to the null-effect threshold ($\beta = 0$). Coefficient estimates from the multivariable model of the AEPI in surveyed SMDZ farms. Points represent estimated regression coefficients and horizontal bars indicate 95% confidence intervals. Rural location was positively associated with AEPI, whereas Input Intensity Score showed a negative association in the primary model. These coefficients represent conditional associations within the cross-sectional dataset and should not be interpreted as causal effects. An education-adjusted sensitivity model and additional diagnostics are reported in Table S7. Mixed topography and professional organization membership also showed positive effects, suggesting that landscape heterogeneity and collective institutional structures may enhance diversification and adaptive management capacity. By contrast, increasing input intensity displayed a clear negative association with the AEPI, confirming that greater dependence on external agricultural inputs tends to reduce ecological integration within farming systems. Age and farm size exhibited comparatively weaker or more uncertain effects, whereas sloped topography showed high variability, reflecting the heterogeneous influence of geomorphological constraints on agroecological management strategies. Overall, the model demonstrates that agroecological intensity in SMDZ is shaped less by individual farm characteristics alone than by the interaction between territorial context, institutional organization, landscape structure, and dependence on external-input systems.

Table 4. Robust multivariable regression model explaining the AEPI.

Predictor	Coefficient	Robust HC3 SE	*p*-Value
Intercept	3.582	0.296	<0.001
Rural location	0.631	0.298	0.0379
Input intensity	−0.346	0.151	0.0251
Slope topography	0.096	0.376	0.7989
Mixed topography	0.617	0.331	0.0675
Professional organization	0.402	0.359	0.2668
Age (per 10 years)	−0.112	0.118	0.3458
log(area + 1)	0.024	0.277	0.9308

Model performance: R^2 = 0.235; adjusted R^2 = 0.149.

3.4. Association Between Agroecological Practice Integration and Input Intensity

The full six-component AEPI was negatively correlated with the Input Intensity Score (Spearman ρ = −0.252, p = 0.0354; Figure 5b). In the primary multivariable model, IIS was also negatively associated with the AEPI after adjustment for rural location, topography, farmer age, farm size, and professional organization membership (β = −0.346, p = 0.0251; Table 4), whereas rural location was positively associated with AEPI (β = 0.631, p = 0.0379).

However, the leave-one-component-out sensitivity analysis indicated that the bivariate association between AEPI and IIS was sensitive to index composition. When the "absence of chemical inputs" component was removed from the AEPI, the correlation with IIS became negligible and non-significant (ρ = −0.016, p = 0.896; Table S6). Similarly, removal of the organic/mixed-fertilization component attenuated the association (ρ = −0.222, p = 0.065; Table S6). These results are important because AEPI and IIS contain partially inverse components: chemical-input use contributes positively to IIS whereas its absence contributes positively to AEPI, and mineral-only fertilization contributes to IIS whereas organic or mixed fertilization contributes to the AEPI. Consequently, part of the observed inverse relationship between the full indices reflects their mathematical construction, and the baseline correlation should not be interpreted as independent evidence of a substantive trade-off between agroecological practice integration and external-input use.

An additional multivariable sensitivity analysis was conducted to assess potential socio-demographic confounding by including formal education as an additional covariate (Table S7). In this expanded model, rural location remained positively associated with AEPI (β = 0.654, 95% CI: 0.071 to 1.238, p = 0.028). The coefficient for IIS remained negative but was attenuated and became borderline at the conventional significance threshold (β = −0.303, 95% CI: −0.607 to 0.001, p = 0.0507). Formal education was not significantly associated with AEPI (β = −0.500, p = 0.086). The expanded model explained 27.1% of the variation in AEPI (adjusted R^2 = 0.175), and all variance inflation factors were below 1.5, providing no indication of problematic multicollinearity.

Taken together, the primary analyses indicate an inverse association between the full AEPI and IIS, but the magnitude and statistical evidence for this relationship depend on both index composition and model specification. The relationship should therefore be interpreted descriptively and with caution. In particular, the results do not demonstrate that external-input or technology use reduces agroecological practice integration, nor do they imply that technological innovation is intrinsically incompatible with agroecological management. Because the study is cross-sectional and observational, the relationships reported here represent statistical associations and should not be interpreted as evidence that external-input use causes reductions in agroecological practice integration.

3.5. Typology of Farming Systems

The priori classification based on the AEPI and IIS identified four distinct management configurations among the surveyed farms (Table 5; Figure 5c). These categories represent descriptive management configurations and should not be interpreted as direct indicators of ecological vulnerability or resilience. Rather, they summarize how the selected agroecological practices and external-input or technology-mediated practices coexist within individual farming systems.

Table 5. Typology of SMDZ farming systems.

Farming Profile	N	%	Mean AEPI	Mean Input Intensity	Mean AITI
Agroecological custodians	43	61.43	4.628	0.581	0.626
Low-intensity traditional systems	12	17.14	2.667	0.750	0.257
Input-dependent vulnerable systems	11	15.71	2.545	2.455	−0.190
Hybrid agroecological intensifiers	4	5.71	4.250	2.500	0.083

Agroecological Custodians represented the largest group, comprising 43 farms (61.43% of the sample). Farms in this category had the highest mean AEPI (4.628), the lowest mean IIS (0.581), and the highest mean Agroecological–Input Integration Index (AITI = 0.626). Their position within the AEPI–IIS space therefore reflects relatively high integration of the agroecological practices included in the AEPI together with relatively low reliance on the external-input and technology-mediated practices represented by the IIS. This configuration was characterized by the frequent presence of practices such as organic nutrient management, agroforestry, crop rotation, crop–livestock integration, and traditional water management practices. These characteristics describe the management profile of this group but do not, in themselves, demonstrate superior ecological performance, sustainability, or resilience.

Hybrid Agroecological Intensifiers represented four farms (5.71% of the sample). This group combined a relatively high mean AEPI (4.250) with the highest mean IIS (2.500), resulting in a mean AITI of 0.083. This configuration shows that substantial agroecological practice integration can coexist with greater use of the external-input and technology-mediated practices included in the IIS. It therefore illustrates a management strategy in which agroecological, and technology-mediated practices are combined rather than treated as mutually exclusive approaches. However, the present analysis does not establish whether this combination produces different agronomic, ecological, economic, or resilience-related outcomes compared with the other configurations.

Input-Dependent Systems accounted for 11 farms (15.71% of the sample) and combined a lower mean AEPI (2.545) with a higher mean IIS (2.455), resulting in a negative mean AITI (−0.190). This profile describes the relative position of these farms within the AEPI–IIS management space and indicates greater reliance on the external-input and technology-mediated practices included in the IIS relative to the agroecological practices represented by the AEPI. Importantly, this classification should not be interpreted as evidence of ecological degradation, economic vulnerability, reduced adaptive capacity, or greater exposure to climatic risk, as these outcomes were not directly measured in the present study.

Low-Intensity Traditional Systems comprised 12 farms (17.14% of the sample). These farms combined a relatively low mean AEPI (2.667) with a relatively low mean IIS (0.750), resulting in a positive mean AITI (0.257). This configuration indicates that low external-input intensity does not necessarily coincide with high integration of the agroecological

practices included in the AEPI. Accordingly, the category describes a particular combination of management characteristics rather than a lower or higher level of sustainability, ecological functioning, or resilience.

Taken together, the four profiles illustrate substantial heterogeneity in the ways agroecological practices and external-input, or technology-mediated management are combined across the surveyed farms. Agroecological Custodians were the predominant configuration, whereas Hybrid Agroecological Intensifiers demonstrate that higher agroecological practice integration can coexist with higher input intensity. Input-Dependent Systems and Low-Intensity Traditional Systems occupy different positions within the same two-dimensional management space. These categories represent descriptive management configurations and should not be interpreted as direct indicators of ecological vulnerability or resilience. Because the classification is based exclusively on the AEPI and IIS, determining whether these configurations differ in ecological functioning, agricultural performance, economic outcomes, adaptive capacity, or resilience will require independent biophysical, agronomic, and socio-economic validation.

3.6. Perceived Benefits and Multifunctionality of Agroecological Practices

Beyond their structural prevalence, agroecological practices were associated with broadly positive perceptions among surveyed farmers regarding multiple agronomic, environmental, and socio-economic dimensions, as summarized in Table 6 and illustrated in Figure 5. Improved soil fertility was the most frequently reported benefit, with 88.6% of respondents expressing a net positive perception and 57.1% identifying it as a major benefit. Increased crop yield stability was positively perceived by 80.0% of respondents, including 45.7% who considered it a major benefit.

Water-related benefits were also prominently reported. Enhanced water availability received a net positive perception from 78.6% of respondents and was identified as a major benefit by 50.0%. Reduced production costs were positively perceived by 75.7% of farmers, with 48.6% identifying cost reduction as a major benefit. Similarly, 75.7% of respondents perceived agroecological practices as contributing positively to greater resilience to drought, although a smaller proportion (41.4%) identified this dimension as a major benefit.

Positive perceptions were also reported for biodiversity conservation and household income, although at comparatively lower frequencies. Biodiversity conservation received a net positive perception from 70.0% of respondents and was identified as a major benefit by 37.1%, whereas improved household income was positively perceived by 67.1% of respondents and identified as a major benefit by 35.7% (Table 6). Overall, the distribution of responses indicates that farmers associate agroecological practices with multiple perceived benefits spanning soil fertility, production stability, water availability, production costs, drought response, biodiversity conservation, and household income.

These findings provide evidence of perceived multifunctionality rather than direct measurements of agronomic, ecological, hydrological, or socio-economic outcomes. In particular, the reported perceptions of improved soil fertility, enhanced water availability, yield stability, and greater resilience to drought should not be interpreted as demonstrating measured improvements in soil properties, water use efficiency, production stability, or resilience. Establishing such effects would require complementary biophysical and longitudinal evidence, including soil quality measurements, water use indicators, repeated yield observations, and farm-level economic data.

As illustrated in Figure 5, these perceived benefits span several dimensions, including soil fertility, production stability, water availability, production costs, drought response, biodiversity conservation, and household income.

Table 6. Farmers' perceived benefits of agroecological practices.

Benefit	Net Positive Perception (%)	Major Benefit (%)
Improved soil fertility	88.6	57.1
Increased crop yield stability	80.0	45.7
Enhanced water availability	78.6	50.0
Reduced production costs	75.7	48.6
Greater resilience to drought	75.7	41.4
Biodiversity conservation	70.0	37.1
Improved household income	67.1	35.7

3.7. Functional Integration, Multifunctionality, and Institutional Conditions of Agroecological Transition

The co-occurrence analysis revealed that agroecological management in SMDZ is structured through highly interconnected practice bundles rather than isolated technical interventions (Figure 7a; Table 7). Descriptive co-occurrence patterns showed that several agroecological practices were frequently implemented within the same farms. These patterns represent joint adoption frequencies and should not be interpreted as statistical associations or evidence of functional interactions among practices. Traditional water-harvesting systems also frequently co-occurred with agroforestry, organic fertilization, and diversified cropping systems, highlighting the integrated nature of ecological regulation mechanisms within semi-arid mountain agroecosystems. This pattern demonstrates that agroecological performance in SMDZ depends not only on the presence of individual practices, but on their functional articulation across soil fertility management, water conservation, biodiversity regulation, and production diversification.

Table 7. Prevalence of major agroecological and traditional practices in SMDZ farming systems.

Practice	Farmers Adopting the Practice (%)	Agroecological Function
Organic or mixed fertilization	91.4	Nutrient recycling, soil fertility restoration
Crop rotation	74.3	Soil fertility maintenance, pest regulation, yield stabilization
Traditional gravity irrigation	72.9	Water distribution, collective resource management
Agroforestry	71.4	Microclimate buffering, diversification, erosion control
Intercropping	55.7	Biodiversity enhancement, ecological complementarity
Livestock integration	52.9	Circular nutrient flows, manure supply, livelihood diversification
Chemical input use	31.4	Indicator of partial external-input dependence

The co-occurrence pattern shown in Figure 7a indicates that several practices were frequently adopted within the same farming systems. Because the analysis is descriptive, these co-occurrences should not be interpreted as evidence that the practices interact functionally or that particular combinations generate resilience. These practices reinforce one another through cumulative ecological processes: organic amendments improve soil structure and water retention, crop rotations reduce pest and nutrient-depletion risks, agroforestry enhances microclimatic buffering and biomass flows, and livestock integration sustains circular nutrient cycling. Consequently, the ecological coherence observed in

SMDZ reflects the persistence of territorially embedded adaptive strategies capable of maintaining multifunctionality under severe hydro-climatic constraints.

Beyond their structural integration, agroecological practices were also perceived by farmers as generating substantial agronomic, ecological, hydrological, and socio-economic co-benefits (Figure 7b; Table 6). Improved soil fertility emerged as the most strongly recognized benefit, with 88.6% of farmers reporting a positive perception and 57.1% identifying it as a major benefit. Increased crop yield stability was also widely acknowledged, indicating that diversified ecological management is not perceived locally as a productivity constraint, but as a stabilizing mechanism under semi-arid climatic conditions. Enhanced water availability, reduced production costs, and greater resilience to drought were also highly valued, confirming that farmers interpret agroecology through tangible adaptive functions directly linked to soil, water, costs, and production stability. Figure 7b indicates that farmers primarily value agroecological practices for their immediate functional contributions to soil fertility, water availability, yield stability, and cost reduction. Biodiversity conservation and household income received comparatively lower, though still clearly positive, evaluations. This suggests that farmers do not necessarily interpret agroecology first through abstract environmental discourse, but through its concrete capacity to secure production under uncertainty. The results therefore reinforce the interpretation of SMDZ farming systems as multifunctional agroecosystems in which ecological processes are valued because they directly support livelihood stability, drought adaptation, and production continuity.

Despite this strong agroecological coherence and perceived multifunctionality, farmers identified several structural barriers limiting the adoption, consolidation, and scaling-up of agroecological practices (Figure 7(c1–c3); Table 8). Limited access to water emerged as the most frequently cited constraint, affecting 57.1% of farmers surveyed, and was also perceived as the most severe limitation, with 62.5% of affected farmers considering it highly severe. High costs of agricultural inputs and technologies, lack of technical knowledge, labour constraints, limited access to credit, and weak extension services also appeared as important barriers. These findings reveal that the main bottleneck is not the absence of local ecological knowledge, but the insufficient alignment between agroecological practices and the institutional, financial, and infrastructural conditions required to sustain them.

Table 8. Main barriers limiting agroecological adoption in SMDZ farming systems.

Barrier	Frequency (%)	High Severity Perception (%)
Limited access to water	57.1	62.5
High cost of inputs/technologies	50.0	57.1
Lack of technical knowledge	45.7	53.1
Labour constraints	37.1	38.5
Limited access to credit	31.4	40.9
Weak extension services	28.6	30.0
Land tenure insecurity	20.0	35.7
Market access constraints	15.7	27.3

The ranking and severity patterns shown in Figure 7(c1–c3) and Table 8 reveal a major paradox of agroecological transition in semi-arid mountain systems: the farms that maintain the strongest ecological coherence are often those exposed to the harshest hydro-climatic and socio-economic pressures. Water scarcity, technological costs, and technical-support deficits occupy the upper tier of constraints, while labour shortages and limited access to credit reflect deeper rural vulnerability. The high severity associated with water access is particularly important because water availability controls the viability of agroforestry, crop

diversification, livestock integration, and traditional irrigation systems. Thus, ecological diversification alone cannot guarantee resilience when the institutional conditions for water security, technical assistance, and financial support remain fragile.

The policy and institutional expectations expressed by farmers further clarify the enabling conditions required for scaling agroecological transitions in SMDZ (Figure 7d; Table S3). Training and technical assistance emerged as the highest priority need, identified by 78.6% of respondents as important. Financial incentives or subsidies, improved access to water, affordable inputs, extension services, and access to credit were also strongly prioritized. These results show that farmers do not perceive agroecological transition as a simple return to tradition, but as a dynamic adaptive pathway requiring continuous learning, technical support, public investment, and selective innovation embedded within local ecological systems.

The close correspondence between the constraints listed in Table 8 and the support needs presented in Figure 7d and Table S3 shows that agroecological transition in SMDZ is already technically and socially meaningful, but institutionally under-supported. Water scarcity, limited technical knowledge, financial constraints, and weak extension services appear simultaneously as major barriers and priority intervention domains. This convergence suggests that the future of agroecology in semi-arid mountain regions depends less on introducing entirely new practices than on strengthening the governance, advisory, financial, and infrastructural systems that can stabilize and scale existing agroecological portfolios. Collectively, Figure 6, Tables 5 and 7 demonstrate that SMDZ farming systems combine strong ecological integration, widely perceived multifunctional benefits, persistent structural vulnerabilities, and clearly identified institutional needs. Agroecological transition therefore emerges not as a simple technological substitution process, but as a territorial resilience strategy requiring the simultaneous reinforcement of ecological knowledge, adaptive governance, public investment, and socio-economic support.

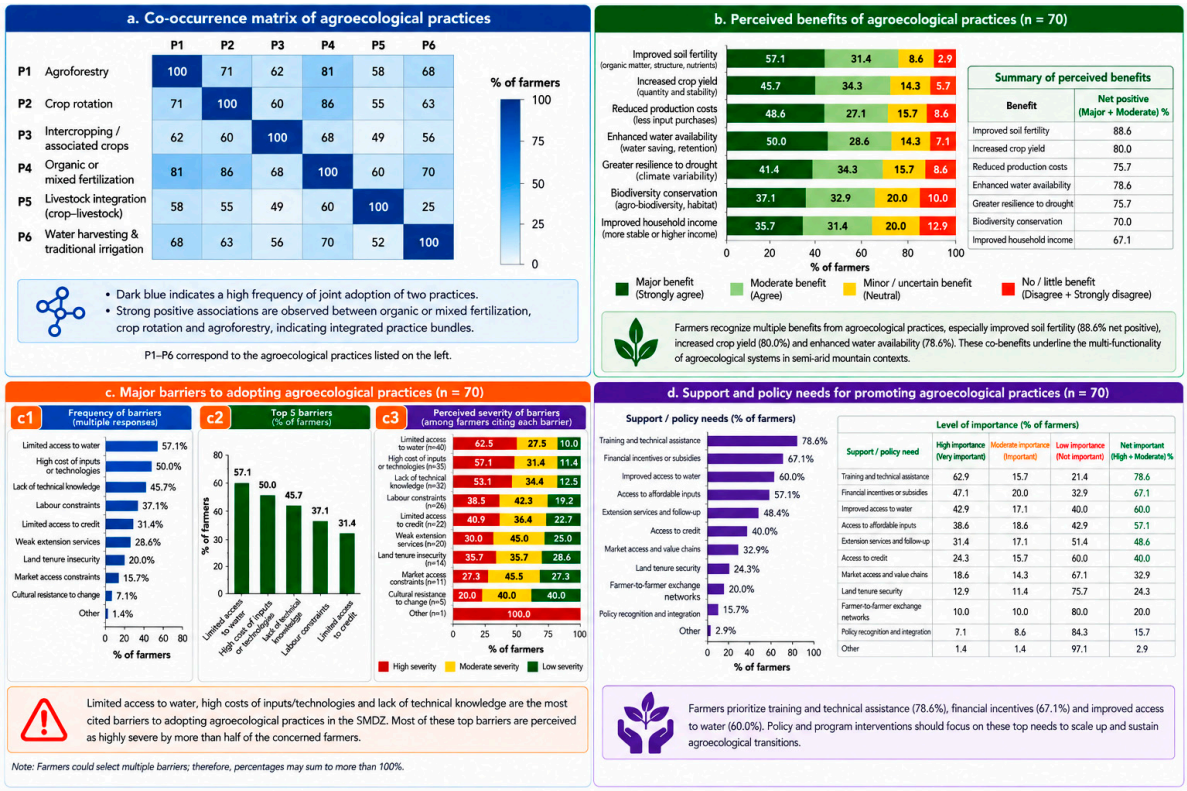


Figure 7. Functional integration, perceived multifunctionality, and institutional constraints shaping agroecological transitions in the semi-arid mountain systems of SMDZ Agroecological resilience in

SMDZ emerges from tightly interconnected ecological practice bundles, generating multiple agronomic and hydrological co-benefits while remaining constrained by severe hydro-economic and institutional barriers. (**a**) A co-occurrence matrix illustrating the degree of joint adoption among major agroecological practices in SMDZ farming systems (n = 70). Strong associations between agroforestry, crop rotation, organic or mixed fertilization, and traditional irrigation systems reveal highly integrated ecological management portfolios structured around complementary soil–water–biodiversity regulation processes. Darker blue gradients indicate stronger co-occurrence frequencies, highlighting the existence of multifunctional agroecological bundles rather than isolated practices. (**b**) Farmers' perceived benefits of agroecological practices across agronomic, ecological, hydrological, and socio-economic dimensions. Improved soil fertility (88.6% net positive perception), crop yield stability (80.0%), enhanced water availability (78.6%), and drought resilience (75.7%) emerged as the most strongly recognized benefits, demonstrating that agroecological systems are locally perceived as adaptive and multifunctional resilience mechanisms under semi-arid conditions. (**c1**–**c3**) Structural barriers limiting agroecological adoption and scaling-up. (**c1**) Frequency of reported barriers among surveyed farmers; (**c2**) ranking of the five dominant constraints; (**c3**) perceived severity levels associated with each barrier. Limited access to water, increasing technological and input costs, and insufficient technical support emerged simultaneously as the most frequent and most severe constraints, revealing the strong dependence of agroecological resilience on broader hydro-economic and institutional conditions. (**d**) Main support and policy needs identified by farmers for strengthening agroecological transitions. Training and technical assistance (78.6%), financial incentives (67.1%), improved water access (60.0%), and affordable agricultural inputs (57.1%) were identified as the principal enabling conditions required to stabilize and scale agroecological systems in semi-arid mountain territories. Collectively, the figure demonstrates that agroecological transition in SMDZ is not driven by isolated technological substitution, but by the interaction between ecological integration, multifunctional resilience benefits, and the institutional capacity to sustain territorially embedded adaptive systems under increasing climatic and socio-economic pressures.

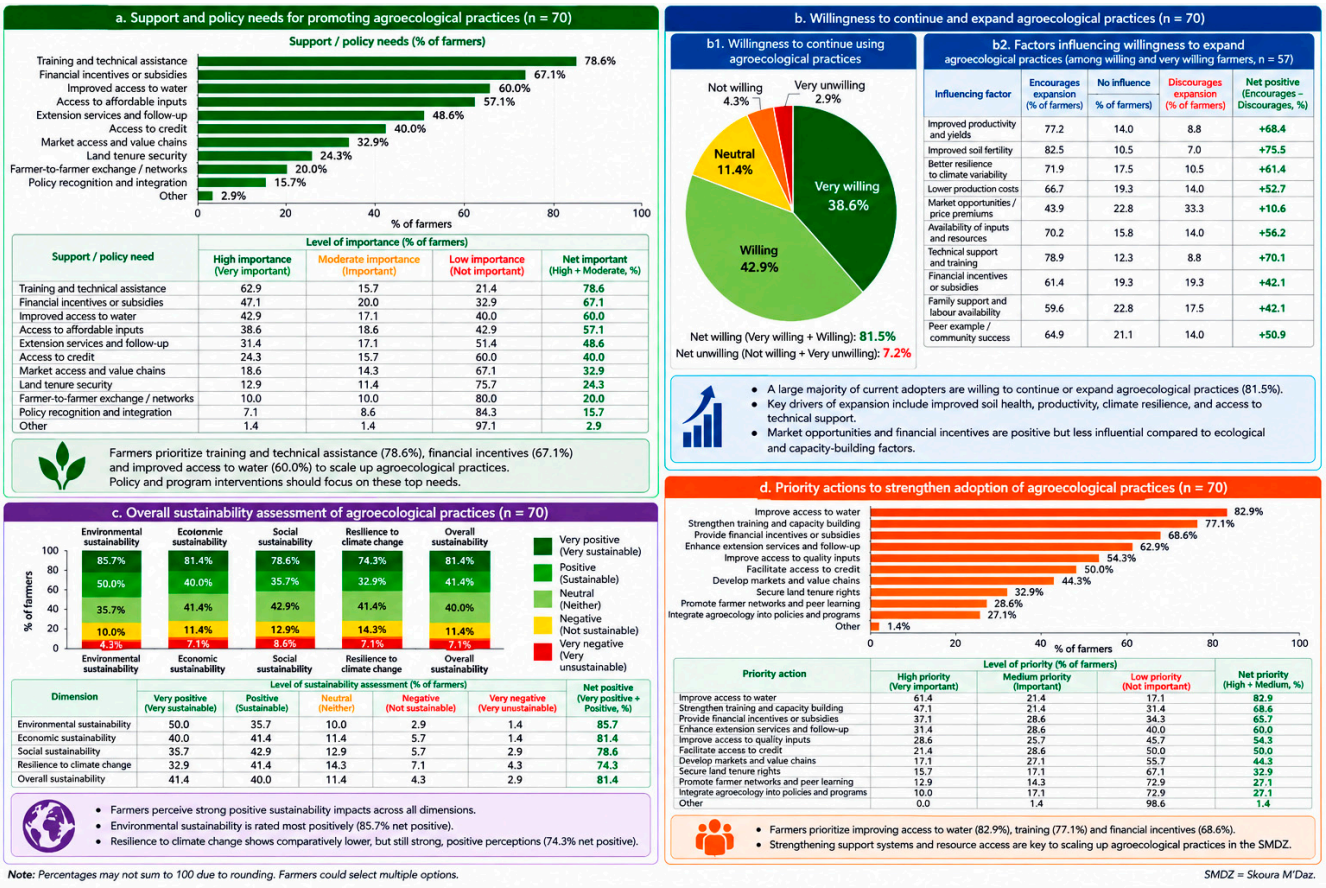
3.8. Willingness to Continue and Expand Agroecological Practices

One of the most important findings emerging from this study is the remarkably strong willingness of farmers to maintain and further expand agroecological practices despite the multiple structural and institutional constraints identified previously. As illustrated in Figure 8(b1), more than four-fifths of farmers surveyed (81.5%) declared themselves either willing or very willing to continue and expand agroecological management strategies, whereas only 7.2% expressed unwillingness. This result highlights the high degree of local social legitimacy already associated with agroecological systems within the semi-arid mountain agroecosystems of SMDZ. Rather than being perceived as marginal or obsolete traditional practices, agroecological approaches appear increasingly recognized as credible adaptive pathways capable of improving resilience under growing hydro-climatic uncertainty.

The factors motivating this willingness further reinforce the adaptive and multifunctional nature of agroecological systems. As shown in Figure 8(b2) and detailed in Table S4, the strongest positive drivers encouraging agroecological expansion were improved soil fertility and land health (+75.5%), technical support and training (+70.1%), and improved productivity and yields (+68.4%). Better resilience to climate variability also displayed a strong positive influence (+61.4%), followed by improved availability of inputs and resources (+56.2%) and reduced production costs (+52.7%). Interestingly, peer/community success (+50.9%) also played a substantial role, indicating the importance of territorial learning dynamics and local demonstration effects in reinforcing agroecological diffusion processes.

By contrast, purely market-oriented incentives exerted comparatively weaker influence on farmers' willingness to expand agroecological practices. Market opportunities generated

the lowest positive influence (+10.6%), while financial incentives and subsidies remained only moderately influential (+42.1%) relative to ecological and agronomic motivations (Figure 8(b2)). These findings suggest that farmers' decision-making processes remain primarily structured around ecological functionality, production stability, and risk reduction rather than solely short-term market profitability. In other words, agroecological adoption in SMDZ appears driven less by economic opportunism than by the search for long-term socio-ecological stability under semi-arid conditions.



Support / policy need	Level of importance (% of farmers)			
	High importance (Very important)	Moderate importance (Important)	Low importance (Not important)	Net important (High + Moderate, %)
Training and technical assistance	62.9	15.7	21.4	78.6
Financial incentives or subsidies	47.1	20.0	32.9	67.1
Improved access to water	42.9	17.1	40.0	60.0
Access to affordable inputs	38.6	18.6	42.9	57.1
Extension services and follow-up	31.4	17.1	51.4	48.6
Access to credit	24.3	15.7	60.0	40.0
Market access and value chains	18.6	14.3	67.1	32.9
Land tenure security	12.9	11.4	75.7	24.3
Farmer-to-farmer exchange / networks	10.0	10.0	80.0	20.0
Policy recognition and integration	7.1	8.6	84.3	15.7
Other	1.4	1.4	97.1	2.9

Influencing factor	Encourages expansion (% of farmers)	No influence (% of farmers)	Discourages expansion (% of farmers)	Net positive (Encourages − Discourages, %)
Improved productivity and yields	77.2	14.0	8.8	+68.4
Improved soil fertility	82.5	10.5	7.0	+75.5
Better resilience to climate variability	71.9	17.5	10.5	+61.4
Lower production costs	66.7	19.3	14.0	+52.7
Market opportunities / price premiums	43.9	22.8	33.3	+10.6
Availability of inputs and resources	70.2	15.8	14.0	+56.2
Technical support and training	78.9	12.3	8.8	+70.1
Financial incentives or subsidies	61.4	19.3	19.3	+42.1
Family support and labour availability	59.6	22.8	17.5	+42.1
Peer example / community success	64.9	21.1	14.0	+50.9

Dimension	Level of sustainability assessment (% of farmers)					Net positive (Very positive + Positive, %)
	Very positive (Very sustainable)	Positive (Sustainable)	Neutral (Neither)	Negative (Not sustainable)	Very negative (Very unsustainable)	
Environmental sustainability	50.0	35.7	10.0	2.9	1.4	85.7
Economic sustainability	40.0	41.4	11.4	5.7	1.4	81.4
Social sustainability	35.7	42.9	12.9	5.7	2.9	78.6
Resilience to climate change	32.9	41.4	14.3	7.1	4.3	74.3
Overall sustainability	41.4	40.0	11.4	4.3	2.9	81.4

Priority action	Level of priority (% of farmers)			
	High priority (Very important)	Medium priority (Important)	Low priority (Not important)	Net priority (High + Medium, %)
Improve access to water	61.4	21.4	17.1	82.9
Strengthen training and capacity building	47.1	21.4	31.4	68.6
Provide financial incentives or subsidies	37.1	28.6	34.3	65.7
Enhance extension services and follow-up	31.4	28.6	40.0	60.0
Improve access to quality inputs	28.6	25.7	45.7	54.3
Facilitate access to credit	21.4	28.6	50.0	50.0
Develop markets and value chains	17.1	27.1	55.7	44.3
Secure land tenure rights	15.7	17.1	67.1	32.9
Promote farmer networks and peer learning	12.9	14.3	72.9	27.1
Integrate agroecology into policies and programs	10.0	17.1	72.9	27.1
Other	0.0	1.4	98.6	1.4

Figure 8. Socio-institutional conditions, sustainability perceptions, and future scaling pathways of agroecological transitions in the semi-arid mountain systems of SMDZ (n = 70). This composite figure synthesizes farmers' perceptions regarding the institutional requirements, sustainability performance, and future expansion potential of agroecological systems in the semi-arid mountain region of Skoura M'Daz (SMDZ). (**a**) The main support and policy needs identified for strengthening agroecological transitions. Training and technical assistance (78.6%), financial incentives or subsidies (67.1%), and improved access to water (60.0%) emerged as the most important enabling conditions for sustaining and scaling agroecological systems. Extension services, affordable inputs, and access to credit were also identified as critical operational requirements, whereas formal policy integration and farmer-network structures were perceived as comparatively lower priorities under current territorial constraints. (**b1**,**b2**) Farmers' willingness to continue and expand agroecological practices. (**b1**) Distribution of willingness levels toward maintaining or expanding agroecological systems; (**b2**) factors influencing the expansion of agroecological practices among willing farmers. More than 81% of respondents declared themselves willing or very willing to continue agroecological management. The strongest positive drivers included improved soil fertility and land health (+75.5%), technical support and training (+70.1%), improved productivity (+68.4%), and enhanced resilience

to climatic variability (+61.4%). Market opportunities and financial incentives exerted comparatively weaker influence, suggesting that ecological functionality and production stability remain central determinants of farmers' decision-making processes. (**c**) Overall sustainability assessment of agroecological systems across environmental, economic, social, and climate resilience dimensions. Environmental sustainability received the highest positive perception (85.7%), followed by economic sustainability and overall sustainability (81.4%). Although resilience to climate variability displayed slightly lower values (74.3%), perceptions remained strongly positive overall, confirming that agroecological systems are widely recognized as adaptive socio-ecological resilience mechanisms under semi-arid hydro-climatic conditions. (**d**) Priority actions required to strengthen agroecological adoption and territorial scaling-up. Improving access to water (82.9%), strengthening training and capacity-building systems (77.1%), and increasing financial incentives (68.6%) emerged as the dominant strategic priorities. Farmers also emphasized the importance of extension services, quality inputs, and access to credit, highlighting the central role of institutional support systems and hydro-economic governance in stabilizing long-term agroecological transitions. Collectively, the figure demonstrates that agroecological systems in SMDZ are not only socially accepted and ecologically valued, but also widely perceived as viable resilience pathways for confronting climatic uncertainty and resource scarcity. However, their future expansion depends strongly on reinforcing institutional support structures, technical assistance mechanisms, water governance, and socio-economic accessibility capable of sustaining multifunctional agroecosystems under accelerating environmental change.

Collectively, the results presented in Figure 8(b1,b2) demonstrate that local populations already possess substantial adaptive motivation and a strong willingness to sustain agroecological transition pathways. Consequently, the principal limitation to future agroecological expansion may reside less in farmers' attitudes or cultural resistance than in the broader institutional, technical, and hydro-economic conditions governing access to resources, training, infrastructure, and public support mechanisms.

3.9. Overall Sustainability Perceptions and Priority Actions

Farmers' overall assessments indicated broadly positive perceptions of agroecological practices across environmental, economic, social, and climate-related dimensions. As shown in Figure 8c, environmental sustainability received the highest net positive evaluation (85.7%), followed by economic sustainability and overall sustainability, both at 81.4%. Social sustainability was also evaluated positively by a large majority of respondents (78.6%) (Table S5). Perceived contribution to climate resilience received a slightly lower, though still predominantly positive, evaluation (74.3%). These results reflect farmers' perceptions of the sustainability-related benefits associated with agroecological management and should not be interpreted as direct evidence of environmental performance, economic viability, social sustainability, or resilience to climate change.

The distribution of responses presented in Figure 8c further shows that most respondents rated agroecological practices as either positive or very positive across all assessed dimensions. Environmental sustainability recorded the highest proportion of "very positive" responses (50.0%), indicating that farmers strongly associate agroecological management with environmental benefits. However, because soil conservation, water regulation, biodiversity, and ecosystem functioning were not directly quantified in this analysis, these responses should be understood as farmer-reported evaluations rather than measured ecological outcomes.

Economic sustainability was also perceived favourably, suggesting that respondents generally did not view agroecological management as economically disadvantageous. Instead, many farmers associated it with potentially useful economic attributes, including lower dependence on purchased inputs and greater production stability. Nevertheless, these perceptions were not supported by direct measurements of farm profitability, gross

margins, production costs, or income variability, and the results should therefore be interpreted cautiously.

The comparatively lower positive evaluation of climate resilience (74.3%) may reflect the continued importance of recurrent drought, water scarcity, and climatic variability in the study area. Although respondents generally perceived agroecological practices as relevant to coping with these pressures, the survey did not directly measure the capacity of farms to maintain or recover production, income, or ecological functions during climatic disturbances. Accordingly, the findings document perceived resilience-related benefits rather than demonstrated resilience outcomes.

Farmers also identified a clear set of priorities for strengthening agroecological management in SMDZ. As illustrated in Figure 8d, improving access to water was the most frequently identified priority (82.9%), followed by training and capacity building (77.1%), financial incentives or subsidies (68.6%), and improved extension services and technical follow-up (62.9%). Access to quality inputs (54.3%) and credit (50.0%) were also considered important, whereas market development, land tenure security, and farmer networking structures received comparatively lower levels of priority.

Taken together, these responses suggest that the continued development of agroecological management in SMDZ depends not only on the practices already adopted at farm level, but also on the broader institutional, financial, technical, and water management conditions in which farmers operate. The findings should therefore not be interpreted as demonstrating that agroecological systems are already ecologically validated or inherently resilient. Rather, they indicate a high level of farmer acceptance and identify the support mechanisms considered most important for maintaining and expanding agroecological practices under semi-arid conditions.

Future interventions may therefore benefit from prioritizing water access, technical assistance, farmer training, financial support, and extension services while evaluating their effects through independent agronomic, ecological, and socio-economic indicators. Such an approach would allow future research to determine whether the positive perceptions reported by farmers translate into measurable improvements in sustainability and resilience-related outcomes over time.

4. Discussion

4.1. Traditional Mountain Farming as an Integrated Agroecological Configuration

Traditional mountain farming systems are sometimes portrayed as residual forms of agriculture characterized by low productivity, limited technological development, and weak adaptive capacity. The findings from SMDZ provide a more nuanced picture. Across the surveyed farms, the mean Agroecological Practice Intensity Index (AEPI) was 3.94 out of 6, corresponding to 65.7% of the maximum possible score. This level of practice integration was observed despite fragmented landholdings, limited mechanization, relatively low levels of formal education, and substantial hydro-climatic constraints. This pattern provides quantitative evidence that multiple agroecological practices are integrated within the surveyed farming systems. In particular, the relatively widespread adoption of organic or mixed fertilization, crop rotation, agroforestry, livestock integration, and traditional irrigation is consistent with agroecological principles related to recycling, input reduction, biodiversity, synergies, co-creation of knowledge, and natural-resource governance described in the literature [4,11].

These findings should nevertheless be interpreted within the scope of the variables directly examined in this study. The empirical evidence concerns the presence and joint adoption of agroecological practices, AEPI and IIS values, farmer perceptions, management configurations, and statistical associations observed among the surveyed farms. Resilience,

adaptive capacity, ecological buffering, and long-term system stability were not directly measured. References to these broader concepts therefore reflect possible interpretations of management characteristics commonly discussed in agroecological and socio-ecological literature rather than demonstrated resilience outcomes.

The AEPI contributes to this analysis by moving beyond a simple inventory of individual practices and providing a standardized measure of the extent to which several agroecological practices are integrated within the same farming system. This distinction is relevant because farm-level assessments may document the prevalence of individual practices without necessarily considering their simultaneous adoption. In SMDZ, the descriptive co-occurrence analysis showed that agroforestry, crop rotation, organic or mixed fertilization, traditional irrigation, and other practices were frequently implemented within the same farms. These co-occurrence patterns indicate diversified management portfolios, but they should not be interpreted as statistical evidence of dependence, functional interactions, ecological synergies, or causal relationships among practices.

From an agroecological perspective, the simultaneous presence of different practices is nevertheless informative because these practices address distinct aspects of farm management, including nutrient cycling, crop diversification, water management, biomass use, and crop–livestock integration. Their joint adoption therefore indicates a broader integration of agroecological practices that would be captured by considering each practice separately. However, the present study does not demonstrate that these combinations improve soil functioning, biodiversity conservation, water regulation, production stability, or the capacity of farms to withstand climatic disturbances.

The management configurations observed in SMDZ may therefore be considered to include characteristics that are potentially relevant to resilience, rather than being interpreted as evidence of resilience itself. Diversification, resource cycling, crop–livestock integration, and reduced reliance on selected external inputs are frequently discussed in agroecological and socio-ecological research as attributes that may contribute to adaptive capacity. In the present study, however, these characteristics were documented as management features rather than measured resilience outcomes. Establishing whether farms with greater agroecological practice integration maintain ecological functions, agricultural production, or household livelihoods more effectively during droughts or other disturbances will require longitudinal studies combining direct biophysical, agronomic, and socio-economic measurements.

4.2. Territorial Embeddedness Matters More than Expected

The territorial pattern observed in SMDZ suggests that agroecological practice integration is associated not only with farm-level management choices but also with the broader context in which those choices are made. Rural farms displayed higher meaning AEPI values than urban or peri-urban farms, and rural location remained positively associated with AEPI in the multivariable analysis. However, this relationship should be interpreted cautiously. Rural location was used as a contextual variable and does not constitute a direct measure of territorial embeddedness. The observed association may therefore reflect a combination of demographic, institutional, social, and management characteristics that tend to differ across territorial settings.

This interpretation is consistent with the view that agroecology is not simply a collection of technical practices, but a context-dependent form of agricultural management shaped by local ecological conditions, knowledge systems, social organization, and access to resources. In rural settings, the persistence of collective water management arrangements, intergenerational knowledge transmission, locally adapted farming practices, and long-term interaction with the landscape may help explain why multiple agroecological

practices continue to be implemented together. Nevertheless, these mechanisms were not directly quantified in the present study and should therefore be regarded as plausible contextual explanations rather than demonstrated causal pathways.

The result is relevant to sustainability science because agricultural transition strategies are often designed around technologies that can be transferred across locations, whereas agroecological management is inherently dependent on local ecological and socio-institutional conditions. Agroecological principles therefore need to be adapted to specific territorial contexts rather than implemented as uniform technological packages [1,11]. In this sense, the positive association between rural location and the AEPI is consistent with the broader argument that place-based knowledge, institutions, and resource management arrangements may influence the persistence and integration of agroecological practices.

At the same time, the present data does not demonstrate that territorial embeddedness itself enhances resilience. Resilience, adaptive capacity, and long-term system stability were not directly measured, and the rural–urban/peri-urban contrast should not be interpreted as evidence that rural farms are inherently more resilient. Instead, the findings support the more limited conclusion that rural location was positively associated with agroecological practice integration within the surveyed SMDZ farms. Future research should directly measure dimensions of territorial embeddedness, including social networks, knowledge transmission, collective governance, market access, and resource management institutions, and test whether these factors are associated with independently measured biophysical, economic, and resilience outcomes over time.

4.3. External-Input Dependence and Agroecological Practice Integration

The relationship between agroecological practice integration and external-input intensity represents an important dimension of the management heterogeneity observed in SMDZ. In the primary analyses, farms characterized by greater reliance on the selected external-input and technology-mediated practices tended, on average, to exhibit lower AEPI values. However, this relationship requires careful interpretation. The cross-sectional design does not establish that technological adoption or external-input use causes a reduction in agroecological practice integration, and the IIS should not be interpreted as an inverse sustainability indicator. Rather, it describes reliance on a selected set of management practices—including chemical inputs, mineral-only fertilization, mechanized labour, and drip irrigation—that may have different agronomic and environmental implications depending on their context of use.

An additional methodological consideration is the partial structural overlap between AEPI and IIS. The leave-one-component-out analysis showed that the negative correlation was strongly attenuated when components that are conceptually inverse across the two indices were removed from AEPI. Most notably, removing the "absence of chemical inputs" component reduced the AEPI–IIS correlation from $\rho = -0.252$ to $\rho = -0.016$ ($p = 0.896$), while removing organic/mixed fertilization attenuated it to $\rho = -0.222$ ($p = 0.065$) (Table S6). Thus, the baseline negative correlation cannot be regarded as independent evidence that greater external-input intensity displaces agroecological practices. Instead, it partly reflects the way the two composite indicators were constructed.

The multivariable analyses nevertheless provide useful information about how these management dimensions covary within the surveyed farms. IIS was negatively associated with AEPI in the primary model after adjustment for location, topography, age, farm size, and professional organization membership ($\beta = -0.346$, $p = 0.0251$; Table 4). When formal education was additionally included, the coefficient remained negative but was attenuated to -0.303 and became borderline at the conventional significance threshold ($p = 0.0507$; Table S7). The modest explanatory capacity of these models further indicates that AEPI

variation cannot be attributed to input intensity alone and likely reflects multiple farm-level, territorial, institutional, and management characteristics that are only partially represented in the available dataset.

These findings support a nuanced interpretation of the relationship between agroecology and technological innovation rather than treating them as mutually exclusive development pathways. Technologies such as mechanization, drip irrigation, decision-support tools, and other agricultural innovations may help address labour, water, productivity, or management constraints when appropriately adapted to local conditions. However, the present study did not evaluate the ecological or economic effects of individual technologies and therefore cannot determine whether specific innovations complement, reinforce, or constrain agroecological processes. Instead, the observed patterns document heterogeneity in the ways agroecological practices and technology-mediated management are combined across SMDZ farms.

This distinction is particularly relevant to debates on agricultural modernization in semi-arid smallholder systems. Rather than framing agricultural development in terms of greater or lesser technological intensity, a more pertinent question concerns the conditions under which technological innovation can be integrated with diversified ecological management and locally adapted farming strategies. Addressing this question requires evidence beyond the present cross-sectional survey, including longitudinal observations, biophysical measurements, farm-level economic assessments, and explicit evaluation of individual technologies. The SMDZ findings therefore provide an empirical basis for developing and testing hypotheses about different pathways of agricultural transition, rather than demonstrating a causal opposition between external-input use and agroecological management.

This perspective also connects with broader sustainability debates concerning the capacity of agricultural systems to operate within planetary environmental limits. Global environmental pressures are associated with multiple interacting processes, including land use change, biodiversity loss, freshwater alteration, and disruptions of biogeochemical cycles. Richardson et al. [13] reported that six of the nine planetary boundaries had been transgressed, including boundaries related to biosphere integrity, freshwater change, and biogeochemical flows. Within this broader context, the SMDZ case illustrates the relevance of examining how technological innovation and ecological diversification coexist within farming systems. The present results do not establish that combinations produce greater sustainability or resilience; rather, they highlight the need for future research to determine which combinations of ecological practices, technological innovations, and locally adapted management strategies can support sustainable agricultural transitions under increasing climatic and environmental pressures.

4.4. Agroecological Custodians: Not Marginal Farmers, but Strategic Actors

The AEPI–IIS typology identified four descriptive management configurations among the surveyed farms: Agroecological Custodians, Hybrid Agroecological Intensifiers, Input-Dependent Systems, and Low-Intensity Traditional Systems. Agroecological Custodians represented the largest group and were characterized by higher-category AEPI values, lower-category input intensity, and the highest mean AITI. Rather than indicating superior ecological performance or resilience, this configuration reflects the simultaneous integration of several agroecological practices with relatively limited reliance on the external-input and technology-mediated practices included in the IIS. These farms therefore illustrate the persistence of diversified, relatively low-input management strategies within the contemporary SMDZ farming landscape.

The other configurations further emphasize that agroecological management cannot be reduced to a simple distinction between "traditional" and "modern" agriculture. Low-Intensity Traditional Systems combined relatively low input intensity with lower agroecological practice integration, indicating that limited reliance on external inputs does not necessarily coincide with a highly diversified agroecological management portfolio. Conversely, Hybrid Agroecological Intensifiers combined higher-category AEPI with higher-category IIS, showing that the adoption of technology-mediated or external-input practices can coexist with substantial agroecological practice integration. This configuration is particularly relevant because it cautions against treating technological innovation and agroecology as mutually exclusive pathways.

Input-Dependent Systems occupied a different position within the AEPI–IIS space, combining lower-category AEPI with higher-category IIS. However, this configuration should not be interpreted as intrinsically vulnerable or environmentally inferior. Neither ecological vulnerability nor exposure to economic or climatic shocks was directly measured in this study. Similarly, the typology does not establish that increasing external-input intensity causes the displacement of agroecological practices. As demonstrated by the sensitivity analyses, part of the inverse relationship between AEPI and IIS reflects structural overlap in the construction of the two indices. The four categories should therefore be understood as descriptive positions within a two-dimensional management space rather than as distinct sustainability or resilience trajectories.

From this perspective, the typology contributes to a more differentiated understanding of agricultural transition in semi-arid smallholder systems. The observed configurations suggest that farms can combine agroecological practices and technology-mediated management in several ways, rather than following a single transition from "traditional" to "modern" agriculture. This heterogeneity is important because it shifts attention from predefined development pathways toward the specific combinations of practices, technologies, resources, and locally adapted management strategies present within individual farming systems.

Whether these different configurations ultimately differ in ecological functioning, economic performance, adaptive capacity, or resilience remains an open empirical question. The present cross-sectional analysis cannot determine whether farms classified as Agroecological Custodians maintain yields, soil functions, water availability, or household livelihoods more effectively during climatic disturbances than farms belonging to the other configurations. Testing these relationships will require independent validation of the AEPI, IIS, AITI, and associated typology against longitudinal biophysical and socio-economic indicators. The categories identified here should therefore be regarded as a reproducible framework for generating and testing hypotheses about agricultural transition, rather than as externally validated classifications of farm sustainability or resilience.

4.5. Farmers' Perceptions of Multifunctionality and Management Priorities

Farmers' responses revealed broadly positive perceptions of the multiple benefits associated with agroecological practices. Improvements in soil fertility, crop yield stability, water availability, production costs, and responses to drought were among the benefits most frequently reported by respondents. These perceptions indicate that farmers primarily associate agroecological practices with tangible agronomic and livelihood-related benefits. They provide valuable insight into how farmers evaluate agroecological management under the environmental and socio-economic conditions of SMDZ. However, these responses represent farmer-reported perceptions rather than independently measured changes in soil properties, water use efficiency, production stability, economic performance, or resilience. They should therefore be interpreted as evidence of the benefits that farmers associate

with agroecological practices, rather than as direct evidence of their biophysical or socio-economic effectiveness.

The pattern of responses also helps identify which dimensions of agroecology are most relevant from the farmers' perspective. Respondents placed particular emphasis on outcomes closely related to everyday farm management under semi-arid conditions, especially soil fertility, water availability, yield stability, and production costs. This suggests that farmers perceive the relevance of agroecological practices not only in environmental terms, but also in relation to practical agronomic and livelihood concerns. This farmer-centred perspective is consistent with the FAO framing of agroecology as an integrated approach that applies ecological and social principles to food and agricultural systems, as well as with the HLPE perspective [4,6], which emphasizes the potential contribution of agroecological approaches to food security and nutrition through diversity, resilience-related processes, and reduced dependence on external resources.

These perceptions also have implications for how agroecological transitions are communicated and supported. Previous studies have shown that the adoption and continued use of agroecological practices are influenced by the extent to which environmental objectives are connected to tangible agronomic, economic, and livelihood considerations [22–25]. In SMDZ, the importance attributed to soil fertility, water availability, yield stability, and production costs suggests that policies and extension strategies may be more meaningful to farmers when broader environmental objectives are linked to the management challenges they experience directly. This does not imply that the practices necessarily produce the reported outcomes; rather, it shows that farmers perceive these dimensions as important benefits associated with agroecological management.

Biodiversity conservation and household income received comparatively lower evaluations than benefits related to soil, water, and production. This variation indicates that farmers do not assign the same importance to all dimensions commonly associated with agroecological multifunctionality. Under the semi-arid conditions of SMDZ, benefits that are closely connected to immediate resource management and agricultural production appear to be more salient in farmers' assessments than outcomes that may be less directly observable or may emerge over longer time horizons. These differences should not be interpreted as evidence that biodiversity conservation or household income are unimportant, but rather reflecting the relative priorities expressed by respondents within the specific context of the study.

From a policy perspective, these findings highlight the importance of aligning agroecological interventions with locally expressed priorities while avoiding assumptions about benefits that have not been independently demonstrated. Measures addressing soil management, water constraints, technical assistance, production stability, and farm-level economic concerns may provide practical entry points for supporting the continued adoption and development of agroecological practices. Such interventions should nevertheless be evaluated using independent indicators to determine whether the benefits perceived by farmers translate into measurable outcomes.

Future research should therefore complement perception-based evidence with direct biophysical, agronomic, and socio-economic measurements. Indicators of soil quality, water use performance, biodiversity, yield level and stability, production costs, household income, and responses to climatic disturbances would provide an independent basis for assessing the outcomes associated with different management configurations. Such validation is necessary to determine whether the multifunctional benefits perceived by farmers correspond to measurable sustainability and resilience-related outcomes over time.

4.6. The Transition Trap: Strong Agroecology, Weak Institutional Support

The barriers reported by farmers reveal a major paradox: the systems with the strongest ecological coherence are often the least institutionally supported. Limited access to water, high input and technology costs, lack of technical knowledge, labour constraints and weak extension services emerged as major barriers. This confirms that the main constraint is not a lack of agroecological potential, but a lack of institutional architecture capable of sustaining it.

This is where the Moroccan case becomes highly instructive. North Africa and the Mediterranean are expected to face increasing water scarcity, declining soil moisture and reduced groundwater recharge under climate change [26–33].

In such a context, agroecological systems may be more necessary than ever, but also harder to maintain because drought, outmigration and financial fragility erode implementation capacity. This is the core of the hydro-agroecological transition trap: the need for agroecology rises precisely when the capacity to sustain it declines.

The policy needs identified by farmers confirms this interpretation. Training, technical assistance, financial incentives, improved water access, affordable inputs and extension services were prioritized. Farmers are not asking to abandon agroecology; they are asking for the institutional conditions to make it viable. This is a decisive policy message. Agroecological transition in SMDZ is not blocked by cultural resistance. It is blocked by underinvestment.

4.7. Mediterranean Implications: Modernization Must Be Redefined

The SMDZ results offer a broader lesson for Mediterranean agriculture. The Mediterranean Basin is increasingly exposed to drought, heat stress, scarcity and ecosystem degradation.

Under such conditions, highly specialized systems dependent on groundwater, synthetic inputs and energy-intensive technologies may become increasingly fragile. Traditional mountain systems, by contrast, evolved historically under variability, scarcity and topographic constraints. Terraces, agroforestry, gravity irrigation and crop–livestock integration were not signs of underdevelopment; they were adaptive technologies of another kind [34–36].

This does not mean that Mediterranean agriculture should return nostalgically to the past. That would be scientifically naïve. Many traditional systems are labour-intensive, economically vulnerable and threatened by youth outmigration. The real challenge is selective hybridization: protecting the ecological intelligence of traditional systems while integrating appropriate innovations that reinforce rather than replace local resilience mechanisms.

This argument is controversial because it challenges the implicit hierarchy in which modernity is always assumed to be superior to tradition. The SMDZ case suggests the opposite may sometimes be true: some traditional systems may be more resilient than modern systems precisely because they are diversified, redundant, locally governed and less dependent on external flows. In an unstable climate, redundancy is not inefficiency; it is insurance.

4.8. Conceptual Contribution: From Efficiency Metrics to Integrated Management Metrics

A broader conceptual contribution of this study lies in complementing conventional performance-based assessments with an explicit characterization of how management practices are combined within farming systems. Agricultural sustainability assessments commonly rely on indicators such as yield, input use efficiency, carbon balance, or water productivity. These measures remain essential for evaluating farm performance, but they do not fully describe the diversity of management strategies through which farmers

combine ecological practices, external inputs, and technology-mediated interventions under environmental and socio-economic uncertainty. Examining these combinations provides an additional perspective on the organization and heterogeneity of farming systems.

Within this framework, the AEPI, IIS, and AITI serve as complementary descriptors of farm management rather than as direct measures of sustainability, ecological performance, or resilience. The AEPI summarizes the extent to which the selected agroecological practices are integrated within individual farms, whereas the IIS characterizes reliance on selected external-input and technology-mediated practices. The AITI describes the relative position of these two normalized management dimensions. None of these indices directly measure ecological functioning, resource use efficiency, adaptive capacity, vulnerability, or resilience. Their contribution is therefore primarily analytical: they provide a transparent and reproducible framework for characterizing management heterogeneity and examining how agroecological practices and technology-mediated management coexist within farming systems.

This distinction is particularly important when considering resilience-related interpretations. Farm performance under observed conditions and the capacity to respond to disturbance are related but conceptually different properties. Indicators such as yield, water productivity, and input use efficiency can provide direct information on aspects of farm performance, whereas resilience involves the capacity of a system to maintain, adapt, or recover its functions when exposed to disturbances. Evaluating such capacity requires observations of system responses through time or during actual shocks. Because the present study is cross-sectional, it cannot determine whether farms with higher AEPI values, lower IIS values, or particular AEPI–IIS configurations maintain production, ecological functions, or livelihoods more effectively during droughts, market disruptions, labour shortages, or other disturbances.

Nevertheless, several management characteristics documented in SMDZ are relevant to future research on adaptation and resilience. Diversification, resource cycling, crop–livestock integration, locally adapted resource management, and reduced reliance on selected external inputs are frequently discussed in agroecological and socio-ecological research as attributes that may contribute to adaptive capacity. The present study shows that several of these characteristics coexist within the surveyed farming systems, but it does not establish that their presence results in greater resilience. Similarly, the observed territorial differences in the AEPI provide a basis for investigating the possible roles of place-based knowledge, institutions, social organization, and resource management arrangements, but territorial embeddedness itself was not directly quantified as a resilience mechanism.

The conceptual value of the proposed framework therefore lies in complementing conventional performance indicators with an explicit characterization of farm management configurations. The AEPI, IIS, and AITI may serve as explanatory or stratification variables in future studies in which ecological, agronomic, economic, and resilience-related outcomes are measured independently. Such an approach would make it possible to test whether particular management configurations are associated with differences in yield stability, soil functioning, water availability, household income stability, or other independently measured system properties during climatic or socio-economic disturbances.

Future research should therefore evaluate the proposed indices against independent biophysical, agronomic, and socio-economic indicators and across a broader range of farming contexts. Longitudinal and multi-site studies could test whether the management configurations identified here are associated with measurable differences in soil organic carbon, infiltration capacity, biodiversity, water use performance, interannual yield variability, production costs, income stability, and responses to climatic disturbances. Such independent validation is necessary before the AEPI, IIS, or AITI can be empirically asso-

ciated with sustainability or resilience-related outcomes. Accordingly, the SMDZ study should be viewed as providing a framework for characterizing management configurations and generating testable hypotheses for future research, rather than as providing a direct measurement or validation of resilience.

4.9. Limitations, External Validity, and Future Research

Several limitations should be considered when interpreting the findings of this study. First, the analysis is based on 70 farms from a single semi-arid mountain farming system. Although the sample captures substantial heterogeneity in farm structure and management within SMDZ, it cannot be assumed to represent the diversity of farming systems found across Morocco or in other Mediterranean, mountain, oasis, or semi-arid regions. The findings should therefore be interpreted as context-specific evidence from SMDZ rather than as estimates that can be generalized directly to broader agricultural populations. Comparative studies involving larger samples and multiple agroecological and socio-economic contexts will be necessary to determine the extent to which the patterns observed here are transferable beyond the study area.

This limitation is particularly relevant to the interpretation of the AEPI, IIS, AITI, and the associated farming system typology. These indicators were developed as analytical tools for characterizing management configurations within the present dataset and should not be regarded as externally validated measures of sustainability, ecological performance, vulnerability, or resilience. The leave-one-component-out analysis provides information on the internal robustness of AEPI rankings and on the sensitivity of the AEPI–IIS relationship to index construction, but it does not constitute external validation of the index. Similarly, the operational thresholds used to construct the four AEPI–IIS management configurations provide a transparent and reproducible classification within the present study, but their relevance in other farming systems remains to be established independently.

A second limitation concerns the binary structure of the AEPI and IIS components. Binary indicators provide a simple and reproducible representation of whether selected practices are present or absent, but they do not capture variation in implementation intensity, spatial extent, duration, management quality, or ecological effectiveness. Two farms may therefore receive the same AEPI score while differing substantially in the proportion of land under agroforestry, the frequency and complexity of crop rotations, the quantity and origin of organic amendments, or the degree of crop–livestock integration. Future refinements could incorporate such dimensions, provided that additional complexity improves explanatory or predictive performance without compromising transparency and reproducibility.

Third, the cross-sectional and observational design limits both causal inference and resilience-related interpretation. The statistical relationships identified in this study represent associations observed at a single period and cannot establish whether particular management practices or configurations produce specific ecological, agronomic, or socio-economic outcomes. In particular, higher AEPI values cannot be interpreted as evidence that farms maintain yields, soil functions, water availability, household income, or other system properties more effectively during droughts or other disturbances. Demonstrating resilience would require longitudinal observations of system performance before, during, and after climatic, economic, or other shocks.

External validation of the proposed indices should therefore be a priority for future research. AEPI, IIS, and AITI should be evaluated against independent biophysical, agronomic, hydrological, and socio-economic indicators rather than validated against variables that contribute directly to their construction. Relevant biophysical indicators could include soil organic carbon, aggregate stability, infiltration capacity, soil moisture dynamics,

vegetation or crop diversity, and water use efficiency. Agronomic validation could incorporate yield levels, interannual yield variability, crop failure frequency, and recovery following drought. Socio-economic validation could examine production costs, gross margins, household income stability, labour requirements, market dependence, and livelihood diversification. Such analyses would allow researchers to determine whether the management configurations described by the indices are actually associated with independently measured sustainability or resilience-related outcomes.

Longitudinal and multi-site research would be particularly valuable for this purpose. Repeated observations across contrasting climatic years could test whether farms occupying different positions in the AEPI–IIS space differ in their capacity to maintain or recover production and ecological functions during disturbances. Expanding the framework to other Moroccan mountain, oasis, and semi-arid farming systems, and subsequently to comparable Mediterranean environments, would also allow for an assessment of convergent, predictive, and external validity. Remote sensing and participatory monitoring could complement farm-level measurements by linking management configurations with changes in vegetation dynamics, land cover, water availability, and other landscape-scale processes. Such approaches would provide a stronger empirical basis for determining whether the indices developed here have explanatory value beyond the SMDZ case study.

The sampling structure introduces an additional limitation. Although the original survey covered farms distributed across 22 villages, the anonymized analytical dataset did not retain sufficiently standardized village identifiers to reconstruct all village-level clusters unambiguously. Village-level dependence could therefore not be explicitly incorporated into the inferential models. As a result, some residual correlation among farms originating from the same villages may remain, potentially affecting the estimated statistical uncertainty. Future surveys should preserve standardized cluster identifiers from data collection through analysis and, where sample size permits, apply multilevel models or appropriate cluster-robust inference to distinguish farm-level from village-level variability.

The multivariable model also explained only a modest proportion of the observed variation in AEPI (R^2 = 0.235; adjusted R^2 = 0.149). The estimated coefficients should therefore be interpreted as partial associations rather than as a comprehensive explanation of agroecological practice integration. A substantial proportion of between-farm heterogeneity is likely to reflect factors not fully represented in the present model, including household characteristics, economic conditions, institutional arrangements, resource access, local knowledge, social networks, and spatial context.

Relatedly, information on off-farm income and precise distance to input and output markets was not systematically available. These variables could plausibly influence both farm location and management decisions, and their absence prevented complete adjustment for potential socio-economic and market access confounding. Residual confounding of the observed rural–urban/peri-urban association therefore cannot be excluded. Future studies should incorporate more detailed household economic, market access, institutional, and spatial variables to determine whether the territorial pattern observed in SMDZ persists after broader adjustment.

Taking together, these limitations define the appropriate scope of inference from the present study. The results provide a detailed characterization of agroecological practice integration and management heterogeneity within SMDZ, but they do not establish the ecological effectiveness, resilience, or broader geographical validity of the identified configurations. The principal next step is therefore not simply to apply the proposed indices to larger samples, but to test whether they are associated with independently measured biophysical and socio-economic outcomes across locations and through time.

4.10. Toward a Context-Sensitive Framing of Agroecological Modernization

The SMDZ case illustrates the importance of examining technological innovation, ecological diversification, local knowledge, and institutional support as potentially complementary dimensions of agricultural transition. Given the context-specific and cross-sectional nature of the present evidence, these findings should not be generalized as a demonstrated model for Mediterranean agriculture. Instead, they provide hypotheses that can be tested through comparative and longitudinal research across contrasting semi-arid farming systems.

The management configurations observed in SMDZ further suggest that agricultural modernization should not necessarily be framed as a choice between traditional ecological practices and technological innovation. Agroecological practices, external inputs, and technology-mediated management occurred in different combinations across the surveyed farms, highlighting the heterogeneity of management strategies within the study area. This diversity supports a context-sensitive interpretation of agricultural transition, in which the relevance of particular practices and technologies depends on local environmental conditions, farm resources, knowledge systems, institutional arrangements, and farmers' priorities.

From this perspective, technological innovation and agroecological management should not be regarded as inherently opposing pathways. Technologies related to water management, information, mechanization, and other aspects of farm management may complement agroecological practices when they address locally identified constraints. At the same time, the present results do not demonstrate that greater technological or external-input intensity either improves or reduces sustainability. The consequences of different combinations of practices and technologies need to be evaluated independently using agronomic, ecological, economic, and social indicators.

The findings also point to the potential relevance of territorial context for understanding differences in agroecological practice integration. Rural location was positively associated with the AEPI in the present analyses, but rural location is not equivalent to territorial embeddedness, and territorial embeddedness itself was not directly quantified. The observed association should therefore not be interpreted as evidence that place-based characteristics necessarily enhance adaptive capacity or resilience. Future studies could examine more directly how local knowledge, collective resource governance, farmer organizations, market access, institutional support, and technological innovation interact in shaping farm management decisions and their outcomes.

The broader relevance of the SMDZ case therefore lies in the questions it raises rather than in its direct generalizability. The present findings document heterogeneous combinations of agroecological and technology-mediated management within one semi-arid mountain farming system, but they do not establish that these configurations will occur, or produce comparable outcomes, in other contexts. Comparative studies across different Moroccan and Mediterranean semi-arid farming systems would be valuable for assessing the transferability of the observed patterns.

Longitudinal research would also be needed to determine whether particular management configurations are associated with measurable differences in ecological functioning, production stability, household livelihoods, or responses to climatic disturbances. Combining such studies with independent biophysical, agronomic, and socio-economic indicators would provide a stronger empirical basis for identifying which combinations of agroecological practices, technological innovation, local knowledge, and institutional support can contribute to sustainable agricultural transitions under increasing environmental uncertainty.

5. Conclusions

This study provides an empirical characterization of agroecological practice integration and management heterogeneity among smallholder farms in the semi-arid mountain agroecosystem of Skoura M'Daz, Morocco. The surveyed farms frequently combined multiple practices commonly associated with agroecological management, including agroforestry, crop rotation, organic or mixed fertilization, crop–livestock integration, and reduced chemical-input use. The mean AEPI of 3.94 out of a maximum possible score of 6 indicates that agroecological practices were commonly implemented in combination rather than exclusively as isolated management options. This finding documents substantial agroecological practice integration within the surveyed farming systems but should not be interpreted as a direct measure of ecological performance, adaptive capacity, or resilience.

The analytical framework developed in this study—combining the Agroecological Practice Intensity Index (AEPI), the Input Intensity Score (IIS), and the Agroecological–Input Integration Index (AITI)—provides a reproducible approach for describing different dimensions of farm management. Three principal patterns emerged. First, agroecological practices were frequently integrated within surveyed farms. Second, rural location was positively associated with the AEPI, although the strength of the unadjusted rural–urban/peri-urban contrast varied between statistical tests, indicating that the territorial pattern should be regarded as suggestive rather than unequivocal. Third, the full AEPI was inversely associated with IIS in the primary analyses, but this relationship was sensitive to index composition and model specification. In particular, component-removal analysis demonstrated that part of the inverse AEPI–IIS relationship resulted from structural overlap between the two composite indices.

These results call for a cautious interpretation of the relationship between agroecological management and technological or external-input use. The study does not demonstrate that external inputs reduce agroecological practice integration, nor that technological innovation is intrinsically incompatible with agroecology. Because the study is cross-sectional and observational, the reported relationships represent statistical associations rather than causal effects. The farming system configurations identified in the AEPI–IIS space should similarly be understood as descriptive management profiles rather than naturally occurring, externally validated farm types or distinct resilience trajectories.

Farmers nevertheless reported multiple perceived benefits associated with agroecological practices, particularly in relation to soil fertility, crop yield stability, water availability, production costs, and drought response. These perceptions highlight the multidimensional value that respondents attribute to agroecological management. However, they constitute perceived benefits rather than direct measurements of soil functioning, water use efficiency, economic performance, or resilience. Demonstrating whether farms characterized by greater agroecological practice integration actually maintain ecological functions, production, or livelihoods more effectively under climatic stress will require longitudinal observations combined with biophysical and economic indicators.

The findings also underline the importance of institutional and resource constraints in shaping the future of agroecological management in SMDZ. Farmers identified needs related to technical assistance, financial support, water access, affordable inputs, extension services, credit, and market development. These priorities suggest that maintaining or expanding agroecological practices cannot be considered solely a farm-level technical challenge; it also depends on the institutional, economic, and resource conditions under which farmers make management decisions. Policies supporting agroecological transitions in semi-arid mountain regions may therefore benefit from combining locally adapted ecological practices with appropriate technological innovation, improved water governance,

extension support, farmer organizations, and accessible financial mechanisms rather than treating traditional knowledge and modernization as mutually exclusive alternatives.

The scope of inference should nevertheless remain centred on the surveyed SMDZ farming systems. The relatively small sample (n = 70), cross-sectional design, incomplete reconstruction of village-level clustering in the anonymized analytical dataset, and reliance on composite indicators and farmer-reported perceptions limit causal inference and broader generalization. The patterns documented here should therefore be regarded as context-specific evidence and as hypotheses for comparison with other semi-arid mountain farming systems rather than as representative of Mediterranean agriculture as a whole. Future research should test the transferability of these patterns using larger and spatially structured samples, longitudinal designs, and direct measurements of soil quality, water dynamics, yield stability, biodiversity, farm economics, and responses to climatic disturbances.

Within these limits, the SMDZ case demonstrates the analytical value of examining agroecological practice integration, external-input intensity, territorial context, and farmers' perceptions jointly rather than reducing agricultural transition to a binary opposition between "traditional" and "modern" farming. A central challenge for future research and policy is to identify management configurations in which technological innovation, ecological diversification, local knowledge, and institutional support can be combined in ways that strengthen the long-term sustainability of semi-arid smallholder farming systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18199740/s1, Table S1: Structural characteristics of surveyed farming systems in SMDZ; Table S2: Territorial differences in agroecological intensity; Table S3: Main policy and support needs identified by farmers in SMDZ; Table S4: Main factors encouraging agroecological expansion; Table S5: Farmers' overall sustainability perceptions; Table S6: Leave-one-component-out sensitivity analysis of the Agroecological Practice Intensity Index (AEPI); Table S7: Education-adjusted multivariable model of factors associated with AEPI and multicollinearity diagnostics.

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Informed Consent Statement: Participation in this study was entirely voluntary. Before completing the questionnaire, all participants received clear information regarding the objectives of the research, the nature of the questions, and the intended use of the collected data. Participants provided their informed consent electronically before accessing the survey and were informed that they could withdraw from the study at any time without any consequences. To protect participants' privacy, no personally identifiable information was collected, and all responses were treated confidentially and analyzed in an anonymous and aggregated manner.

Data Availability Statement: The anonymized farm-level dataset supporting the findings of this study and the analytical code used to reproduce the main statistical analyses are available from

the corresponding author upon reasonable request, subject to applicable confidentiality and data-protection requirements.

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