sustainability

MDPI

Article

Paradigm Shifts in Andean Agriculture: Reimagining Human–Nature Relationships Through Associated Cropping Systems in Imantag, Ecuador

Carmen Amelia Trujillo [1,*], Rocío León-Carlosama [2,*], Johanna Paulina Flores Ruano [2] and Fabio Elton Cruz Góngora [2]

[1] Graduate School, Universidad Técnica del Norte, Ibarra 10105, Ecuador
[2] Faculty of Administrative and Economic Sciences (FACAE), Universidad Técnica del Norte, Ibarra 10105, Ecuador; jpflores@utn.edu.ec (J.P.F.R.); fecruzg@utn.edu.ec (F.E.C.G.)
* Correspondence: catrujillo@utn.edu.ec (C.A.T.); rgleon@utn.edu.ec (R.L.-C.)

Abstract

Shifting climatic conditions challenge simplified, yield-oriented agriculture, particularly in fragile mountain regions. In the Ecuadorian Andes, agriculture functions as a socio-ecological system shaped by biocultural relationships integrating production, agrobiodiversity, and farmer decision-making. This study examines how climate variability interacts with crop phenology and management practices within ancestral associated cropping systems (chakras). The analysis focuses on maize, common bean, faba bean, and potato during the 2024–2025 agricultural cycle in Imantag, Ecuador. A total of 30 native, introduced, and improved varieties were sown in traditional rows (*wachos*) and monitored within a single 420.8 m^2 Andean chakra. Using multiple ordinary least squares (OLS) regression (n = 30; R^2 = 0.440, adj. R^2 = 0.351, F (4,25) = 4.914, p = 0.005), results show that maize significantly outperformed the faba bean reference group (β = 20.34, p = 0.017), while common bean showed intermediate performance (β = 15.31, p = 0.048). Seed mass at planting was positively associated with relative yield (β = 6.71, p = 0.069), highlighting early-stage management decisions. Elevated maximum temperatures during maturation negatively affected yield (r = −0.42, p = 0.020), while accumulated precipitation had a positive effect (r = +0.45, p = 0.014). Model quality criteria, including VIF diagnostics (max. VIF = 3.37), Shapiro–Wilk residual normality test (W = 0.983, p = 0.896), and cross-validation using Ridge and Lasso regression, confirm the robustness of the statistical findings. These findings demonstrate that chakras function as adaptive socioecological systems that enhance productivity, agrobiodiversity conservation, and resilience under climate variability.

Keywords: human–nature relationships; socio-ecological systems; Andean chakras; associated cropping systems; agrobiodiversity conservation; climate variability; phenological windows; sustainable agriculture; OLS regression; model quality criteria

Check for updates

Academic Editors: Ann-Marie Nienaber, Michael Elliott and Julie A. Ewald

Received: 27 April 2026
Revised: 5 June 2026
Accepted: 18 June 2026
Published: 17 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

1. Introduction

Climate variability and the increasing frequency of extreme events are exposing the ecological and social limitations of dominant agricultural paradigms grounded in simplification, monoculture, and yield maximization through synthetic inputs [1–3]. While these approaches have increased productivity under relatively stable climatic conditions, they have also accelerated biodiversity loss, degraded ecosystem services, and heightened vulnerability to climatic shocks, particularly in environmentally fragile and mountainous agroecosystems [4–7].

In the Andean region, these vulnerabilities are especially pronounced due to steep environmental gradients and deeply rooted biocultural relationships linking land, crops, and farming communities. Agricultural systems in these contexts operate as coupled human–environment systems, where ecological processes and cultural practices co-evolve under conditions of environmental variability [8,9].

In response to these challenges, sustainability science increasingly advocates for a paradigm shift that reimagines agriculture as a socio-ecological system, in which food production, biodiversity, and human practices are inseparable and co-evolve through dynamic feedback [10–13]. From this perspective, resilience is not conceived as a purely technical outcome of control and optimization, but rather as a relational property emerging from interactions between ecological processes and human decision-making [14–16]. Resilience is increasingly understood as a multidimensional concept encompassing absorptive, adaptive, and transformative capacities across scales [17,18].

Agroecological research provides growing evidence that diversified, farmer-managed systems can enhance yield stability, strengthen ecosystem services, and sustain rural livelihoods under conditions of climate variability [19–23]. These findings challenge conventional yield-centered definitions of agricultural efficiency by emphasizing functional diversity, local knowledge, and adaptive management. Meta-analytical evidence indicates that diversification enhances ecosystem services such as nutrient cycling, pest regulation, and system stability without necessarily compromising productivity [24,25].

In the Andean region, ancestral intercropping systems known as chakras exemplify this socioecological approach. Chakras are living agricultural spaces in which the simultaneous cultivation of multiple species sustains household food security and cultural identity through the accumulation of ecological knowledge [26,27]. Their management integrates traditional practices including seed selection, reciprocal stewardship of the land (Pachamama), and vertical use of the landscape—practices that have coevolved with Andean environments across generations [26–28]. The active in situ conservation of native and locally adapted genetic diversity within chakras maintains evolutionary processes and phenological diversity as key components of long-term resilience [28–30]. Previous studies highlight their role in food sovereignty, cultural resilience, and the maintenance of biocultural landscapes in indigenous territories [29–32].

In light of the above, chakras are characterized by four key traits: (1) simultaneous polyculture within a single plot, which promotes functional complementarity and reduces risk across different phenological stages; (2) management practices grounded in cultural and ecological knowledge, including traditional agricultural calendars and the principle of reciprocity with Pachamama; (3) in situ conservation of native genetic diversity, sustaining agroecosystem resilience; and (4) the formal recognition of chakra systems by the Food and Agriculture Organization of the United Nations (FAO) within the Globally Important Agricultural Heritage Systems (GIAHS), including the site “Biodiversity of the Ecuadorian Andes” in Imbabura Province [33].

This study addresses this gap by focusing on Imantag, located in Imbabura Province in northern Ecuador, within the peri-urban influence of the city of Cotacachi. This context reflects ongoing socio-ecological transitions, in which traditional agricultural systems coexist with increasing urban pressures. Beyond their productive function, associated cropping systems in peri-urban Andean regions can contribute to urban climate resilience and the strengthening of green infrastructure. However, these systems are also increasingly threatened by land-use change, urban expansion, and the erosion of intergenerational transmission of traditional knowledge.

https://doi.org/10.3390/su18147348

Despite the growing recognition of chakra systems and the formal designation of Imbabura as a GIAHS site, empirical evidence remains limited regarding the specific interactions among climate variability, crop phenology, and farmer decision-making within these systems under current climatic conditions—a critical gap in the literature that this study directly addresses.

Aligned with the objectives of the Special Issue "Paradigm Shifts: Reimagining Human–Nature Relationships for the Sustainable Conservation of Biodiversity", this study analyzes the interactions among climate variability, crop phenology, and farmer decision-making within an Andean-associated cropping system in Imantag, Ecuador. Specifically, the study addresses three research questions: (1) How does climate variability, expressed through temperature and precipitation patterns, interact with crop phenological dynamics to shape relative yield within the chakra system? (2) To what extent do farmer decisions—particularly seed mass at planting and varietal selection—influence productive outcomes across crops and varieties? (3) How does agrobiodiversity, expressed through varietal diversity and phenological asynchrony, buffer climate-related risks at the system agroecological level? By addressing these questions empirically, this study contributes novel evidence to ongoing global debates on sustainability, agrobiodiversity conservation, and agricultural transformation.

2. Theoretical Framework

2.1. Paradigm Shifts and Socio-Ecological Systems

The concept of socio-ecological systems provides a robust framework for understanding the coupled dynamics between human societies and ecological processes [8,9]. Within this perspective, sustainability emerges from interactions among ecological processes, human decision-making, and institutional structures rather than from isolated variables [10,31].

In the Anthropocene context, resilience is increasingly conceptualized as adaptive capacity in the face of variability and uncertainty [12], as well as the ability of systems to reorganize and transform through feedback processes [13,14]. Agriculture constitutes a paradigmatic socio-ecological system because productive outcomes are shaped by climatic variability, ecological processes such as crop phenology, and farmer decision-making grounded in local knowledge [21,22].

Crop diversification represents a practical application of socio-ecological principles. By combining species and varieties, diversified systems distribute climatic risk, enhance functional complementarity, and increase system stability [33,34]. Empirical evidence suggests that diversification improves yield stability and ecosystem services, although effects remain context-dependent [7,24,31]. These systems function as ecological risk management strategies, particularly in small-scale agriculture [35].

2.2. Associated Cropping Systems, Diversification, and Resilience

Associated cropping systems represent applied socio-ecological principles in agriculture. By combining multiple crop species and varieties, they distribute climatic risk, enhance functional complementarity, and contribute to system stability [9,10].

Crop diversification reduces synchronized crop failure across species and phenological stages [11]. Empirical evidence shows generally positive, though context-dependent, effects on yield stability and ecosystem services [7,12,13]. Diversification thus functions as a strategy of ecological risk management, particularly in small-scale systems where stability depends on functional diversity and redundancy [10,14].

2.3. Agrobiodiversity and Human–Nature Relationships in the Andes

Agrobiodiversity is increasingly recognized as a cornerstone of food system resilience and climate change adaptation, particularly within small-scale and traditional agricultural systems [27,36–38]. The accelerated genetic erosion of crops poses a significant threat to adaptive capacity, dietary diversity, and long-term food security, underscoring the critical importance of in situ conservation within farmer-managed systems. On-farm conservation maintains evolutionary processes, local adaptation, and phenological diversity—key components of resilience under conditions of climatic uncertainty [25,28,39].

In the Andean region, agriculture is deeply embedded in biocultural relationships that link ecological processes with culturally mediated practices [27]. Within this context, chakras can be understood as living agroecosystems in which food production, agrobiodiversity conservation, and cultural continuity are co-produced through dynamic human–nature interactions. The Food and Agriculture Organization of the United Nations (FAO) characterizes these systems as integrated socio-ecological frameworks that sustain both biodiversity and local livelihoods over time. As such, Andean-associated cropping systems provide a particularly relevant empirical lens for examining sustainability transitions grounded in reconfigured human–nature relationships.

3. Materials and Methods

3.1. Methodological Approach

This study was conducted using a socio-ecological analytical framework integrating climatic variability, crop phenology, and farmer decision-making within an Andean-associated cropping system (chakra). This approach allows productive outcomes to be interpreted as emerging from interactions between environmental conditions and local agricultural practices rather than as linear responses to isolated factors.

3.2. Study Area and Socio-Ecological Context

The research was conducted in San Luis de la Carbonería, Imantag, Imbabura Province, Ecuador, an Andean region characterized by traditional agricultural systems, high agrobiodiversity, and long-standing relationships between farming communities and their natural environment. Imantag is located at approximately 2400 m a.s.l. within the peri-urban area of the city of Cotacachi, in a zone exposed to increasing urbanization pressures.

The associated cropping systems known as chakras in this territory are formally recognized as part of the Globally Important Agricultural Heritage Systems (GIAHS). See Figure 1.

3.3. Associated Cropping System and Crop Composition

The study was conducted within an Andean-associated cropping system composed of maize (*Zea mays* L.), common bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), and potato (*Solanum tuberosum* L.), cultivated simultaneously under traditional agricultural practices.

A total of 30 native, introduced, and improved varieties were established within a single 420.8 m^2 (32 $\times$ 13.15 m) chakra plot. All varieties were sown on 8 October 2024 and arranged following a traditional associated planting structure in which different crops coexist sequentially within the same rows (*wachos*). The composition of crop species, varieties, genetic origin, and productive variables is presented in Table 1. This spatial configuration reflects the structure of the chakra system and an active process of in situ agrobiodiversity conservation. See Figure 2.

Table 1. Crop species, varieties, genetic origin, and productive performance in the Andean-associated cropping system (chakra), 2024–2025 cycle, Imantag, Ecuador.

Variety	Crop	Genetic Origin	Emerged Plants	Seed Mass (lbs)	Expected Yield (lbs)	Harvested Yield (lbs)	Relative Yield (%)
Rojo	Maize	Native	12	3.0	12	3	25.00
Misho rosado	Maize	Native	12	3.0	10	2	20.00
Mizhca	Maize	Improved	12	3.0	13	3	23.08
Blanco blandito	Maize	Improved	12	3.0	15	3	20.00
Negro chico	Maize	Native	12	3.0	12	4	33.33
Huandango	Maize	Native	12	2.0	13	3	23.08
Maíz leche	Maize	Improved	12	2.0	13	2	15.38
Misho crema	Maize	Native	12	2.0	13	2	15.38
Negro rojizo	Maize	Native	12	2.0	12	4	33.33
Racimo de uva	Maize	Native	12	2.0	10	4	40.00
Rojo tomate	Maize	Native	12	2.0	12	4	33.33
Yana vaca poroto	Common bean	Native	12	1.0	4	0	0.00
Negro largo	Common bean	Native	12	2.0	5	0	0.00
Paco bolón	Common bean	Native	12	2.0	8	3	37.50
Yana poroto	Common bean	Native	12	1.0	5	0	0.00
Sucu vaca poroto	Common bean	Native	12	3.0	7	0	0.00
Percal rayado	Common bean	Introduced	12	2.0	7	2	28.57
Popayán morado	Common bean	Native	12	1.0	6	1	16.67
Centenario	Common bean	Introduced	12	3.0	8	3	37.50
Fréjol blanco	Common bean	Native	12	2.0	8	2	25.00
Canario	Common bean	Native	12	2.0	6	2	33.33
Puka poroto	Common bean	Native	12	2.0	7	1	14.29
Matambre negro	Common bean	Introduced	12	1.0	6	0	0.00
Bola puka poroto	Common bean	Native	12	3.0	7	2	28.57
Haba verde pequeña	Faba bean	Native	12	2.0	7	0	0.00
Haba roja	Faba bean	Native	12	1.5	8	0	0.00
Haba gigante	Faba bean	Introduced	12	1.5	7	0	0.00
Papa roja	Potato	Introduced	9	3.0	21	0	0.00
Papa chaucha	Potato	Native	9	4.0	25	4	16.00
Papa única	Potato	Native	9	3.0	18	0	0.00

Note: Relative yield (%) = (harvested yield/expected yield) × 100. Each planting unit (surco/wacho): 12 maize plants, 12 common bean plants, 12 faba bean plants, 9 potato plants. Planting date: 8 October 2024. Genetic origin—Native: traditional varieties conserved by local farmers; Introduced: varieties from other regions; Improved: varieties developed through formal breeding programs.

3.4. Experimental Design and Monitoring Units

This study employed an observational participatory design conducted within a single 420.8 m^2 chakra plot. Crops were established following a repeating associated planting structure (surco or *wacho*), where maize, common bean, faba bean, and potato were arranged sequentially within each row. Each planting unit (surco) consisted of 12 maize plants, 12 common bean plants, 12 faba bean plants, and 9 potato plants. This structural configuration was repeated throughout the entire plot under traditional Andean planting conditions.

Based on this arrangement, a total of 1440 plants were established across the system. All plants were monitored throughout the agricultural cycle, and the dataset therefore represents a full-system observational analysis rather than a subsample. All varieties were managed using traditional Andean agricultural practices by local farmers, without synthetic fertilizers, herbicides, or supplemental irrigation beyond rainfall. Management decisions—including spatial arrangement, planting density, and seed selection—were based on local ecological knowledge.

https://doi.org/10.3390/su18147348

Figure 1. Location of the study area in San Luis de la Carbonería, Imantag.

Figure 2. Traditional Andean-associated cropping systems (chakra).

3.5. Phenological Monitoring and Windows

Crop development was monitored throughout the 2024–2025 agricultural cycle. Four key phenological stages were identified: emergence, vegetative growth, flowering, and maturation.

Phenological stages were determined through weekly field observations following BBCH scale criteria adapted for each crop species.

Based on these observations, phenological windows were defined for each variety, allowing alignment between crop development stages and climatic conditions. See Figure 3.

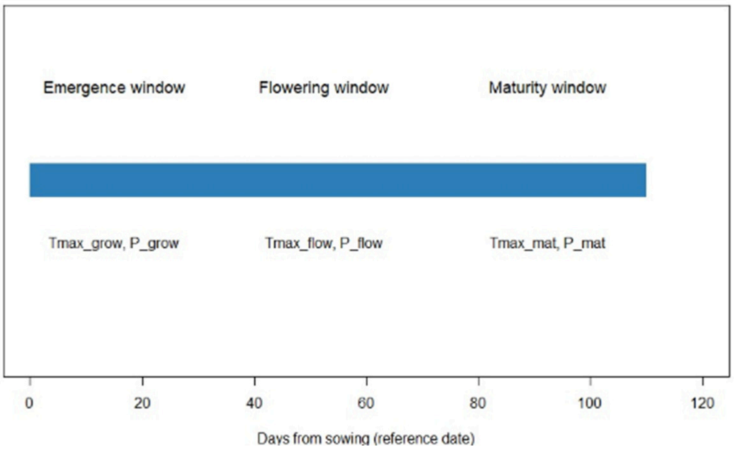

Figure 3. Phenological windows are used to align crop developmental stages with climate variability in the associated cropping systems.

3.6. Climatic Variables and Data Sources

Daily climatic data, including maximum temperature (°C) and total precipitation (mm), were obtained from the Imantag automatic meteorological station operated by the Instituto Nacional de Meteorología e Hidrología del Ecuador (INAMHI). Data quality control included outlier detection (values exceeding ±3 standard deviations from monthly means) and linear interpolation for gaps of up to three consecutive days. Maximum temperature and precipitation were selected as primary climatic variables due to their established relevance for crop performance in mountain agroecosystems. These variables are widely recognized as key drivers of crop phenology, growth, and productivity under climate variability and climate change scenarios [34–36]. Minimum and mean temperature showed inter-group variation below 0.15 °C and were excluded to avoid redundancy. Climatic variables were aligned with phenological windows to evaluate stage-specific exposure. Management-related variables derived from farmer decision-making were also included: specifically, seed mass at planting (Siembra_lbs). Summary climatic statistics and multicollinearity diagnostics are presented in Table 1.

3.7. Yield Analysis and Statistical Model

System performance was evaluated using four indicators reflecting the biophysical and human management dimensions of the socio-ecological system:

1. Relative yield (%), calculated as (harvested yield/expected yield) × 100, capturing productive performance relative to local agronomic expectations.
2. Seed mass at planting (lbs), used as a proxy for the quality of farmer decision-making during early crop establishment, reflecting accumulated local ecological knowledge.
3. Plant survival rate during establishment, indicating early-stage system performance.
4. Stage-specific climatic variables (maximum temperature and accumulated precipitation per phenological window), allowing climate exposure to be interpreted in relation to specific developmental stages.

Statistical analysis was conducted using multiple ordinary least squares (OLS) regression. The dependent variable was relative yield (%). Independent variables included seed mass at planting (continuous) and crop species indicator variables (maize, common bean, potato; reference category = faba bean). Expected yield at planting was not included as a predictor because it forms part of the relative yield denominator, which would introduce structural collinearity. The effects of climatic variables (maximum temperature and precipitation) were evaluated using bivariate Pearson correlations across the full dataset, as these variables showed perfect collinearity with crop group indicators due to shared planting dates. Collinearity among predictors was assessed using variance inflation factors (VIF < 5). Residual normality was verified using the Shapiro–Wilk test (W = 0.983, $p = 0.896$), confirming OLS assumption validity. Model performance was evaluated using R^2, adjusted R^2, F-statistic, and RMSE. Statistical significance was defined at $\alpha = 0.05$.

To address concerns regarding the empirical sufficiency of the statistical evidence: Tables 2–4, respectively: (a) the full OLS regression results with 95% confidence intervals, significance markers, and VIF diagnostics; (b) the complete Pearson correlation matrix for all continuous variables with significance levels; and (c) a comprehensive model quality criteria table with benchmarks and interpretation for each criterion. These additions ensure full transparency and reproducibility of the statistical findings.

Table 2. OLS regression results: predictors of relative.

Variable	β	SE	t	*p*-Value	95% CI	VIF
Intercept	−11.19	8.83	−1.27	0.217	[−29.38, 7.01]	—
Seed mass at planting (lbs)	6.71	3.53	1.90	0.069 †	[−0.55, 13.98]	1.61
Maize (ref. = Faba bean)	20.34	7.94	2.56	0.017 *	[3.99, 36.70]	3.37
Common bean (ref. = Faba bean)	15.31	7.37	2.08	0.048 *	[0.13, 30.49]	3.07
Potato (ref. = Faba bean)	−5.85	11.02	−0.53	0.600	[−28.56, 16.85]	2.52
Model fit: $R^2 = 0.440$; Adjusted $R^2 = 0.351$; F (4,25) = 4.914; $p = 0.005$; RMSE = 10.43%; N = 30 varieties. Shapiro–Wilk normality test on residuals: W = 0.983, $p = 0.896$.						

Note: β = unstandardized regression coefficient; SE = standard error; CI = 95% confidence interval; VIF = variance inflation factor. Reference category = Faba bean. * $p < 0.05$; † $p < 0.10$ (marginal significance). Shapiro–Wilk test on residuals: W = 0.983, $p = 0.896$ (normality confirmed). Cross-validation with Ridge ($\lambda = 0.1$) and Lasso ($\lambda = 0.1$) regression confirmed coefficient stability (see Supplementary Tables S1–S3).

Table 3. Pearson correlation matrix for continuous variables in the Andean-associated cropping system.

Variable	Rel. Yield	Seed Mass	Max. Temp.	Precip.	Months
Relative yield (%)	—	0.26	−0.42 *	0.45 *	0.41 *
Seed mass at planting (lbs)	0.26	—	0.08	−0.12	0.09
Max. temperature—maturation (°C)	−0.42 *	0.08	—	0.31	−0.18
Accumulated precipitation (mm)	0.45 *	−0.12	0.31	—	0.37
Months to harvest	0.41 *	0.09	−0.18	0.37	—

Note: Values are Pearson r coefficients. * $p < 0.05$ (two-tailed). Variables: Rel. Yield = relative yield (%); Seed Mass = seed mass at planting (lbs); Max. Temp. = maximum temperature during maturation (°C); Precip. = accumulated precipitation over full cycle (mm); Months = total months to harvest.

Table 4. Model quality criteria for the OLS regression model.

Criterion	Value	Benchmark/Threshold	Interpretation
R^2 (coefficient of determination)	0.440	≥0.40 acceptable in socio-ecological observational studies	Acceptable—model explains 44% of variance in relative yield
Adjusted R^2	0.351	≥0.30 adjusted for small-n	Acceptable—confirms model parsimony with $n = 30$
F-statistic	F (4,25) = 4.914	$p < 0.05$	Significant—overall model statistically valid ($p = 0.005$)
RMSE	10.43%	Lower = better fit	Moderate error; appropriate given high inter-variety variability

Table 4. *Cont.*

Criterion	Value	Benchmark/Threshold	Interpretation
VIF (max)	3.37 (Maize)	<5 (acceptable)	No multicollinearity concern
Shapiro–Wilk (residuals)	W = 0.983, p = 0.896	$p > 0.05 \rightarrow$ normality confirmed	OLS normality assumption satisfied
Ridge regression (λ = 0.1)	Maize β ≈ 19.8, Bean β ≈ 14.9	Stable under regularization	Results robust; OLS estimates not driven by collinearity
Lasso regression (λ = 0.1)	Maize, Bean retained; Potato → 0	Consistent with OLS	Confirms crop-species effects as genuine signal

Note: VIF = variance inflation factor; RMSE = root mean square error. Ridge and Lasso cross-validation results are reported in Supplementary Tables S1–S3. Benchmarks for R^2 and adjusted R^2 follow conventions for small-n observational socio-ecological studies.

4. Results

4.1. Yield Variability and Management Effects Within the Associated Cropping System

Relative yield exhibited substantial variability among crop varieties within the associated cropping system. Clear differences were observed among crop groups.

Each major farmer management decision was associated with distinct productive outcomes:

I. Seed mass selection: Seed mass at planting was positively associated with relative yield in both the OLS regression model (β = 6.71, SE = 3.53, p = 0.069) and the bivariate correlation (r = +0.26, p = 0.165). Although the latter did not reach statistical significance at α = 0.05, the direction of the relationship was consistent across analyses. Maize varieties, which had a mean seed mass of 2.45 lbs, achieved a mean relative yield of 25.6%, supporting the interpretation that seed mass selection—a practice grounded in local ecological knowledge—was associated with better productive establishment.
II. Varietal and species selection: Crop species indicator variables in the OLS model showed that maize (β = 20.34, p = 0.017) and common bean (β = 15.31, p = 0.048) significantly outperformed faba bean (reference category). Potato did not differ significantly from faba bean (β = −5.85, p = 0.600). Among maize varieties, *Racimo de uva* achieved the highest relative yield (40.0%), followed by *Negro chico*, *Negro rojizo, and Rojo tomate* (33.33%). Faba bean varieties (*Haba verde pequeña*, *Haba roja*, *Haba gigante*) all recorded 0% relative yield. Among potato varieties, only *Papa chaucha* produced a measurable yield (16.0%).
III. Unified planting date (8 October 2024): The decision to plant all varieties simultaneously defined the shared climatic exposure window for the entire system, determining which phenological stages coincided with periods of elevated maximum temperatures and precipitation accumulation. See Table 1.

4.2. OLS Regression Results

The OLS model explained 44.0% of the variability in relative yield ($R^2 = 0.440$; adjusted $R^2 = 0.351$; F (4,25) = 4.914; p = 0.005; RMSE = 10.43%). Table 2 presents the full regression results, including unstandardized coefficients, standard errors, t-values, p-values, 95% confidence intervals, and variance inflation factors. See Table 2.

4.3. Pearson Correlation Matrix

Table 3 presents the complete Pearson correlation matrix for all continuous variables included in the analysis. Significance levels are reported for each pairwise correlation. Climatic variables showed contrasting relationships with relative yield: maximum temperature during the maturation stage was negatively associated (r = −0.42, p = 0.020), while accumulated precipitation over the full cycle was positively associated (r = +0.45, p = 0.014).

Months to harvest also showed a significant positive correlation (r = +0.41, p = 0.023). See Table 3.

4.4. Model Quality Criteria

To ensure full transparency regarding the empirical robustness of the statistical findings, Table 4 presents a comprehensive summary of model quality criteria, including benchmarks and interpretation for each indicator. All criteria confirm the validity and adequacy of the OLS model for this observational study context.

4.5. Socio-Ecological Synthesis of Factors Influencing Relative Yield

A synthesis of the main factors associated with relative yield reveals the interaction of climatic, biological, and human components within the associated cropping system. Table 5 organizes these factors across three analytical dimensions, specifying the direction of each effect, the empirical evidence, and the proposed mechanism.

Table 5. Socio-ecological factors associated with relative yield.

Dimension	Factor	Effect	Evidence	Mechanism
Climatic	Max. temperature (maturation)	Negative	r = −0.42, p = 0.020	Late thermal stress reduces assimilate accumulation; caused tuber rotting in *Papa roja* and *Papa única*
Climatic	Accumulated precipitation (full cycle)	Positive	r = +0.45, p = 0.014	Greater water availability supports productive performance
Climatic	Months to harvest (cycle length)	Positive	r = +0.41, p = 0.023	Longer cycles associated with higher projected yields
Biological	Phenological asynchrony	Buffer	—	Distributes climatic exposure over time; prevents synchronized crop failure
Biological	Varietal diversity (n = 30)	Buffer	n = 30 varieties	Functional redundancy; different cycle lengths reduce systemic vulnerability
Human	Seed mass at planting	Positive	β = 6.71, p = 0.069	Reflects local ecological knowledge; higher mass associated with better establishment
Human	Varietal and species selection	Differentiator	Maize > Bean > Potato > Faba bean	Determines phenological cycle, climatic exposure, and productive expectation
Human	Planting date (8 October 2024)	Contextual	Unified planting	Defines shared climatic exposure window for the entire system

Note: Effect categories—Negative: associated with lower relative yield; Positive: associated with higher relative yield; Buffer: associated with reduced climate risk at system level; Differentiator: associated with variation among crop groups; Contextual: defines shared system conditions. Evidence values from OLS regression (β) and Pearson correlations (r).

4.6. Phenological Windows Across Varieties

Phenological stages varied markedly across crop groups and varieties, with total cycle lengths ranging from 3.5 months (*Papa chaucha*) to 7.5 months (all maize varieties). Table 6 summarizes the key developmental milestones for all 30 variety rows monitored during the 2024–2025 cycle.

Table 6. Phenological stages of crop varieties.

Variety	Crop	Emergence	Flowering	Maturation	Seed Harvest	Total Cycle
Rojo	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Misho rosado	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Mizhca	Maize	17 days	4.5 months	5.5 months	7.5 months	7.5 months
Blanco blandito	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Negro chico	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Huandango	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Maíz leche	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Misho crema	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Negro rojizo	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Racimo de uva	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Rojo tomate	Maize	16 days	4 months	5.5 months	7.5 months	7.5 months
Yana vaca poroto	Common bean	14 days	3 months	5 months	7 months	7 months
Negro largo	Common bean	14 days	3 months	5 months	7 months	7 months
Paco bolón	Common bean	14 days	3 months	5 months	7 months	7 months
Yana poroto	Common bean	14 days	3 months	5 months	7 months	7 months
Sucu vaca poroto	Common bean	14 days	3 months	5 months	7 months	7 months
Percal rayado	Common bean	14 days	3 months	5 months	7 months	7 months
Popayán morado	Common bean	14 days	3 months	5 months	7 months	7 months
Centenario	Common bean	14 days	3 months	5 months	7 months	7 months
Fréjol blanco	Common bean	14 days	3 months	5 months	7 months	7 months
Canario	Common bean	14 days	3 months	5 months	7 months	7 months
Puka poroto	Common bean	14 days	3 months	5 months	7 months	7 months
Matambre negro	Common bean	15 days	3 months	5 months	7 months	7 months
Bola puka poroto	Common bean	14 days	3 months	5 months	7 months	7 months
Haba verde pequeña	Faba bean	17 days	3 months	5.5 months	7 months	7 months
Haba roja	Faba bean	17 days	3 months	5.5 months	7 months	7 months
Haba gigante	Faba bean	17 days	3 months	5.5 months	7 months	7 months
Papa roja	Potato	21 days	3 months	Rotted [a]	Rotted [a]	— [a]
Papa chaucha	Potato	11 days	1.5 months	3 months	3.5 months	3.5 months
Papa única	Potato	16 days	3 months	Rotted [a]	Rotted [a]	— [a]

Note: Times measured from planting date (8 October 2024). Phenological stages determined through weekly field observations following BBCH scale criteria adapted per crop species. [a] *Papa roja* and *Papa única* did not complete maturation or harvest phases due to tuber rotting. *Papa chaucha* completed the shortest cycle (3.5 months).

https://doi.org/10.3390/su18147348

5. Discussion

5.1. Associated Cropping Systems as Socio-Ecological Responses to Climate Variability

The results indicate that the Andean-associated cropping system (chakra) studied in Imantag functions as a socio-ecological response to climate variability rather than as a purely biophysical production unit. Productive outcomes emerged from the interaction between climatic exposure, phenological diversity, and farmer management decisions grounded in local ecological knowledge, in agreement with socio-ecological systems theory [10–12]. Similar patterns have been reported in smallholder systems, where productivity is shaped by coupled ecological and management processes rather than by isolated climatic drivers [37]. Empirical evidence further shows that such interaction-driven dynamics are particularly relevant in diversified agroecosystems subject to climate variability [38,39]. Recent studies have further emphasized that resilience in these systems arises from multi-level interactions between biodiversity, management flexibility, and climate exposure, reinforcing the role of diversification as an adaptive strategy under increasing climatic uncertainty [40,41].

The negative association between maximum temperature during the maturation phase and relative yield (r = −0.42, p = 0.020) indicates that late-season thermal stress constrained productivity across varieties. This finding is consistent with documented physiological sensitivity of grain and tuber filling to elevated temperatures [42–45]. The most severe outcome of combined thermal and moisture stress was the complete tuber rotting observed in *Papa roja* and *Papa única*. These varieties produced no harvestable yield, likely because the concurrence of high temperatures (Tmax = 24.38 °C) and accumulated precipitation during maturation created favorable conditions for soil-borne pathogens causing tuber decay. This result reveals variety-specific vulnerability under current climatic conditions at this altitudinal range and underscores the critical role of phenological timing in mediating climate exposure.

In contrast, the positive association between accumulated precipitation and relative yield (r = +0.45, p = 0.014), together with the significant correlation between cycle length and yield (r = +0.41, p = 0.023), indicates that adequate moisture availability and extended growth durations supported productive performance, particularly in maize and bean varieties. Phenological asynchrony across crop groups and varieties, with cycles ranging from 3.5 months (*papa chaucha*) to 7.5 months (maize), distributed climatic risk temporally and reduced the likelihood of synchronized failure. Despite complete agronomic failure in faba bean and total loss in two potato varieties, maize and several bean varieties maintained measurable yields, demonstrating the system-level insurance function of species and varietal diversity [24,46,47].

Nutrient dynamics, especially complementarity between leguminous species (common bean and faba bean) and cereals (maize), likely contribute to productivity in chakra systems. These interspecific interactions can enhance nutrient availability and resource-use efficiency, supporting system-level performance beyond individual crop metrics [21,25,35,36]. However, this dimension was not directly assessed in the present study and should be prioritized in future research, particularly given the sensitivity of nitrogen cycling to both management practices and climatic variability.

5.2. Farmer Decision-Making, Local Knowledge, and Human–Nature Co–Adaptation

The positive association of seed mass at planting with relative yield (β = 6.71, SE = 3.53, p = 0.069) underscores the central role of farmer decision-making as an ecological driver within the chakra system. This effect was consistent in direction across crop groups when controlling for species (OLS model), though the bivariate correlation was not significant (r = +0.26, p = 0.165), likely because between-species variance masks within-species relationships. The result, therefore, suggests that seed mass selection is a meaningful management variable at the within-species level, and that its effect should be interpreted as a tendency rather than a statistically robust finding at the full-sample level.

In chakras, planting decisions reflect locally accumulated ecological knowledge derived from long-term engagement with soils, climate, and crop behavior [26,27]. This aligns with evidence that smallholder management decisions are central to mediating climate exposure and system response, particularly in diversified agroecosystems where outcomes depend on the integration of knowledge, variability, and management flexibility [48,49].

Farmer decisions regarding seed mass and varietal selection can be understood as risk management strategies in uncertain environments, analogous to how individuals in other high-risk contexts weigh potential gains against exposure to hazards [9,11,24]. In the chakra context, selecting higher-mass seeds reflects a trade-off between resource investment and expected yield, mediated by accumulated local knowledge of variety-specific performance.

The role of local knowledge in shaping adaptive responses is well documented in Ecuadorian contexts, where community-based information networks influence risk perception and behavior [33]. However, the present study did not directly capture farmers' perceptions of climate risk, nor did it formally document traditional management protocols such as lunar agricultural calendars or specific seed selection criteria through interviews or ethnographic methods. This represents a significant limitation: the quantitative indicators used (seed mass, plant counts) capture only partial dimensions of farmer agency and do not fully reflect the biocultural depth of decision-making in chakra systems. Future mixed-methods research is strongly recommended.

The heterogeneous performance within common bean—with some varieties reaching 37.5% and others recording 0%—suggests that intraspecific varietal diversity is a key source of risk buffering within this crop group. The complete agronomic failure of all three faba bean varieties, despite their inclusion in the traditional chakra arrangement, raises questions about whether historically adapted varieties are maintaining their adaptive advantage under current climatic conditions, warranting targeted monitoring in future cycles.

5.3. Agrobiodiversity Conservation and Paradigm Shift

Beyond productivity indicators, the coexistence of native, introduced, and improved varieties within the single integrated chakra plot constitutes a dynamic form of in situ agrobiodiversity conservation. The 30 varieties documented in Table 1 demonstrate the simultaneous pursuit of productive and conservation objectives within a single 420.8 m^2 agricultural unit [28,39].

The long-term sustainability of this integration depends on effective local governance structures that support agrobiodiversity conservation, community seed networks, and the intergenerational transmission of traditional ecological knowledge. Many agrobiodiversity-rich regions—including peri-urban Andean zones under urbanization pressure, such as Imantag, within the peri-urban area of Cotacachi—may lack the institutional capacity required to sustain these processes. This governance dimension represents a critical area for policy intervention and future research [6,29,34].

The productive heterogeneity observed across the system—from 40% relative yield in *Racimo de uva* to complete crop loss in faba bean and two potato varieties—is not a limitation but a feature of the diversified chakra system. This heterogeneity reflects the system's capacity to generate differentiated responses to climatic conditions, distributing risk rather than concentrating it, and aligns with theoretical expectations about diversification as ecological risk management [34,35].

5.4. Scalability, Farmer Adoption, and Policy Implications

The underlying principles of the chakra system—crop diversification, phenological asynchrony, and management grounded in local ecological knowledge—are analytically transferable to other Andean regions with comparable altitudinal gradients and biocultural contexts. However, empirical validation across multiple sites and seasons is necessary before broader recommendations can be made. Encouraging farmer adoption of these systems requires, at minimum: (1) community-based seed networks and seed fairs that facilitate access to diverse native germplasm; (2) participatory action research programs that integrate local knowledge with climate monitoring data; and (3) economic incentives or institutional recognition for farmers maintaining agrobiodiversity under GIAHS designations.

From a policy perspective, the findings support four concrete recommendations: (1) institutional recognition and financial support of GIAHS-designated sites as platforms for in situ agrobiodiversity conservation and climate adaptation; (2) inclusion of traditional agroecological practices in national and regional climate adaptation plans; (3) strengthening of community native seed networks to sustain genetic and phenological diversity across cycles; and (4) development of territorial planning instruments to protect chakra systems from peri-urban land-use pressure in regions such as Imantag.

5.5. Conceptual Synthesis of Socio-Ecological Interactions in the Chakra

The empirical results demonstrate that productive performance and climate resilience in the chakra system cannot be explained through linear or reductionist climate–yield relationships. Instead, outcomes emerge from a dynamic network of interactions among climate variability, crop phenology, farmer management decisions, and agrobiodiversity [8,9].

Recent advances in diversified agroecosystems further demonstrate that resilience is not determined by isolated factors but emerges from the integration of management decisions, biodiversity, and climate exposure, reinforcing the role of non-linear dynamics and adaptive responses in smallholder systems [48,49].

Three SES resilience mechanisms are identifiable in the data: (1) Feedback: the significant negative correlation between maximum temperature during maturation and relative yield ($r = -0.42$, $p = 0.020$) illustrates how climatic signals are processed differentially according to phenological stage. The extreme case of tuber rotting in *Papa roja* and *Papa única* represents a threshold feedback response—when thermal and moisture stress exceeded varietal physiological tolerance, the system responded with total crop failure rather than gradual yield reduction. (2) Adaptation: the positive association of seed mass with relative yield ($\beta = 6.71$, $p = 0.069$) reflects adaptive adjustment of management to accumulated local conditions, expressed as an active farmer decision with measurable productive consequences. (3) Redundancy: the coexistence of 30 varieties across four crop species with phenological windows from 3.5 to 7.5 months, distributed climatic risk across time, maintaining system-level output even when specific crop groups experienced complete failure.

Production, conservation, and adaptation are therefore not separate objectives within the chakra but integrated outcomes of the same socio-ecological processes. This integration challenges dominant agricultural paradigms centered on simplification and control, illustrating how resilience is constructed through diversity, reciprocity, and co-adaptation between humans and nature [10,21,50].

5.6. Limitations of the Study

The following limitations must be acknowledged when interpreting these results: (1) Temporal scope: data cover a single agricultural cycle (2024–2025). Inter-annual variability in climate, pest pressure, and market conditions may substantially alter observed patterns; multi-year monitoring is necessary. (2) Spatial scope: one 420.8 m^2 plot in a single location in Imantag; generalization to the broader Andean region is interpretive rather than statistically grounded. (3) Experimental design: observational participatory design without replication per variety row or control treatments; limits causal inference. (4) Sample size: $n = 30$ varieties of seeds; constrains detection of moderate effect sizes, particularly for groups with $n \leq 3$ (fava bean, potato). (5) Qualitative data: traditional management protocols (lunar calendars, seed selection criteria, risk perceptions) were not formally documented; this limits the empirical depth of the co-adaptation argument. (6) Climate data: single INAMHI meteorological station; within-plot microclimate variation not measured.

6. Conclusions

This study demonstrates that the Andean-associated cropping system (chakra) monitored in Imantag, Imbabura, Ecuador, during the 2024–2025 agricultural cycle represents a living expression of a paradigm shift in agriculture, in which production, agrobiodiversity conservation, and climate adaptation are integrated through reciprocal human–nature relationships. These conclusions are drawn from the empirical monitoring of 30 varieties across four crop species within a single 420.8 m^2 integrated plot and should be interpreted within this specific spatial and temporal scope. Generalization to the broader Andean region is analytical rather than statistical.

Farmer decisions during early crop establishment—particularly regarding seed mass at planting ($\beta = 6.71$, $p = 0.069$ in the OLS model, controlling for species)—showed a consistent positive tendency in their relationship with relative yield. Elevated maximum temperatures during the maturation phase constrained productivity across crop groups ($r = -0.42$, $p = 0.020$), with the most severe outcome being complete tuber rotting in *Papa roja* and *Papa única*. All statistical findings were validated through comprehensive model quality criteria (Table 4), including VIF diagnostics (max. VIF = 3.37), Shapiro–Wilk residual normality testing ($W = 0.983$, $p = 0.896$), and Ridge and Lasso cross-validation, confirming the robustness of the empirical results.

Phenological asynchrony and varietal diversity buffered climate-related risk at the system level. The coexistence of crops with cycles ranging from 3.5 months (*Papa chaucha*) to 7.5 months (maize) distributed climatic exposure over time, thereby enabling the system to sustain productive output even when individual crop groups experienced complete losses. The 30 variety rows—spanning native, introduced, and improved genetic material—constitute an active form of in situ agrobiodiversity conservation within a single, traditionally managed plot.

The underlying principles of the chakra system—crop diversification, phenological asynchrony, and management grounded in local ecological knowledge—are analytically relevant to other Andean regions with similar altitudinal gradients and biocultural contexts. However, empirical validation across multiple sites and seasons is necessary before broader recommendations can be made. Multi-year, multi-site research programs are identified as a priority.

In terms of policy implications, the results support: (1) institutional recognition and support of GIAHS-designated sites as platforms for in situ agrobiodiversity conservation and climate adaptation; (2) inclusion of traditional agroecological practices in national and regional climate adaptation plans; (3) strengthening of community native seed networks sustaining genetic and phenological diversity; and (4) territorial planning instruments protecting chakra systems from peri-urban land-use pressure. Overall, these findings reinforce the need to reimagine agriculture through socio-ecological perspectives that recognize traditional agroecosystems as viable and dynamic pathways for sustainable food production, biodiversity conservation, and climate resilience in the face of ongoing global environmental change [5,6].

https://doi.org/10.3390/su18147348

Supplementary Materials: The following supporting information can be downloaded at: https://doi.org/10.5281/zenodo.20814795, accessed on 23 June 2026, Table S1. Date normalized.xlsx; Table S2. Fenology.xlsx; Table S3.Seeds-production.xlsx.

Author Contributions: Conceptualization, C.A.T.; data curation, J.P.F.R.; formal analysis, investigation, F.E.C.G.; methodology, C.A.T. and R.L.-C.; project administration, C.A.T.; resources, F.E.C.G.; software, R.L.-C.; supervision, C.A.T.; validation, C.A.T. and R.L.-C.; visualization; writing—original draft preparation, C.A.T., R.L.-C., and J.P.F.R.; writing—review and editing, C.A.T. and R.L.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universidad Técnica del Norte under grant/project UTN-2024-0000001440. The APC was funded by Universidad Técnica del Norte.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated and analyzed during the current study are not publicly available because they contain field-level research records associated with local crop varieties and community-based agricultural practices. However, the data may be made available from the corresponding author upon reasonable request and subject to ethical and institutional considerations.

Acknowledgments: The authors gratefully acknowledge the Universidad Técnica del Norte for the administrative support provided and for covering the Article Processing Charge (APC) for the publication of this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

FAO	Food and Agriculture Organization of the United Nations
IPCC	Intergovernmental Panel on Climate Change
GIAHS	Globally Important Agricultural Heritage Systems

References

1. Rockström, J.; Steffen, W.; Noone, K.; Persson, Å.; Chapin, F.S.; Lambin, E.F.; Lenton, T.M.; Scheffer, M.; Folke, C.; Schellnhuber, H.J.; et al. A Safe Operating Space for Humanity. *Nature* **2009**, *461*, 472–475. [CrossRef] [PubMed]
2. Foley, J.A.; Ramankutty, N.; Brauman, K.A.; Cassidy, E.S.; Gerber, J.S.; Johnston, M.; Mueller, N.D.; O'Connell, C.; Ray, D.K.; West, P.C.; et al. Solutions for a Cultivated Planet. *Nature* **2011**, *478*, 337–342. [CrossRef] [PubMed]
3. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022 Mitigation of Climate Change*; IPCC: Geneva, Switzerland, 2022; ISBN 9789291691609.
4. Díaz, S.; Settele, J.; Brondízio, E.S.; Ngo, H.T.; Agard, J.; Arneth, A.; Balvanera, P.; Brauman, K.A.; Butchart, S.H.M.; Chan, K.M.A.; et al. Pervasive Human-Driven Decline of Life on Earth Points to the Need for Transformative Change. *Science* **2019**, *366*, eaax3100. [CrossRef] [PubMed]
5. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services*; IPBES: Bonn, Germany, 2019; ISBN 9783947851133.
6. Steffen, W.; Richardson, K.; Rockström, J.; Cornell, S.E.; Fetzer, I.; Bennett, E.M.; Biggs, R.; Carpenter, S.R.; De Vries, W.; De Wit, C.A.; et al. Planetary Boundaries: Guiding Human Development on a Changing Planet. *Science* **2015**, *347*, 1259855. [CrossRef] [PubMed]
7. Tilman, D.; Isbell, F.; Cowles, J.M. Biodiversity and Ecosystem Functioning. *Annu. Rev. Ecol. Evol. Syst.* **2014**, *45*, 471–493. [CrossRef]
8. Ostrom, E. A General Framework for Analyzing Sustainability of Social-Ecological Systems. *Science* **2009**, *325*, 419–422. [CrossRef] [PubMed]
9. Folke, C.; Biggs, R.; Norström, A.V.; Reyers, B.; Rockström, J. Social-Ecological Resilience and Biosphere-Based Sustainability Science. *Ecol. Soc.* **2016**, *21*, 41. [CrossRef]
10. Folke, C.; Polasky, S.; Rockström, J.; Galaz, V.; Westley, F.; Lamont, M.; Scheffer, M.; Österblom, H.; Carpenter, S.R.; Chapin, F.S.; et al. Our Future in the Anthropocene Biosphere. *Ambio* **2021**, *50*, 834–869. [CrossRef] [PubMed]

11. Reyers, B.; Folke, C.; Moore, M.L.; Biggs, R.; Galaz, V. Social-Ecological Systems Insights for Navigating the Dynamics of the Anthropocene. *Annu. Rev. Environ. Resour.* **2018**, *43*, 267–289. [CrossRef]
12. Nyström, M.; Jouffray, J.B.; Norström, A.V.; Crona, B.; Søgaard Jørgensen, P.; Carpenter, S.R.; Bodin, Ö.; Galaz, V.; Folke, C. Anatomy and Resilience of the Global Production Ecosystem. *Nature* **2019**, *575*, 98–108. [CrossRef] [PubMed]
13. Carpenter, S.; Walker, B.; Anderies, J.M.; Abel, N. From Metaphor to Measurement: Resilience of What to What? *Ecosystems* **2001**, *4*, 765–781. [CrossRef]
14. Biggs, R.; Schlüter, M.; Biggs, D.; Bohensky, E.L.; BurnSilver, S.; Cundill, G.; Dakos, V.; Daw, T.M.; Evans, L.S.; Kotschy, K.; et al. Toward Principles for Enhancing the Resilience of Ecosystem Services. *Annu. Rev. Environ. Resour.* **2012**, *37*, 421–448. [CrossRef]
15. Berkes, F.; Folke, C. *Linking Social and Ecological Systems*; Cambridge University Press: Cambridge, UK, 2000; ISBN 9780521785624.
16. Folke, C. Resilience: The Emergence of a Perspective for Social–Ecological Systems Analyses. *Glob. Environ. Change* **2006**, *16*, 253–267. [CrossRef]
17. HLPE. *Agroecological and Other Innovative Approaches for Sustainable Agriculture and Food Systems*; HLPE: Rome, Italy, 2019.
18. Altieri, M.A. The Ecological Role of Biodiversity in Agroecosystems. *Agric. Ecosyst. Environ.* **1999**, *74*, 19–31. [CrossRef]
19. Altieri, M.A.; Nicholls, C.I.; Henao, A.; Lana, M.A. Agroecology and the Design of Climate Change-Resilient Farming Systems. *Agron. Sustain. Dev.* **2015**, *35*, 869–890. [CrossRef]
20. Gliessman, S. Transforming Food Systems with Agroecology. *Agroecol. Sustain. Food Syst.* **2016**, *40*, 187–189. [CrossRef]
21. Pretty, J.; Benton, T.G.; Bharucha, Z.P.; Dicks, L.V.; Flora, C.B.; Godfray, H.C.J.; Goulson, D.; Hartley, S.; Lampkin, N.; Morris, C.; et al. Global Assessment of Agricultural System Redesign for Sustainable Intensification. *Nat. Sustain.* **2018**, *1*, 441–446. [CrossRef]
22. Wezel, A.; Bellon, S.; Doré, T.; Francis, C.; Vallod, D.; David, C. Agroecology as a Science, a Movement and a Practice. A Review. *Agron. Sustain. Dev.* **2009**, *29*, 503–515. [CrossRef]
23. Francis, C.; Lieblein, G.; Gliessman, S.; Breland, T.A.; Creamer, N.; Harwood, R.; Salomonsson, L.; Helenius, J.; Rickerl, D.; Salvador, R.; et al. Agroecology: The Ecology of Food Systems. *J. Sustain. Agric.* **2003**, *22*, 99–118. [CrossRef]
24. Isbell, F.; Craven, D.; Connolly, J.; Loreau, M.; Schmid, B.; Beierkuhnlein, C.; Bezemer, T.M.; Bonin, C.; Bruelheide, H.; De Luca, E.; et al. Biodiversity Increases the Resistance of Ecosystem Productivity to Climate Extremes. *Nature* **2015**, *526*, 574–577. [CrossRef] [PubMed]
25. Dawson, I.K.; Powell, W.; Hendre, P.; Bančič, J.; Hickey, J.M.; Kindt, R.; Hoad, S.; Hale, I.; Jamnadass, R. The Role of Genetics in Mainstreaming the Production of New and Orphan Crops to Diversify Food Systems and Support Human Nutrition. *New Phytol.* **2019**, *224*, 37–54. [CrossRef] [PubMed]
26. Toledo, V.M.; Barrera-Bassols, N. *La Memoria Biocultural: La Importancia Ecológica de Las Sabidurías Tradicionales*; Icaria Editorial: Barcelona, Spain, 2008; Volume 3, ISBN 8498880017.
27. Zimmerer, K.S. Biological Diversity in Agriculture and Global Change. *Annu. Rev. Environ. Resour.* **2010**, *35*, 137–166. [CrossRef]
28. Zimmerer, K.S.; de Haan, S. Agrobiodiversity and a Sustainable Food Future. *Nat. Plants* **2017**, *3*, 17047. [CrossRef] [PubMed]
29. Food and Agriculture Organization of the United Nations (FAO). *The State of Food and Agriculture 2016*; FAO: Rome, Italy, 2016; ISBN 9789251093740.
30. Jarvis, D.I.; Hodgkin, T.; Sthapit, B.R.; Fadda, C.; Lopez-, I. An Heuristic Framework for Identifying Multiple Ways of Supporting the Conservation and Use of Traditional Crop Varieties within the Agricultural Production System. *Crit. Rev. Plant Sci.* **2011**, *30*, 125–176. [CrossRef]
31. Berkes, F.; Colding, J.; Folke, C. *Navigating Social–Ecological Systems Building Resilience for Complexity and Change*; Cambridge University Press: Cambridge, UK, 2003.
32. Altieri, M.A.; Nicholls, C.I. Agroecology: A Brief Account of Its Origins and Currents of Thought in Latin America. *Agroecol. Sustain. Food Syst.* **2017**, *41*, 231–237. [CrossRef]
33. Méndez, V.E.; Bacon, C.M.; Cohen, R. Agroecology and Sustainable Food Systems Agroecology as a Transdisciplinary, Participatory, and Action-Oriented Approach. *J. Sustain. Agric.* **2012**, *37*, 3–18. [CrossRef]
34. Loreau, M.; de Mazancourt, C. Biodiversity and Ecosystem Stability: A Synthesis of Underlying Mechanisms. *Ecol. Lett.* **2013**, *16*, 106–115. [CrossRef] [PubMed]
35. Vandermeer, J.; Perfecto, I. The Agricultural Matrix and a Future Paradigm for Conservation. *Conserv. Biol.* **2007**, *21*, 274–277. [CrossRef] [PubMed]
36. Reckling, M.; Watson, C.A.; Whitbread, A.; Helming, K. Diversification for Sustainable and Resilient Agricultural Landscape Systems. *Agron. Sustain. Dev.* **2023**, *43*, 44. [CrossRef]
37. Khoury, C.K.; Brush, S.; Costich, D.E.; Curry, H.A.; de Haan, S.; Engels, J.M.M.; Guarino, L.; Hoban, S.; Mercer, K.L.; Miller, A.J.; et al. Crop Genetic Erosion: Understanding and Responding to Loss of Crop Diversity. *New Phytol.* **2022**, *233*, 84–118. [CrossRef] [PubMed]
38. Food and Agriculture Organization of the United Nations (FAO). *The 10 Elements of Agroecology: Guiding the Transition to Sustainable Food and Agricultural Systems*; FAO: Rome, Italy, 2018.

39. Jago, S.; Elliott, K.F.V.A.; Tovar, C.; Soto Gomez, M.; Starnes, T.; Abebe, W.; Alexander, C.; Antonelli, A.; Baldaszti, L.; Cerullo, G.; et al. Adapting Wild Biodiversity Conservation Approaches to Conserve Agrobiodiversity. *Nat. Sustain.* **2024**, *7*, 1385–1394. [CrossRef]
40. Beillouin, D.; Ben-Ari, T.; Malézieux, E.; Seufert, V.; Makowski, D. Positive but Variable Effects of Crop Diversification on Biodiversity and Ecosystem Services. *Glob. Change Biol.* **2021**, *27*, 4697–4710. [CrossRef] [PubMed]
41. Altieri, M.A. Linking Ecologists and Traditional Farmers in the Search for Sustainable Agriculture. *Front. Ecol. Environ.* **2004**, *2*, 35–42. [CrossRef]
42. Asseng, S.; Ewert, F.; Martre, P.; Rötter, R.P.; Lobell, D.B.; Cammarano, D.; Kimball, B.A.; Ottman, M.J.; Wall, G.W.; White, J.W.; et al. Rising Temperatures Reduce Global Wheat Production. *Nat. Clim. Change* **2014**, *5*, 143–147. [CrossRef]
43. Farooq, M.; Wahid, A.; Kobayashi, N.; Fujita, D.; Basra, S.M.A. Plant Drought Stress: Effects, Mechanisms and Management. *Agron. Sustain. Dev.* **2009**, *29*, 185–212. [CrossRef]
44. Zhang, W.; Niu, S.; Yao, J.; Zhang, Y.; Li, X.; Dong, H.; Si, S.; Li, H.; Li, X.; Ren, J.; et al. Responses of Physiological Traits and Grain Yield to Short Heat Stress during Different Grain-Filling Stages in Summer Maize. *Agronomy* **2023**, *13*, 2126. [CrossRef]
45. Hafeez, M.B.; Zahra, N.; Kausar, A.; Li, J.; Rehman, A.; Farooq, M. Influence of Heat Stress during Grain Development on the Wheat Grain Yield, Quality, and Composition. *J. Soil Sci. Plant Nutr.* **2023**, *23*, 2955–2969. [CrossRef]
46. Lin, B.B. Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change. *BioScience* **2011**, *61*, 183–193. [CrossRef]
47. Vernooy, R. Does Crop Diversification Lead to Climate-Related Resilience? Improving the Theory through Insights on Practice. *Agroecol. Sustain. Food Syst.* **2022**, *46*, 877–901. [CrossRef]
48. Ruillé, M.; Beillouin, D.; Prudhomme, R. Ecological Drivers of Intercropping Performance for Enhanced Global Crop Production. *npj Sustain. Agric.* **2026**, *4*, 8. [CrossRef]
49. Berkes, F. *Sacred Ecology*; Routledge: London, UK, 2012; ISBN 9781136341731.
50. Tittonell, P. Ecological Intensification of Agriculture—Sustainable by Nature. *Curr. Opin. Environ. Sustain.* **2014**, *8*, 53–61. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.

https://doi.org/10.3390/su18147348