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Irrigation Increases Crop Species Diversity in Low-Diversity Farm Regions of Mexico

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Abstract: Although agricultural intensification generally has homogenizing effects on landscapes that reduce crop diversity, the specific effects of different input strategies on crop diversity are unclear. This study examines the effects of irrigation inputs on crop species diversity in Mexico. We assess the richness and evenness diversity of 297 crop species across 2455 municipalities while controlling for environmental and socioeconomic factors and farm structural and functional characteristics. Using a quantile regression approach, we assess relationships across conditional quantiles of low-, medium-, and high-diversity farm regions. Results show irrigation level (% cropland irrigated) is a strong positive predictor of crop species richness and evenness diversity across all quantile regions. Moreover, the quantile effects of irrigation on evenness diversity are five times greater in low-diversity rather than high-diversity regions. With implications for agricultural water policy in Mexico, this study illustrates the potential benefits of sustainable irrigation expansion in water-rich but irrigation-poor farming regions. Specifically, by enhancing crop species diversity, carefully targeted irrigation expansion can support the transition to sustainable intensification.

Keywords: crop diversity; intensification; irrigation; Mexico; quantile regression; sustainability

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1. Introduction

Crop diversity is an important factor in food and livelihood security, sustainable agriculture, and ecosystem services production [1–3]. Crop diversity also serves as a hedge against risk by reducing farm-level vulnerability to climatic change or commodity market shocks [4,5]. Erosion of crop diversity is of growing concern to global food systems security, the health and primary productivity of agricultural landscapes, and the long-term stability of socio-environmental systems [6–9]. Enhancing crop diversity is now a core component of agri-environmental policies around the world, including multiple initiatives of the Food and Agriculture Organization of the United Nations [10,11]. Despite this policy focus, many of the drivers of crop diversification are poorly understood [12,13].

Studies often frame the drivers of crop diversification categorically as factors associated with broad farm types or cultivation strategies. A prime example is agricultural intensification, which is widely recognized as a key driver of diversity loss [14,15]. Agricultural intensification tends to have homogenizing effects on landscapes that lead to specialized monocropping and erosion of biodiversity [16–18]. Therefore, high-intensity, conventional agricultural systems are typically associated with lower crop diversity, while low-intensity, more traditional or agroecological systems are often associated with higher crop diversity. Within this framework, the categorical effects of agricultural intensification on crop diversity are clear. Less clear is how the partial (individual) effects of conventional inputs (e.g., chemical fertilizers, mechanization, irrigation) impact crop diversification.

There are at least two reasons why disaggregating 'intensification' and examining its partial effects on diversity is important. First, farm systems today often incorporate the characteristics of multiple farm types, blending attributes of traditional, agroecological, conventional, industrial, and other systems [19–21]. In Mexico, for example, many low-input, traditional, smallholder farm systems nonetheless use high levels of chemical fertilizers [22]. While understanding relationships between general farm system types, intensification levels, and crop diversity is informative, this level of analysis obscures the effects of specific inputs on diversity.

Second, the effects of intensification on crop diversity are poorly understood in the context of sustainable intensification. Increasingly, sustainable intensification is recognized as crucial to meeting future demands for food and minimizing environmental degradation [23,24]. Although enhancing crop diversity is a key component of sustainable intensification [25–27], it is conspicuously unclear how the mechanisms of intensification, whether conventional or sustainable, enhance crop diversity. In part, this is because high crop diversity is typically associated with low-intensity systems. While research on 'scaling-up' low-intensity practices to meet future demands for food is promising [28,29], many conceptual and practical barriers remain [30,31].

More immediate and feasible pathways to sustainable intensification are needed. Conventional input strategies have variable impacts on productivity and the environment. If properly managed, some conventional strategies can boost productivity without significant biodiversity loss [32]. Though again, more research is needed to determine the effects of specific inputs on diversity loss or gain. Ultimately, a better understanding of input-diversification relationships is critical for transitioning to sustainable intensification—a transition that will inevitably require tradeoffs between conventional and agroecological approaches [33–36].

Mexico presents an ideal case study of input-diversification relationships. Existing research has focused largely on maize genetic (landrace) diversity and the traditional intercropping systems (milpa) where much of this diversity is found [37–39]. Beyond maize genetic diversity, less attention has been given to other forms of crop diversity, especially at higher taxonomic levels (e.g., species) and larger spatial scales (e.g., national level). Further, while several studies have examined the potential effects that changes in irrigation would have on crop production in Mexico—changes desperately needed to address growing regional- and national-level water scarcity [40,41]—the potential effects of such changes on crop diversity are poorly understood.

To address these research gaps, this study seeks to answer two questions: (1) Does irrigation lead to higher or lower crop species diversity (hereafter, CSD) at regional and national levels in Mexico? (2) Are the effects of irrigation on CSD different in low-, medium-, and high-diversity regions? To answer these, we examine irrigation effects on crop species richness and evenness diversity using a quantile regression approach. We compare irrigation effects across conditional quantiles of low-, medium-, and high-diversity regions after adjusting for a range of socioeconomic, environmental, and farm characteristic factors. Findings are discussed in the contexts of water resources management and agricultural policy in Mexico, and the broader role of irrigation in sustainable intensification.

2. Materials and Methods

2.1. Data Sources and Variables

Data for this study came from four main sources. First, crop production data were obtained from the Food, Fisheries, and Nutritional Information Services (SIAP) database of Mexico's Secretary of Agriculture and Rural Development, which provides the official yearly production totals for each municipality (n = 2455). Second, data on farm characteristics came from the latest national agricultural census (2007), which provides the most comprehensive accounting of farm-level agricultural activity in the country [42]. Third, socioeconomic data were derived from Mexico's Marginalization Index, a broadly used indicator of poverty based on a composite measure of 10 sociocultural and economic indicators (e.g., income level, ethnic identity, educational access) [43]. Finally, climate data were derived from the National Commission on Arid Zones classification, which outlines eight distinct climate regions based on modified Thornthwaite projections [44]. The smallest administrative unit common to all variables, the municipality, was chosen as the unit of analysis for the study.

Species diversity indices (dependent variables). We calculated CSD from the productivity measures of 297 crop species across the country [45]. Each crop was expressed in terms of area (hectares cropped) following SIAP formatting and previous agronomic studies [7,46–48]. CSD was quantified as species richness and evenness, two related but distinct measures of diversity (Figure 1) [49]. Richness diversity is a measure of species abundance or the total number of distinct species in a community (municipality). Because species abundance measures are sensitive to sample size, the Margalef richness index was used. The index weights species abundance by the logarithm of the sample size, thereby controlling for this sensitivity:

$$R = \frac{(S-1)}{\ln N} \tag{1}$$

where R is Margalef richness diversity, S is the total number of individual crop species per municipality, and N is total number of cropped hectares per municipality.

Simpson's evenness diversity index was used to express crop evenness. Simpson's index quantifies species abundance and how similar these abundances are within a community. Higher evenness indicates a more balanced distribution of species, while lower evenness indicates a skewed distribution where only a few species dominate. To match the direction of the richness index, for which higher measures indicate higher diversity, the complement of Simpson's index was used:

$$E = 1 - \frac{\sum n(n-1)}{N(N-1)} \tag{2}$$

where E is Simpson's evenness diversity, n is the number of cropped hectares of an individual species per municipality, and N is the total number of cropped hectares per municipality. Both indices were used as separate dependent variables for comparative purposes, a common practice in agronomic and ecological studies [50]. Once calculated, R and E values were standardized to facilitate analysis.

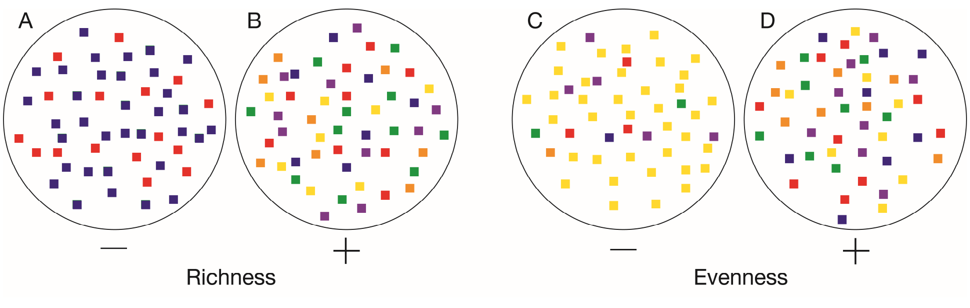


Figure 1. Illustration of richness and evenness diversity. Richness is a measure of the number of species (S) in a community, and evenness is a measure of the distribution of the abundance of species in a community. Each square represents one hectare, and each color is a distinct crop species. Area (**A**) has lower richness than area (**B**) since $S_A = 2$ and $S_B = 6$. Area (**C**) has lower evenness than area (**D**) since the distribution in area (**C**) (Red = 3, Green = 2, Blue = 1, Orange = 1, Purple = 5, Yellow = 38) is more skewed than in area (**D**) (Red = 9, Green = 8, Blue = 8, Orange = 9, Purple = 8, Yellow = 8).

Determinants of crop species diversity (independent variables). Independent variable selection followed a two-step process. First, topically relevant determinants of CSD were considered based on existing literature. An initial list of 32 variables was considered, though data availability limited these to 18. Next, a lasso screening procedure was used to refine this selection, using the Bayesian information criterion as validation [51]. For both richness and evenness models, a subset of 11 variables (9 continuous and 2 categorical) was found relevant (Table 1).

Nine variables were derived from the agricultural census data. This included three land-use variables (land ratios), each expressed as the percent of cultivated land per municipality: (1) to receive irrigation, (2) to receive chemical fertilizers, and (3) to be cultivated with maize. Three other variables expressed farmer perceptions of production challenges. These variables were calculated as the percent of farms in each municipality identifying primary challenges to production as: (4) high input costs, (5) soil infertility, and (6) barriers to commercialization or marketing of crops. Labor inputs were quantified as (7) the percent of farms in each municipality that primarily use mechanization. Farm production type was quantified as (8) the percent of farms in each municipality primarily practicing subsistence production. Additionally, a mean farm size indicator was calculated as (9) the mean farmland area (MFA) of each municipality. Here, five MFA classes were calculated by dividing the total cultivated area by the total number of farms per municipality following previous studies [52–54]. Municipality-level poverty (10) was quantified using the standardized Marginalization Index [43]. Lastly, each municipality was assigned to one of eight climate regions (11) based on the location of its geometric centroid within the CONAZA and UACH classification [44].

Table 1. Independent variables per municipality.

				Municipalities (*N* = 2455)	
Continuous	**Variable**	**Unit**	**Code**	**Mean**	**SD**
Land use	Irrigation land ratio	% cropland	Irrigation	0.19	0.28
	Chemical fertilizer land ratio		chemfertz.	0.28	0.27
	Maize land ratio		Maize	0.49	0.32
Farm challenges	Input costs	% farms	ch.inputs $	0.22	0.20
	Soil fertility		ch.soils	0.23	0.20
	Commercialization		ch.comm.	0.54	0.25
Labor	Mechanized		mechan.	0.32	0.31
Production	Subsistence		subsistence	0.72	0.25
Socioeconomic	Marginalization	index (std.)	marginality	0.00	1.00
				N	**%**
Categorical				2455	100
Mean farm area (MFA)	Very small (0–2 ha)		v.small (mfa)	421	17
	Small (2–5 ha) *		small (mfa)	871	35
	Medium (5–15 ha)		med. (mfa)	727	30
	Large (15–50 ha)		large (mfa)	350	14
	Very large (>50 ha)		v.large (mfa)	86	4
				2455	100
Climate region	Perhumid (A)		A	334	14
	Humid (B)		B	333	14
	Moist subhumid (C2)		C2	246	10
	Dry subhumid (C1) *		C1	704	29
	Semiarid light (D3)		D3	388	16
	Semiarid moderate (D2)		D2	258	11
	Semiarid dry (D1)		D1	164	7
	Arid (E)		E	28	1

* reference category. $ costs.

2.2. Quantile Regressions

Quantile regressions were used to examine the effects of the above variables on conditional quantiles of CSD richness and evenness, while standard ordinary least squares (OLS) regression was used to test the stability of these results [55]. As an extension of OLS regression, quantile regression offers several distinct advantages. First, while OLS regression estimates the conditional mean of a dependent variable across values of independent variables, quantile regression estimates the conditional median of the dependent variable across different conditional quantiles [56]. Quantile regression is therefore more robust to dependent variable distributions or outliers and does not assume constant variance of residuals [57,58]. Analytically, by estimating variable effects at different conditional intervals (quantiles), the full range of unit change effects can be observed [59]. In other words, while OLS regression provides the singular unit effect on the mean of the dependent variable, quantile regression provides the full range of unit effects at different conditional quantile levels. Therefore, it allows the comparison of variable effects at lower (e.g., 10th), middle (50th or median), and higher (e.g., 90th) levels of the dependent variable, which ultimately allows a fuller explanation of relationship dependencies [60].

CSD richness and evenness were each modeled as dependent variables, first using OLS and then quantile regressions. The OLS regression followed the standard form:

$$LS(y_i) = \beta_0 + \beta_1 x_{i1} + \cdots + \beta_p x_{ip} + \varepsilon_i, i = 1, \ldots, n \quad (3)$$

where OLS(y_i) is the conditional mean of the dependent variable, β_0 is the constant, β_i are the coefficients, x_i are the independent variables, and ε_i is the error term. As an extension of the OLS form, the quantile regression followed:

$$Q_\tau(y_i) = \beta_0(\tau) + \beta_1(\tau)x_{i1} + \cdots + \beta_p(\tau)x_{ip} + \varepsilon_i(\tau), i = 1, \ldots, n \quad (4)$$

where $Q_\tau(y_i)$ is the conditional median of response variable y_i at quantile τ ($0 < \tau < 1$).

For each model, quantile process plots were used to illustrate the entire range of coefficient values (standardized effects) across conditional quantiles of the dependent variables. For comparison, the OLS coefficients (constant, standardized) were also included in the plots. For both sets of coefficients, 95% confidence bands were included. Forest plots were used to make side-by-side comparisons of the effects of variables on richness and evenness diversity at selected quantiles (τ = 0.10, 0.25, 0.50, 0.75, 0.90.).

To further explore irrigation effects, the richness and evenness diversity of irrigated and rainfed crops were compared across climatic regions. Non-parametric Kruskal–Wallis and Dunn's post-hoc tests ($p < 0.05$) were used to determine significant differences across climatic regions. Finally, national-level crop species richness and evenness diversity and the irrigation and maize land ratios were mapped. All analyses were performed with JMP Pro 15.2.1 (SAS Institute, Cary, NC, USA).

3. Results

About 19% of municipality cropland received irrigation and about 28% received chemical fertilizers (Table 1). About one-half (49%) of cropland was dedicated to maize cultivation, which broadly aligns with previous studies [61,62]. On average, about 25% of farms cited the costs of inputs as a primary challenge, about 25% cited soil infertility, and more than one-half (54%) cited the challenge of commercializing or marketing crops. On average, about one-third (32%) of farms relied on mechanized labor and about 72% practiced subsistence agriculture. About 65% of municipalities had small (2–5 ha) or medium (5–15 ha) MFA (35 and 30%, respectively), and about 17%, 14%, and 4% had very small (0–2 ha), large (15–50 ha), or very large (>50 ha) MFA.

3.1. Model Results (OLS)

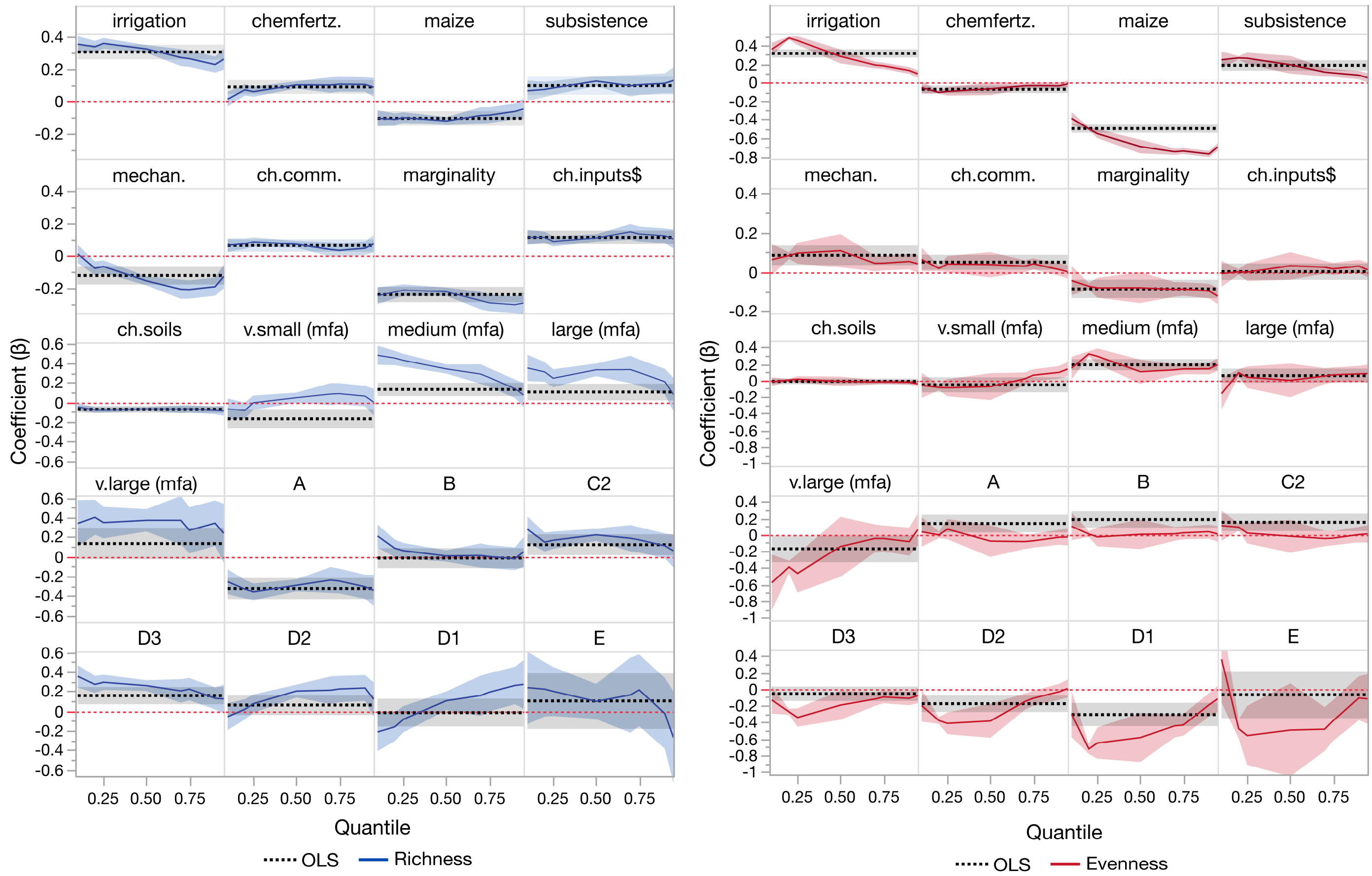
OLS models explained about 40% of the variances in both crop richness and evenness diversity, with adjusted r-squared values of 0.38 and 0.39, respectively (Tables A1 and A2). These values were similar to that of a previous national-level study on the determinants of CSD [47]. The irrigation land ratio had the strongest positive effect on richness diversity (0.30), which was twice the effect of the next strongest positive predictor, location in the light semiarid (D3) climate region (0.15). The irrigation land ratio also had the strongest positive effect on evenness diversity (0.31), followed by subsistence agriculture (0.19), medium MFA (0.19), and location in the humid (B) region.

The strongest negative effects on richness diversity were location in the humid (B) region (−0.33), marginality level (−0.24), very small MFA (−0.17), mechanization challenges (−0.12), and the maize land ratio (−0.11). The strongest negative effects on evenness diversity were the maize land ratio (−0.50), locations in the semiarid dry (D1) and semiarid moderate (D2) regions (−0.31 and −0.18, respectively), and very large MFA (−0.17).

3.2. Model Results (Quantile)

The irritation land ratio also had the strongest positive effects on both richness and evenness diversity under quantile regression (Figure 2a,b). Importantly, the positive effects on evenness diversity were up to five times larger in lower quantiles than in higher quantiles: effects in the 10th, 20th, and 25th quantiles of evenness diversity were 0.36, 0.50, and 0.35, respectively; while in the 75th, 90th, and 95th quantiles the effects were 0.18, 0.13, and 0.10, respectively (Figure 2b). Additionally, the positive effects of medium MFA on richness diversity were more than three times as large in lower quantiles than in higher quantiles, which differed significantly from OLS results (i.e., where the 95% confidence intervals did not overlap).

The negative effects identified in OLS regression were mostly confirmed by quantile regression, except in the case of the maize land ratio effect on evenness diversity. Though maize continued to have the strongest effects, these varied by quantile, falling well below the lower boundary of the OLS confidence band (Figure 2b). In contrast to the effects pattern of irrigation, the negative effects of the maize land ratio were about twice as large in higher quantiles of evenness diversity than in lower quantiles (−0.8 to −0.4, respectively). In other words, while the maize land ratio negatively predicted crop evenness diversity across all quantiles, the effects were twice as large in municipalities with higher, rather than lower evenness diversity. As in the case of the irrigation land ratio, these quantile distinctions were not detectable under standard OLS regression.



(**a**) (**b**)

Figure 2. Process plots for quantile and OLS regressions on (**a**) crop richness and (**b**) evenness diversity. Standardized coefficients shown with 95% confidence bands. Effects are statistically significant where shaded bands do not intersect with zero (dashed red line). Differences between quantile and OLS effects are statistically significant where confidence bands do not overlap. See Table 1 for variable explanations.

3.3. Forest Plot Comparisons

Side-by-side comparison of richness and evenness models showed irrigation effects were relatively consistent and stronger at lower, rather than higher quantiles (Figure 3). In contrast, the negative effects of maize on richness and evenness diversity were less consistent, with strong negative effects on evenness diversity but weaker effects on richness diversity. In addition, while the negative effects of maize on richness were small across all quantiles (−0.06 to −0.11), the effects on evenness were large, ranging from −0.39 in lower quantiles to −0.77 in higher quantiles.

Aridity generally had negative effects on evenness diversity, though its effects on richness diversity varied widely across quantiles. These tended to be positive in the moderately dry regions (e.g., C2, D3, D2), negative in the most humid region (A), and small and insignificant in the most arid regions (e.g., D1 and E). Overall, analyses show that the effects of climate on crop diversity, once adjusted for other factors, were either small or statistically insignificant compared to the effects of the irrigation and maize land ratios.

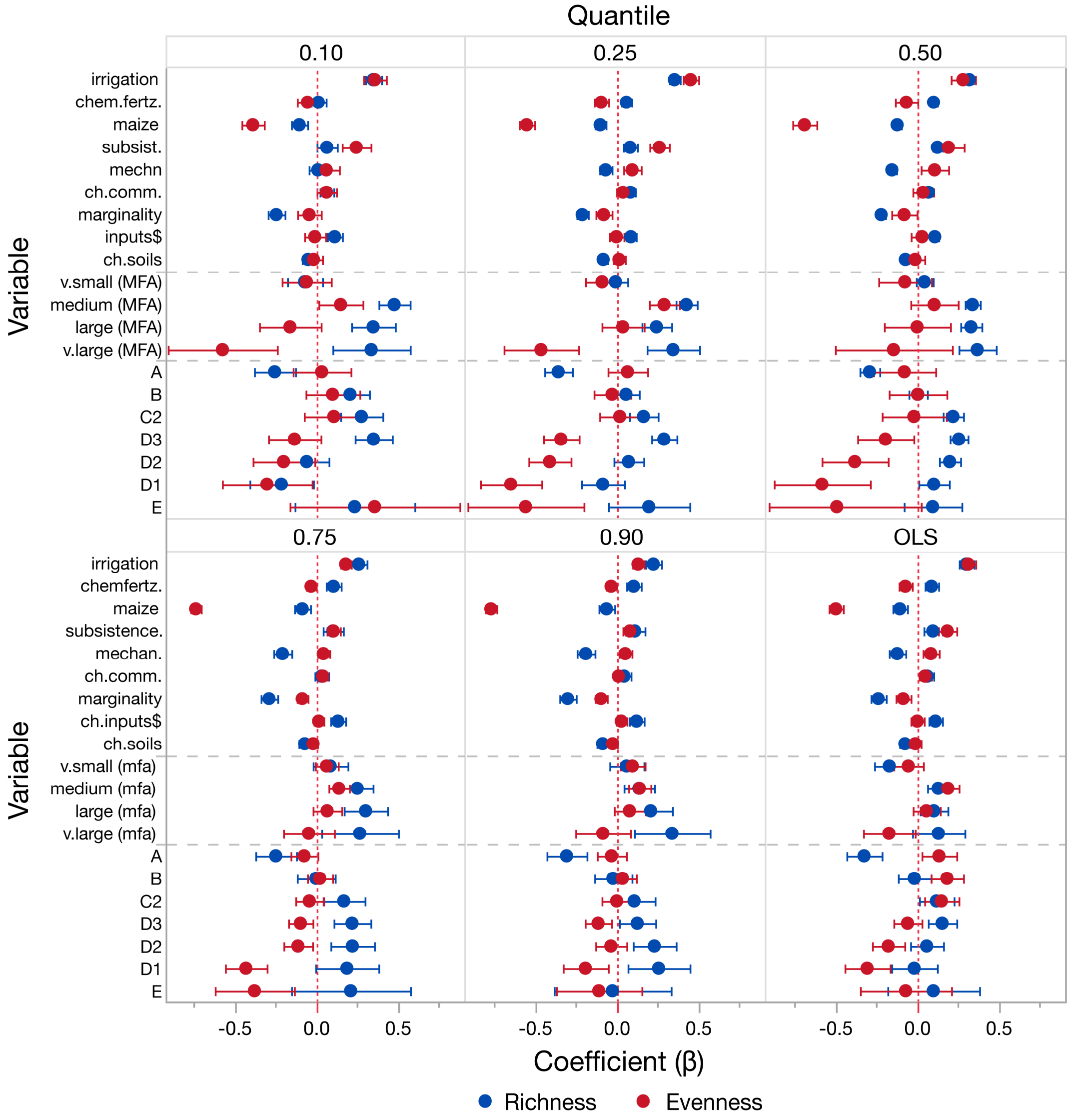


Figure 3. Standardized effects on crop species richness and evenness diversity for quantile and OLS regressions. Error bars represent 95% confidence intervals. Effects are statistically significant when bars do not intersect with zero (dashed red line).

3.4. Rainfed and Irrigated Crop Diversity

When stratified across climate regions, the richness of rainfed CSD varied little, with small and statistically significant differences in only a few regions (Figure 4). The evenness of rainfed CSD varied even less, with no significant differences detected across climate regions. In contrast, irrigated CSD was generally higher than rainfed CSD, except in the most humid (A) region. The gap between rainfed and irrigated CSD tended to widen as aridity increased. The increase was also reflected in the irrigation land ratio—about 70% of cropland received irrigation in the two most arid regions (D1 and E), while less than 22% received irrigation in all other climate regions. The reverse trend was observed for maize, which was cultivated on less than 10% of cropland in the D1 and E regions, but on more than 40% in all other regions.

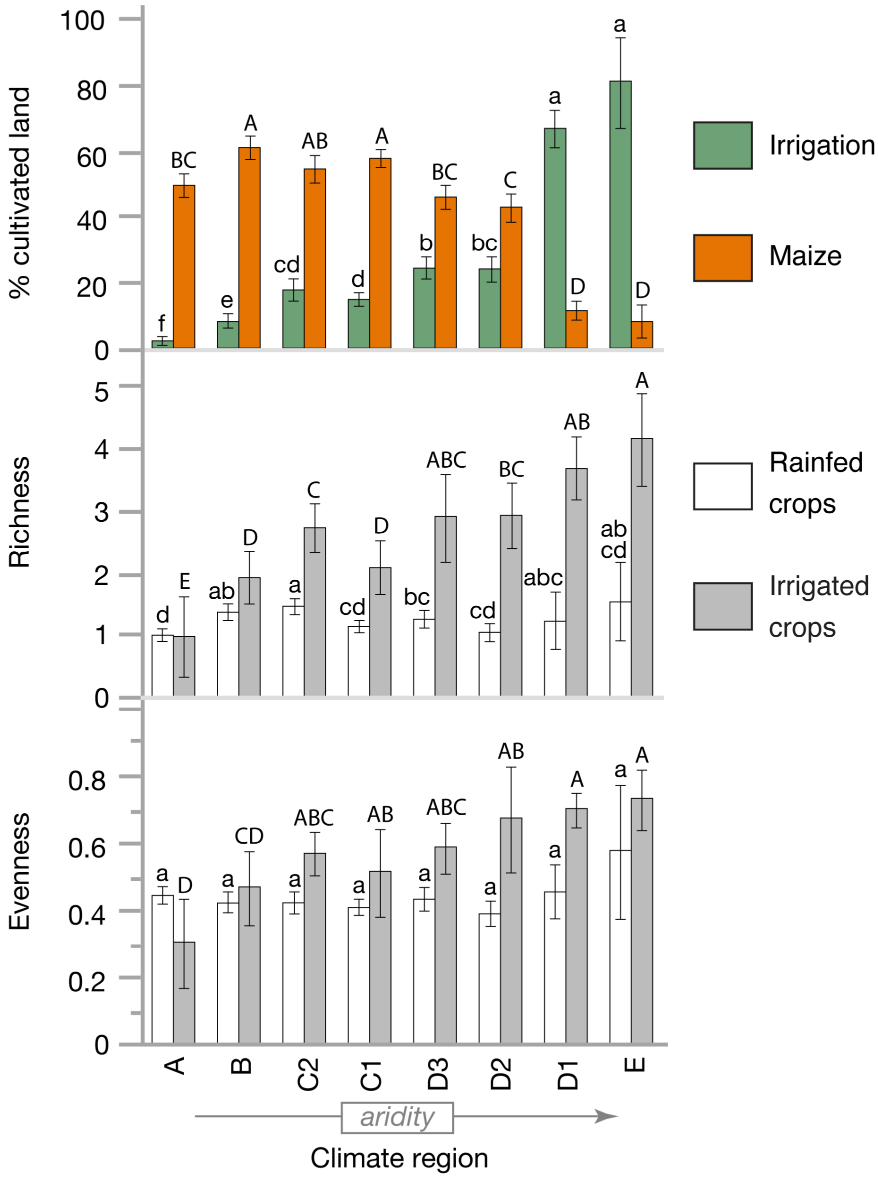


Figure 4. Evenness and richness diversity of rainfed and irrigated crops and the percent of cultivated land irrigated and harvested with maize, all by climate region (see Table 1). Error bars show 95% means confidence intervals. Climate region differences within each category are statistically significant where no letters are shared (Kruskal–Wallis and Dunn's post hoc).

At the municipality level, crop species richness and evenness tended to be highest in Mexico's northern regions, including the Baja Peninsula, northern Pacific coasts, and northern Central Tablelands (Figure 5a,b). Species diversity tended to be lowest in the Southern Highlands region, northwestern mountains, and some areas in the Yucatán Peninsula. The share of cropland receiving irrigation was highest in municipalities of the northern border regions and in isolated patches of central and south-central Mexico (Figure 5c). In contrast, the share of cropland cultivated with maize was highest in the Southern Highlands, Chiapas, the Yucatán Peninsula, and the northwestern and eastern mountains regions (Figure 5d).

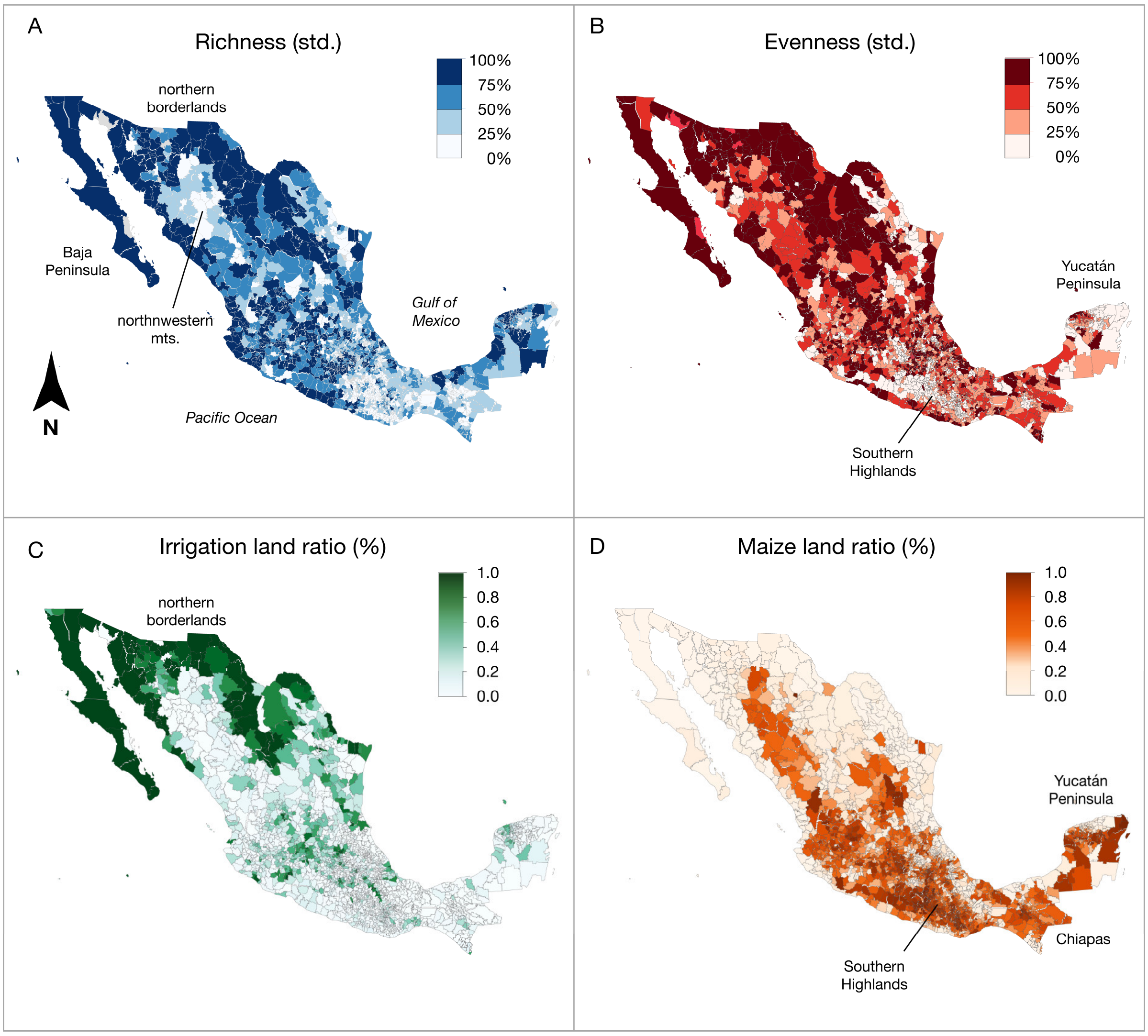


Figure 5. Crop species (**A**) richness and (**B**) evenness diversity (quartiles), and percent of cultivated land (**C**) irrigated and (**D**) under maize production by municipality (n = 2455).

4. Discussion

4.1. Irrigation Enhances Crop Species Richness and Evenness Diversity

The main objective of this study was to determine how irrigation influences CSD at regional and national levels in Mexico. As a broad category of agricultural change, intensification generally leads to crop diversity loss, though the effects of individual inputs on diversity have been poorly understood.

Irrigation is a primary component of agricultural intensification, whether defined as a farm input [63], a driver of increased productivity [64], or both [65]. Irrigation is also at the center of debates over the future of agricultural systems, water resources management, and sustainable development [66,67]. Although the relationship between irrigation and crop diversity has received little direct attention, existing studies suggest two distinct types of effects.

First, irrigation leads to greater crop diversity when farmers take advantage of the broader range of crops that can be grown due to enhanced water availability [26]. This pattern has been observed in farm-, landscape-, and regional-level studies in India [68], Bolivia [69], Nepal [70], Bangladesh [71], Ethiopia [4,72], and several locations in Sub-Saharan Africa [73]. In these cases, irrigation-led diversification often produces value-added crops that can be sold for a greater profit or more nutritionally diverse crops, which can enhance food and nutritional security [74].

In contrast, irrigation leads to lower crop diversity (greater specialization) when farmers use the water to increase productivity (yield) but instead focus on a few water-intensive, high-yielding monocrops [75–77]. Examples are found in several Asian counties where expanded access to irrigation disincentivized shifts toward alternative crops and instead increased cultivation of water-intensive rice [78,79]. In Bangladesh, irrigation led to higher productivity but also to increased specialization in water-intensive wheat, which decreased overall crop diversity [76]. Under both positive- and negative-effect scenarios, studies cite the contextual nature of farmer decisions about diversifying or specializing production, which are largely driven by farm-level responses to perceived opportunities and constraints [80,81].

Only a few studies have assessed the relationships between irrigation and diversification at national levels. Studies from Slovakia [47] and the United States [82] found irrigation expansion led to greater CSD, while a study from China instead found it instead led to specialized monocropping [12]. In general, national-level understanding of the relationship is insufficient, which has served as a barrier to effective policies [83]. These policies increasingly view enhancing crop diversity as central to meeting sustainable development goals [26,84,85].

This study found a positive relationship between irrigation and CSD in Mexico. At regional and national levels, as the share of cropland receiving irrigation increased, crop species richness and evenness increased. This relationship held after controlling for socioeconomic and environmental factors and multiple farm structural and functional characteristics.

In the context of previous research on relationships between irrigation and farmer decision making (above), our study shows that in the aggregate (municipality level), farms in Mexico employ irrigation more to diversify than to specialize crop species production. Regionally, the effects of irrigation on CSD are tied to the availability of existing irrigation infrastructure and other farm-level factors. Though beyond the scope of this study, previous work shows that regional differences in irrigation intensity (Figure 4c) are strongly tied to existing socioeconomic inequalities and the influence of trade agreements [41,86]. As explained below, these differences also manifest as regional differences in municipality-level CSD.

4.2. Irrigation Has Stronger Effects in Regions of Low Crop Species Diversity

The second objective of this study was to determine how irrigation influences CSD across conditional quantiles of low-, middle-, and high-diversity regions. We found that while most variable effects were small or statistically insignificant, those of irrigation were large and statistically significant across quantile ranges. Further, the positive effects of irrigation on species richness were almost twice as large in low-diversity quantiles compared with high-diversity quantiles. An even greater difference was observed with species evenness, as irrigation effects were five times larger in low-diversity compared with high-diversity quantiles.

Interestingly, these findings align with a recent study on the marginal effects of irrigation on maize and wheat yield in Mexico. The study found diminishing marginal returns on yield from increases in the irrigation land ratio in municipalities already receiving high levels of irrigation [22]. The quantile effects on species diversity identified in this study, though distinct from the marginal effect on yield, suggest another form of diminishing returns from irrigation inputs. Together, both findings have implications for agricultural policy and water resources management in Mexico.

Recent studies also highlight the potential benefits of expanding irrigation access in southern Mexico. Southern agricultural regions are largely characterized by rainfed, maize-based cultivation, where crop water scarcity and low access to irrigation contribute to chronically low productivity [22,87,88]. However, southern Mexico has the country's largest reserves of replenishable freshwater resources [89]. Southern regions also have among the highest rates of poverty and are home to many marginalized indigenous communities. Targeted expansion of sustainable irrigation infrastructure (i.e., soft-path approaches) in southern regions could contribute to numerous sustainable development objectives aligned with Mexico's National Water Program priorities [40,41].

Calls to expand irrigation in southern regions come with growing recognition that irrigation strategies in northern regions are unsustainable. The large-scale hydraulic infrastructure built during the 20th century (i.e., hard-path infrastructure) is outdated, and agricultural water-use efficiency has plummeted in the region [41,89]. However, as this study illustrates, municipalities in these regions have among the highest levels of crop species diversity in the country—diversity that is strongly dependent on existing irrigation infrastructure. This pattern of dependency is similar to that of the United States, where the nation's highest levels of crop species diversity are largely dependent on unsustainable irrigation practices in California [82].

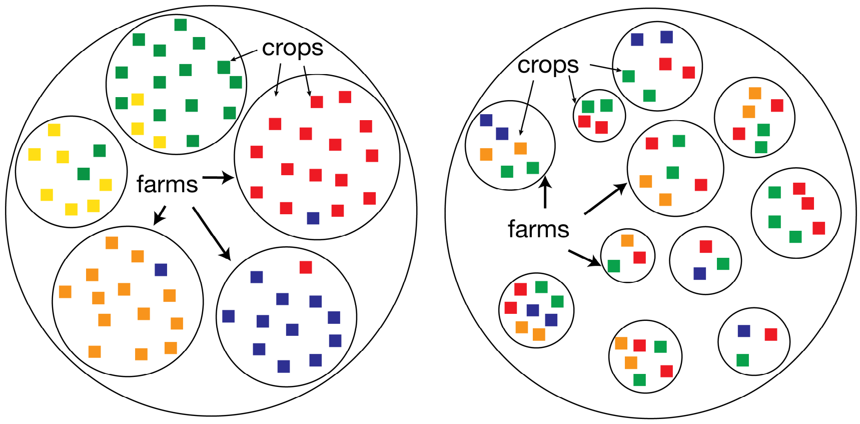
The strong effects of irrigation expansion on CSD observed in lower-quantile regions of southern Mexico adds support to calls for greater irrigation investment in this water-rich but irrigation-poor region, a condition expressed as agricultural-economic water scarcity [90]. To be effective and sustainable, irrigation expansion in the region must be: (1) based on participatory approaches to integrated watershed management [91], (2) carefully planned and targeted to priority regions and tailored to farm-level capacities and needs; (3) primarily limited to existing farmland [27], and (4) focused on building small-scale, 'soft-path' infrastructure that preserves environmental flows [92].

However, before changes in policy are made, a better understanding of the effects of irrigation on crop diversity at multiple taxonomic levels is needed. Specifically, understanding of the potential impacts of irrigation expansion on maize genetic diversity in Mexico is insufficient.

4.3. Crop Species Diversity and Scale: Important Distinctions

Importantly, our findings do not suggest that *farm-level* crop diversity is necessarily lower in regions of low municipality-level diversity (e.g., Southern Highlands). The level of spatial aggregation is a key consideration for measuring crop diversity, as larger-scale measures often differ from farm-level measures [48,93]. The level of spatial aggregation is especially relevant when assessing diversity across heterogeneous agricultural landscapes, where diversity measures are highly scale dependent [94].

To illustrate this point, Figure 6 depicts a hypothetical model of two Mexican municipalities (A and B) with different crop compositions. When measured at the farm level (interior circles), crop richness and evenness diversity are higher in municipality B (see also Figure 1). When measured at the municipality level (exterior circles), both richness and evenness diversity are higher in municipality A (more crop types and more even abundance of types).



Crop diversity	Municipality A	Municipality B
Farm scale		
Richness	—	+
Evenness	—	+
Municipality scale		
Richness	+	—
Evenness	+	—

Figure 6. Crop diversity measures are dependent on the level of aggregation. Municipalities A and B have different farm sizes and crop species compositions (colored squares). Municipality A has fewer but larger farms, and municipality B has more but smaller farms. At the farm scale (inner circles), municipality B has greater crop richness and evenness diversity than municipality A (see also Figure 1). At the municipality scale, municipality A has greater aggregate crop richness and evenness diversity than municipality B.

We suspect a similar pattern exists in regions of Mexico where farm-level diversity and municipality-level diversity contrast. If confirmed, the pattern would be consistent with: (1) the high municipality-level species richness and evenness diversity in northern irrigated regions observed in this study and (2) the high farm-level species diversity observed in smallholder milpa systems of southern Mexico [53]. Additional research on the gamma-, alpha-, and beta-diversity of crops in Mexico is needed to confirm this pattern [95], as is additional research into the possible interaction effects of farm-level factors on CSD.

4.4. Other Limitations

The determinants and effects of diversification vary widely according to the taxonomic level of crops under study [18,96,97]. In this study, we examined *species*-level crop diversity, including the singular species of maize (*Zea mays* L.). We did not consider the rich diversity of maize subspecies, varieties, and genetic (landrace) populations. Indeed, maize-based intercropping systems (milpa) are recognized as key reservoirs of in situ maize genetic diversity [98]. The regions of high maize genetic diversity identified in previous research [99] strongly correlate with the regions of high maize land ratios identified in Figure 4d. At the crop species level, however, we found that the same regions tended to have lower municipality-level crop richness and evenness (Figure 4a,b,d).

These taxonomic distinctions are especially relevant for understanding the potential effects of irrigation on diversity. While irrigation allows farmers to expand the range of crop species that can be grown, species diversification can also lead to genetic (within species) specialization. In the case of irrigation, changes in the hydrologic conditions under which crop landraces developed can render these landraces less able to compete with newly introduced species or cultivars [96].

In sum, crop diversity measures can increase and decrease simultaneously depending on several factors. These include crop taxonomy, the measurement techniques or diversity indices being used (e.g., richness vs. evenness), the spatial scales of analysis, and the levels of data aggregation (e.g., farm level, regional level, national level) [16,100]. Each of these factors has implications for how the different drivers of crop diversity ultimately impact biodiversity and ecosystem services [101]. Therefore, we caution against fully embracing irrigation expansion as a means of enhancing crop diversification without better understanding the full range of potential effects at different taxonomic, spatiotemporal, and functional levels.

5. Conclusions

Irrigation was a strong positive predictor of crop species richness and evenness diversity across Mexico. Moreover, irrigation effects were significantly larger in regions where municipality-level species richness and evenness diversity were lower. These findings have important implications for regional- and national-level water policy in Mexico, which is tasked with directing water management to achieve sustainable agricultural intensification. However, before promoting irrigation expansion in southern regions, careful ex ante assessment of the suitability of different forms of irrigation infrastructure (e.g., hard- vs. soft-path) is needed. Tradeoff assessments must first consider the potential effects of irrigation on agrodiversity across taxonomic levels, spatial scales, and agricultural contexts. Nonetheless, if targeted appropriately, sustainable irrigation expansion has strong potential to create synergies with multiple water policy priorities and sustainable development goals. Among these is the potential to enhance municipality-level crop species diversity.

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Appendix A

Table A1. Results of crop species richness models (OLS and quantile regressions).

Variable	OLS			Richness (Margalef) Quantile Regression														
				10th			25th			50th			75th			90th		
	β	SE		β	SE		β	SE		β	SE		β	SE		β	SE	
irrigation	0.30	0.02	***	0.35	0.03	***	0.35	0.02	***	0.32	0.01	***	0.26	0.02	***	0.23	0.02	***
chemfertz.	0.09	0.02	***	0.01	0.02		0.06	0.02	***	0.10	0.01	***	0.11	0.02	***	0.10	0.02	***
maize	−0.11	0.02	***	−0.10	0.03	***	−0.10	0.17	***	−0.12	0.01	***	−0.09	0.03	***	−0.06	0.02	**
ch.inputs $	0.11	0.02	***	0.11	0.02	***	0.09	0.02	***	0.11	0.01	***	0.13	0.02	***	0.12	0.02	***
ch.soils	−0.07	0.02	***	−0.05	0.02	**	−0.08	0.01	***	−0.07	0.01	***	−0.07	0.02	***	−0.09	0.02	***
ch.comm.	0.06	0.02	***	0.06	0.02	**	0.08	0.02	***	0.07	0.01	***	0.03	0.02		0.05	0.02	*
mechan.	−0.12	0.03	***	0.01	0.03		−0.07	0.02	***	−0.15	0.01	***	−0.21	0.03	***	−0.19	0.03	***
subsistance	0.10	0.03	***	0.06	0.03	*	0.08	0.02	***	0.12	0.02	***	0.10	0.03	**	0.11	0.03	***
marginality	−0.24	0.02	***	−0.25	0.03	***	−0.21	0.02	***	−0.22	0.01	***	−0.29	0.03	***	−0.30	0.03	***
v.small (mfa)	−0.17	0.05	***	−0.07	0.05		−0.01	0.04		0.04	0.03		0.09	0.05		0.06	0.05	
med. (mfa)	0.13	0.03	***	0.48	0.05	***	0.43	0.03	***	0.34	0.02	***	0.25	0.05	***	0.14	0.05	***
Large (mfa)	0.10	0.04	**	0.35	0.07	***	0.24	0.05	***	0.33	0.03	***	0.30	0.07	***	0.21	0.07	**
v.large (mfa)	0.13	0.08	***	0.34	0.12	**	0.35	0.08	***	0.37	0.06	***	0.27	0.12	*	0.34	0.12	**
A	−0.33	0.06	***	−0.26	0.06	***	−0.36	0.04	***	−0.29	0.03	***	−0.25	0.06	***	−0.31	0.06	***
B	−0.02	0.05		0.21	0.06	***	0.06	0.04		0.00	0.03		0.00	0.06		−0.02	0.06	
C2	0.12	0.05	*	0.28	0.07	***	0.16	0.05	***	0.22	0.03	***	0.17	0.07	**	0.11	0.06	
D3	0.15	0.04	***	0.35	0.06	***	0.29	0.04	***	0.26	0.03	***	0.22	0.06	***	0.13	0.06	*
D2	0.06	0.05		−0.06	0.07		0.07	0.05		0.20	0.03	***	0.22	0.07	**	0.23	0.07	***
D1	−0.02	0.07		−0.21	0.10	*	−0.09	0.07		0.10	0.05	*	0.19	0.10	*	0.26	0.10	**
E	0.10	0.14		0.24	0.19		0.20	0.13		0.10	0.09		0.21	0.19		−0.03	0.18	
Adj. R-sqr	0.38																	
F-test	73.29																	

* ($p \leq 0.05$), ** ($p \leq 0.01$), *** ($p \leq 0.001$), all VIF < 2.60.

Table A2. Results of crop species evenness models (OLS and quantile regressions).

Variable	OLS			Evenness (Simpson) Quantile Regression														
				10th			25th			50th			75th			90th		
	β	SE		β	SE		β	SE		β	SE		β	SE		β	SE	
irrigation	0.31	0.02	***	0.36	0.04	***	0.35	0.02	***	0.28	0.04	***	0.18	0.02	***	0.13	0.02	***
chemfertz.	−0.07	0.02	***	−0.05	0.03		0.06	0.02	***	−0.07	0.04		−0.03	0.02	*	−0.03	0.02	*
maize	−0.50	0.02	***	−0.39	0.04	***	−0.10	0.02	***	−0.69	0.04	***	−0.74	0.02	***	−0.77	0.02	***
ch.inputs $	0.00	0.02		−0.01	0.03		0.09	0.02	***	0.03	0.04		0.01	0.02		0.03	0.02	
ch.soils	−0.01	0.02		−0.02	0.03		−0.08	0.01	***	−0.01	0.03		−0.02	0.01		−0.02	0.01	
ch.comm.	0.05	0.02	**	0.06	0.03	*	0.08	0.01	***	0.04	0.03		0.04	0.01	**	0.01	0.02	
mechan.	0.08	0.03	***	0.06	0.04		−0.07	0.02	***	0.11	0.04	*	0.04	0.02	*	0.05	0.02	**
subsistance	0.19	0.03	***	0.25	0.04	***	0.08	0.02	***	0.19	0.05	***	0.10	0.02	***	0.08	0.02	***
marginality	−0.09	0.02	***	−0.04	0.04		−0.21	0.02	***	−0.08	0.04	*	−0.09	0.02	***	−0.10	0.02	***
v.small (mfa)	−0.05	0.05		−0.06	0.08		−0.01	0.04		−0.08	0.08		0.06	0.04		0.10	0.04	*
med. (mfa)	0.19	0.03	***	0.15	0.07	*	0.43	0.03	***	0.10	0.07		0.14	0.03	***	0.14	0.03	***
Large (mfa)	0.06	0.04		−0.16	0.10		0.24	0.05	***	0.00	0.10		0.07	0.05		0.08	0.05	
v.large (mfa)	−0.17	0.08	*	−0.58	0.17	***	0.35	0.08	***	−0.14	0.18		−0.05	0.08		−0.08	0.09	
A	0.13	0.05	*	0.03	0.09		−0.36	0.04	***	−0.08	0.10		−0.07	0.04		−0.03	0.05	
B	0.18	0.05	***	0.10	0.08		0.06	0.04		0.00	0.09		0.02	0.04		0.04	0.04	
C2	0.15	0.05	**	0.11	0.09		0.16	0.04	***	−0.02	0.10		−0.04	0.04		0.00	0.05	
D3	−0.06	0.04		−0.13	0.08		0.29	0.04	***	−0.19	0.09	*	−0.10	0.04	*	−0.11	0.04	**
D2	−0.18	0.05	***	−0.20	0.10	*	0.07	0.05		−0.38	0.10	***	−0.11	0.05	*	−0.04	0.05	
D1	−0.31	0.07	***	−0.30	0.14	*	−0.09	0.07		−0.58	0.15	***	−0.43	0.07	***	−0.19	0.07	**
E	−0.07	0.14		0.36	0.27		0.20	0.13		−0.49	0.29		−0.38	0.12	**	−0.11	0.13	
Adj. R-sqr	0.39																	
F-test	76.78																	

* ($p \leq 0.05$), ** ($p \leq 0.01$), *** ($p \leq 0.001$), all VIF < 2.56.

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