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Estimating Yield Response Functions to Nitrogen for Annual Crops in Iran

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Abstract: Nitrate is a crucial element for crop growth, and its optimal application is essential for maximizing agricultural yield. In Iranian agriculture, there is a substantial gap between recommended nitrate usage and what farmers actually apply. In this study, our primary objective is to determine the most effective utilization of nitrate for crop cultivation. Simultaneously, we aim to analyze the factors that contribute to the disparity between optimal and current nitrate application practices. Furthermore, our research explores the impact of these differences on regional variations in crop yields. This is achieved using a quadratic yield response function model based on unbalanced panel data spanning the years 2000 to 2016, which includes a total of 14 crop activities and encompasses 31 administrative regions. The results show that rice exhibits the highest nitrogen usage, while rain-fed wheat demonstrates the lowest utilization at the optimal point. Depending on whether random- or fixed-effects estimation is found to be the most suitable specification, average yields corresponding to the optimal level of nitrogen use are calculated by region, or the average across all regions. In Iran, the top-performing regions for cereals like rain-fed wheat and irrigated barley can achieve yields of 1.33 and 3 t/ha, respectively. These yields represent a 31% and a 9% increase from the levels observed in 2016. The outcomes derived from the estimated yield response function will be integrated into comprehensive agricultural, economic, and environmental optimization models. These integrated models will facilitate the assessment of various fertilizer policies on fertilizer use, land allocation, farm-household incomes, and environmental externalities, such as nitrate leaching and nitrate balance. This study holds substantial scientific promise, given its exploration of the policy implications surrounding fertilizer usage, making it crucial not only for Iran, but also for many developing nations grappling with inefficient and unsustainable agricultural practices. It represents the first of its kind in the literature, providing estimations of optimal nitrogen use and crop yield points across all regions in Iran. This is achieved through advanced visualization using GIS maps.

Keywords: optimal crop yield; nitrogen fertilizer; quadratic yield response function; Iran

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1. Introduction

For four decades, addressing the food supply for a growing population has been a top priority for the Islamic Republic of Iran. The agricultural sector, contributing 12.4% to the GDP, plays a vital role by supplying 87% of the food, utilizing 10% of the land, and employing 19% of the labor force [1]. In Iran, crops dominate the agricultural landscape, contributing 50% of the sector's value added in the past decade, involving approximately 3 million active production units. Crop production's value and added value were EUR 34.6 billion and EUR 17.3 billion, respectively, with growth rates of 4% and 5%. The total cultivated area is about 30 million hectares, comprising 70% irrigated land and 30% rain-fed land, with 20 million hectares dedicated to annual crops and 10 million hectares to permanent crops [2]. However, the Iranian agricultural sector grapples with challenges like scarce resources, low productivity, limited market access, technological gaps, insecure land tenure, and climate change [3].

The Iranian government has implemented a range of policies, including subsidy reform [4], investment in irrigation infrastructure, water management [5], R&D support, extension services, agricultural insurance, land tenure reforms [6], improved market access, export promotion, and price support, to overcome agricultural sector challenges [7]. These policies are designed to tackle urgent challenges in Iranian agriculture. However, their effectiveness and impact can vary, with one common goal in mind: assisting farmers in enhancing their production and productivity. To meet Iran's increasing food demand in the face of a growing population, limited resources, and land with poor soil fertility, it is crucial to increase agricultural yields by adopting more intensive farming practices and optimizing inputs, particularly fertilizer use [8].

Enhancing nitrate utilization in Iranian agriculture is key to improving crop productivity [9]. Iran's diverse soil profiles, influenced by varied geology and vegetation, impact nitrate availability [10]. The challenge intensifies in Iran's agro-climatic zones, including arid, semiarid, humid, sub-humid, and tropical semiarid regions, where climate factors notably affect nitrogen use in agriculture. Predominantly arid soils like Calcids, Gypsids, Salids, Cambids, Entisols, and Inceptisols cover 97% of Iran's land, mainly in arid and semiarid zones, while Mollisols, Alfisols, and Ultisols in the Caspian Sea region constitute less than 3% [11]. With only 12% of land cultivated, and less than a third irrigated, nitrogen, vital for crop growth, presents challenges, as only a small portion is readily available in the soil, and mineral nitrogen makes up only 2% [12]. Chemical nitrate fertilizers help bridge this gap, but their excessive use can lead to detrimental effects, while deficiency results in stunted, yellowing plants with compromised growth [13].

Due to the diverse climate conditions and soil management practices across Iran's regions, a considerable gap exists between the optimal use of nitrates and their actual application by farmers. This disparity notably impacts yield variations in agriculture [14]. Addressing this difference necessitates precise estimation of the yield response function to nitrogen fertilizer, which determines the most effective application rates [15]. This function emerges as a cornerstone in agriculture, offering multifaceted advantages. It allows the adjustment of nitrogen application rates to change in an economic context (i.e., changes in input and output prices), in terms of climate change (the mitigation of CO_2 emissions and greenhouse gases), and under different policy options [4]. It also enables precision farming [16], allowing targeted nitrogen applications based on soil variations and crop requirements, preventing both over-fertilization and under-fertilization [17]. As climate and soil conditions evolve, re-estimating the yield response function empowers farmers to make informed decisions, adapting nitrogen management practices to the dynamic agricultural landscape [18].

In the Iranian context, the pioneering contribution that stands out for this study is its high spatial resolution, utilizing advanced visualization techniques such as GIS maps to showcase diverse crop rotations and variations in both optimal and actual yields. Leveraging unbalanced panel data from 2000 to 2016 adds temporal relevance to the results, contributing to a dynamic understanding of changes and trends in nitrate application practices and crop yields over the years. A methodological innovation in this study is the use of a quadratic yield response function model, offering a more nuanced understanding of nonlinear yield responses compared to common linear models. Notably, the detailed maps presented in this study are unavailable from established international sources, highlighting their unique and valuable contribution to the scientific community. This research addresses the gap in utilizing optimal yield in farm models for optimization solutions, particularly within the context of farming system simulation models using regional crop programming. By providing crucial primary and secondary information for calibrating models based on optimal yield values, this study provides a more comprehensive understanding of the practical implications of optimal yield in agricultural management and policy decision making [4,6].

This study introduces a distinctive innovation within the existing literature by addressing limitations identified in prior research. While conventional approaches have often employed stochastic plateau functional forms, this work breaks new ground by incorporating the quadratic form into yield response functions. This departure from the norm not only provides a more nuanced explanation for crop responses to nutrient application but also notably enhances the accuracy and robustness of the models [14]. In contrast to studies emphasizing the broader context of agroecosystem dynamics and crop diversity, our primary focus on nutrient application highlights a specific and critical facet of crop management [19]. Moreover, this research aligns with the themes explored in an editorial that emphasizes the interconnected nature of crop traits [20]. This study also underscores the importance of advanced statistical approaches and modeling techniques for national and regional crop yield predictions [21]. By referencing research on spatial variability in crop responses and crop yield responses to water, this study places strong emphasis on regional-scale analyses and the consideration of diverse factors influencing crop yield, contributing to a more holistic understanding of agricultural practices [22,23].

2. Methodology

Experts in agronomy and economics emphasize aligning crop production with fertilizer use, but selecting precise response function forms from empirical data poses challenges due to uncertainties in their shapes and skewness. The literature offers various forms based on theory and data, evaluated by researchers like [24], who assessed 20 functions for criteria such as concavity and goodness-of-fit. Others, like [25], outlined methods for crafting predictive equations from field data. However, many researchers advocate for estimating crop responses with smooth, concave functions, often quadratic in nature [14].

The quadratic function has long been fundamental in modeling crop yield response to nutrients. It suggests that increasing inputs boosts yield until the maximum potential is reached, after which more inputs result in reduced output. Its advantages include addressing diminishing marginal productivity and concavity, offering solutions for optimal input levels, and solving fertilization issues efficiently. These traits, along with its linear parameterization, explain its widespread use. It can be mathematically expressed for nitrate application as [14]

$$Y_i = \beta_0 + \beta_1 N_i + \beta_2 N_i^2 + \varepsilon_i \tag{1}$$

where Y_i is crop yield, N_i is an applied nitrate, N_i^2 is the square of applied nitrate, β_0, β_1, and β_2 are parameters, and $\varepsilon_i \sim N(0, \sigma^2 e)$ is a random disturbance term. The optimal nitrate rate (N^*) is:

$$N^* = \frac{\beta_1}{2\beta_2} \tag{2}$$

In this study, an unbalanced panel dataset is employed to derive yield response functions for 14 annual crops across a 16-year timeframe (2000–2016). This analysis aims to determine the optimal nitrate application rate and the corresponding optimal yield for each crop. Consequently, Equation (3) is reformulated from Equation (1) to conform to a general panel format, presented as follows:

$$\begin{gathered} Y_{it} = \beta_{\mathrm{it}} + \beta_{1\mathrm{it}} N_{it} + \beta_{2\mathrm{it}} N_{it}^2 + \varepsilon_{it} \\ i = 1, \ldots, N \\ t = 1, \ldots, T \end{gathered} \tag{3}$$

where (i) is the individual dimension (region) and (t) is the time dimension. Furthermore, the collected regional-level rainfall data spanning a 16-year period serve as specific parameters (rainfall) in estimating the yield response function, as demonstrated by the following equation:

$$\begin{gathered} Y_{it} = \beta_{\mathrm{it}} + \beta_{1\mathrm{it}} N_{it} + \beta_{2\mathrm{it}} N_{it}^{2} + \beta_{3\mathrm{i}} \mathrm{Rainfall} + \varepsilon_{it} \\ i = 1, \ldots, N \\ t = 1, \ldots, T \end{gathered} \tag{4}$$

Using unbalanced panel data offers unique advantages. Unlike balanced panels, unbalanced datasets adapt to variations in observations across entities or time periods, providing a more realistic view of real-world phenomena. This flexibility captures dynamic changes, accounting for evolving entity characteristics over time, offering a deeper understanding of complex relationships. Unbalanced panels also increase statistical power by using diverse samples or time spans, minimizing bias and improving efficiency [26]. They enable control for individual unobserved heterogeneity, potentially improving the robustness and generalizability of findings, and allow the exploration of both within- and between-entity variations, providing a nuanced understanding of influencing factors [27].

In dealing with unbalanced panel data, the choice between fixed and random-effects models holds crucial importance. Fixed effects handle unobserved individual-specific effects in longitudinal datasets. In unbalanced panel data, where entities are observed over time, individual-specific characteristics can affect the dependent variable. Using individual-specific dummy variables, fixed effects mitigate these effects, focusing on the time-varying impacts of independent variables [28]. This method controls for time-invariant differences among individuals, assuming these traits are unique and uncorrelated with other individual characteristics. A simple fixed-effects model for data observed for a region (*i*) across time (*t*) can be described by the following equation [29]:

$$\begin{gathered} Y_{it} = \beta_{\mathrm{i}} + \beta_{1} N_{it} + \beta_{2} N_{it}^{2} + \beta_{3\mathrm{i}} \mathrm{Rainfall} + \varepsilon_{it} \\ i = 1, \ldots, N \\ t = 1, \ldots, T \end{gathered} \tag{5}$$

where (β_1) is the coefficient for the independent variable. The interpretation of this coefficient would be as follows: for a given entity (region), as nitrate varies across time by one unit, yield increases or decreases by (β_1) units. (β_{i}) is the unobserved entity-specific time-constant error term. It is possibly correlated with (N_{it}) and (N_{it}^2). (ε_{it}) is the error term. This is assumed to be uncorrelated with (N_{it}) and (N_{it}^2).

Random effects treat individual-specific effects as random and uncorrelated variables to handle unobserved heterogeneity [30]. Unlike fixed effects, they allow for variability in these effects and estimate the average impact of independent variables on the dependent variable, accounting for time-varying and time-invariant unobserved factors. They are used when there are concerns about unobserved heterogeneity affecting coefficients, assuming individual-specific effects are genuinely random and unrelated to independent variables [31]. An advantage of random effects is their inclusion of time-invariant variables, unlike fixed effects, where the intercept absorbs all such variables. A simple random-effects model for data observed for region (*i*) across time (*t*) can be described by the following equation:

$$\begin{gathered} Y_{it} = \alpha_{0} + \beta_{\mathrm{i}} + \beta_{1} N_{it} + \beta_{2} N_{it}^{2} + \beta_{3\mathrm{i}} \mathrm{Rainfall} + \varepsilon_{it} \\ i = 1, \ldots, N \\ t = 1, \ldots, T \end{gathered} \tag{6}$$

where (α_0) is the intercept and, contrary to the fixed effect, it can be estimated. (β_{i}) is the unobserved entity-specific time-constant error term. Contrary to fixed effect, it is possibly correlated with (N_{it}) and (N_{it}^2).

The Hausman test in econometrics helps decide between fixed-effects models (assuming constant parameters but allowing for individual-specific effects) and random-effects models (assuming uncorrelated individual-specific effects with the regressors). It tests whether individual-specific effects (random effects) correlate with the model's regressors. If the null hypothesis is not rejected, indicating no systematic relation between individual effects and independent variables, a random-effects model might be suitable. Rejecting the null suggests inconsistency in the random-effects model, favoring fixed effects to address correlated individual-specific effects with regressors [32].

In this study, a crop-specific quadratic yield response function to nitrogen fertilizer is econometrically estimated using a fixed- or random-effects specification following the Hausman test, under the assumption that yield is independent of the acreage planted. Crop yield and nitrogen application rate are the main coefficients in the regression model. However, the inclusion of rainfall per millimeter in the model serves the purpose of enhancing model fitness and robustness. The other fertilizer elements (P and K) are assumed to be applied in a fixed proportion to nitrogen (N) fertilizer, and the remaining inputs, such as pesticides, labor use, etc., are assumed to be independent of fertilizer and employed at a fixed rate by hectare of each specific crop [33] (This assumption lacks rationalization given the strong relationship between nitrate and other inputs. However, due to the lack of data to make a reliable estimate of this relationship, and in order to avoid additional bias, we adopted this assumption following previous studies [34–36].).

Data and Information

The yield response function model relies on the Iranian Agriculture Ministry Jihad [2] database, derived from annual reports aggregating individual farm data collected through surveys. The Information and Communication Technology Centre of the Iranian Agriculture Ministry (ICTC-IMAJ) uses these data to derive input/output quantities via the Cost Bank System (CBS). These databases offer detailed regional info on five crop groups: cereals, legumes, vegetables, industrial crops, and melons. Unbalanced panel data from 2000 to 2016, covering 14 crops, utilize these sources.

Our decision to employ regional models in this study is grounded in the distinctive characteristics of arable farms in Iran. With over 70% of the country's farms being smallholders with less than 3 hectares of land, the relative homogeneity of these farms played a crucial role in shaping our research methodology. This homogeneity not only allowed us to effectively capture the prevailing agricultural landscape, but also facilitated a more nuanced understanding of regional dynamics. An important contributing factor to this homogeneity is the shared technology and equipment among the majority of these smallholder farms, further emphasizing the practicality of utilizing regional models. The prevalence of similar agricultural practices within each region enhances the representativeness of our approach, enabling us to extrapolate our findings to individual farms or fields within those regions.

It is worth noting that, in the broader agricultural context of Iran, large-scale farms constitute a minimal percentage, accounting for less than 0.2% of agricultural holdings. Excluding these large-scale entities, arable farms within the same region exhibit a notable degree of homogeneity, a point underscored by [3]. This relative uniformity in farm size, technology, and equipment within regions led us to conceptualize each region as emblematic of individual farms or fields, thereby providing a solid foundation for our regional modeling approach. Moreover, the decision to employ regional data for assessing nitrate yield response functions is grounded in several considerations aligned with the goals and nature of this research. Firstly, the real-world applicability of the findings is enhanced by capturing the diverse and complex interactions influencing nitrate yields in specific geographic areas. Secondly, the cost-effectiveness of utilizing existing databases, surveys, and observational records for regional data aligns with the resource-efficient nature of the study. Lastly, longitudinal studies facilitated by regional data enable the examination of temporal patterns and changes in nitrate yield responses, offering insights into their dynamics over time [37–39].

Table 1 presents the key statistics for 14 crops in Iran, covering variables like cultivated areas, production, yield, fertilizer, and nitrate application rates across 31 regions averaged over three years. Wheat and barley occupy the largest cultivated areas but yield around 2 t/ha each. In contrast, rice and maize show higher yields at 5 and 7 t/ha, respectively. Cucumber and onion also exhibit high yields at 21 and 37 t/ha, while legumes perform sub-optimally at less than 1 t/ha each. The data reveal a trend of increased fertilizer usage correlating with higher yields, notably exceeding 500 (kg/ha) for high-yield crops like sugar beet and tomato. This trend of intensified fertilizer use aligns with onion and rice cultivation, where usage exceeds 1000 (kg/ha). However, the relationship between increased fertilizer application and nitrate use is evident in the percentage share of nitrate from fertilizer, exceeding 60% in most crops. This highlights the need to assess the optimal balance between nitrate application for maximizing yields in Iranian agriculture, crucial due to the reliance on nitrate-heavy fertilizers and farmers' inclination to amplify fertilizer application for higher yields.

Table 1. Statistical characteristics of variables.

Group	Crops	Area under Cultivation (1000 ha)	Production (1000 ton)	Yield (t/ha)	Fertilizer Use [1] (kg/ha)	Nitrate Use (kg/ha)	Nitrate Contribution from Fertilizer (%)
Cereals	Wheat	5894.07	12,117.70	2.06	302.02	194.46	64.39
	Barley	1739.84	3281.66	1.89	171.97	110.06	64.00
	Rice	332.58	1737.17	5.22	1127.29	695.03	61.65
	Maize	173.53	1249.70	7.20	677.63	441.84	65.20
Legumes	Peas	492.56	236.67	0.48	18.49	11.45	61.93
	Lentils	134.57	74.71	0.56	5.13	3.36	65.50
Vegetables	Tomato	118.76	4878.06	41.08	676.35	427.57	63.22
	Potato	148.45	4726.75	31.84	620.01	371.17	59.87
	Onion	50.16	1861.46	37.11	1033.77	629.38	60.88
Industrial	Sugar beet	100.66	5278.90	52.44	587.20	350.48	59.69
	Canola	60.01	93.63	1.56	425.24	259.02	60.91
	Cotton	72.09	166.30	2.31	132.61	81.2	61.23
Melons	Cucumber	46.25	1007.52	21.78	307.87	209.55	68.06
	Watermelon	112.39	3099.80	27.58	487.34	288.78	59.26
MIN		46.25	74.71	0.48	288.78	3.36	59.26
MAX		5894.07	12,117.70	52.44	1127.29	695.03	68.06
STDEV		1564.68	3248.38	18.14	345.43	211.90	2.58

[1] "Nitrate use" refers to the consumption of nitrate, and "fertilizer use" pertains to the quantity of nitrogen (N), phosphorus (P), and potassium (K) consumed and utilized for each crop. Source: ICTC-IMAJ. Three-year average around 2015 (2014–2016).

3. Results

In choosing the quadratic form for modeling nitrate yield response using unbalanced data, distinguishing fixed or random effects for different crops was crucial to optimize yield and nitrate use. The Hausman test helped determine these effects. Notably, significant Chi-squared values at the 1% level were found for rain-fed barley and irrigated lentils, cotton, cucumber, and watermelon, while the remaining crops showed significance at the 5% level. Further analysis using the Hausman test underscores intriguing distinctions among regions. For irrigated wheat, rice, lentils, sugar beet, cotton, and cucumber and rain-fed barley and watermelon, the absence of regional disparities implies uniform intercepts and optimal yield values across all regions for these crops. Conversely, the results indicate fixed effects for rain-fed wheat, peas, lentils, and canola, and irrigated barley, maize, peas, tomato, potato, onion, canola, and watermelon. This suggests distinct intercepts and optimal yields unique to each region for these specified crops, aligning with the specific characteristics prevalent in each production region (Table 2).

Table 2. Hausman test results for determining fixed or random effects in crops [1].

Group	Crop	Technology	Chi-Squared (χ^2)	Fixed Effect/Random Effect
Cereals	Wheat	Rain-fed	46.23 (0.00) *	Fixed effect
		Irrigated	6.43 (0.02) *	Random effect
	Barley	Rain-fed	4.84 (0.08) **	Random effect
		Irrigated	13.75 (0.00) *	Fixed effect
	Rice	Irrigated	5.89 (0.03) *	Random effect
	Maize	Irrigated	16.28 (0.00) *	Fixed effect
Legumes	Peas	Rain-fed	12.13 (0.00) *	Fixed effect
		Irrigated	14.53 (0.00) *	Fixed effect
	Lentils	Rain-fed	21.34 (0.00) *	Fixed effect
		Irrigated	5.10 (0.05) **	Random effect
Vegetables	Tomato	Irrigated	20.76 (0.00) *	Fixed effect
	Potato	Irrigated	12.53 (0.00) *	Fixed effect
	Onion	Irrigated	19.23 (0.00) *	Fixed effect
Industrial	Sugar beet	Irrigated	10.28 (0.03) *	Random effect
	Canola	Rain-fed	17.05 (0.00) *	Fixed effect
		Irrigated	11.01 (0.01) *	Fixed effect
	Cotton	Irrigated	9.05 (0.05) **	Random effect
Melons	Cucumber	Irrigated	6.52 (0.08) **	Random effect
	Watermelon	Rain-fed	7.10 (0.07) **	Random effect
		Irrigated	8.02 (0.05) **	Fixed effect

[1] Statistical software name: STATA, manufacturer: Stata Corp LLC., version: 16, publisher: College Station, TX, USA. * The *p*-value of the Chi-squared test is significant at the 5% level. ** The *p*-value of the Chi-squared test is significant at the 1% level. Source: model results.

Our study delves into evaluating the optimal yield and nitrate application rate across various regions, focusing on crops that display significant coefficients for rainfall, their nitrate levels, and their squares. Table 3 reveals that multiple crops exhibit significant coefficients at the 5% level, notably wheat (rain-fed), barley (rain-fed and irrigated), rice (irrigated), maize (irrigated), tomato (irrigated), potato (irrigated), onion (irrigated), and canola (rain-fed and irrigated). Of these crops, barley (rain-fed) demonstrates a random effect, while the others showcase fixed effects. For crops displaying random effects, the intercepts have been documented. However, in cases where crops exhibit fixed effects and regions present distinct characteristics, separate definitions for each crop within each region are imperative. Table 4 elaborates on the detailed outcomes derived from this analysis.

Table 3. Coefficients of yield response functions and optimal nitrogen rates.

Group	Crop	Technology	Intercept	Rainfall	N	N^2
Cereals	Wheat [3]	Rain-fed	- [1]	0.53 (0.18) *[2]	10.10 (1.98) *	−0.031 (0.013) *
		Irrigated	1915.70 (475.29) *	1.11 (0.33) *	5.86 (4.46)	−0.004 (0.011)
	Barley	Rain-fed	539.61 (76.72) *	0.40 (0.11) *	4.80 (1.64) *	−0.010 (0.006) ***
		Irrigated	-	1.85 (0.36) *	18.07 (2.14) *	−0.045 (0.007) *
	Rice	Irrigated	3299.83 (363.61) *	0.84 (0.57) ***	1.86 (1.11) ***	−0.001 (0.0004) *
	Maize	Irrigated	-	3.84 (0.83) *	20.27 (1.70) *	−0.021 (0.002) *
Legumes	Peas	Rain-fed	-	0.64 (0.09) *	2.27 (1.22) **	−0.008 (0.010)
		Irrigated	-	2.55 (0.42) *	1.84 (1.50)	−0.003 (0.005)
	Lentils	Rain-fed	-	0.44 (0.08) *	0.27 (1.67)	−0.018 (0.016)
		Irrigated	974.40 (105.35) *	0.08 (0.16)	1.04 (1.20)	−0.001 (0.004)
Vegetables	Tomato	Irrigated	-	23.78 (4.77) *	57.92 (8.29) *	−0.058 (0.010) *
	Potato	Irrigated	-	18.75 (3.39) *	53.71 (6.57) *	−0.066 (0.008) *
	Onion	Irrigated	-	39.91 (6.34) *	54.37 (8.47) *	−0.034 (0.008) *
Industrial	Sugar beet	Irrigated	24,734.92 (7711.08) *	10.43 (10.53)	34.46 (39.83)	−0.039 (0.054)
	Canola	Rain-fed	-	0.84 (0.31) *	11.99 (3.09) *	−0.035 (0.011) *
	Canola	Irrigated	-	1.27 (0.52) *	6.60 (1.27) *	−0.009 (0.003) *
	Cotton	Irrigated	2318.37 (186.67) *	0.19 (0.33)	0.41 (0.72)	−0.0004 (0.0007)
Melons	Cucumber	Irrigated	18,120.04 (3071.62) *	2.20 (2.86)	3.35 (12.70)	−0.005 (0.013)
	Watermelon	Rain-fed	4445.45 (1650.40) *	0.76 (5.52)	104.09 (51.14) *	−0.152 (0.097) ***
		Irrigated	-	2.35 (3.96)	97.39 (12.01) *	−0.152 (0.021) *

[1] Table 4 lists the individual intercepts reported for each crop within a fixed-effects model, defining a specific intercept for each region. [2] Numbers in parentheses denote the standard deviations of the coefficients. * The coefficient is significant at the 1% level. ** The coefficient is significant at the 5% level. *** The coefficient is significant at the 10% level. Coefficients without stars lack significant meaning at either the 1%, 5%, or 10% levels. [3] Crops shaded in grey are selected due to all their coefficients being statistically significant. Source: model results.

Table 4. Region-specific intercepts in yield response functions under fixed-effects models.

Abbr.	Crop	Wheat	Barley	Maize	Peas		Lentils	Tomato	Potato	Onion	Canola		Watermelon
	Region	**Rain-Fed**	**Irrigated**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Irrigated**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Irrigated**
ALB	Alborz	-	1875.59 (326.97) [1,2,*]	-	-	-	-	--	4367.91 (2239.95) **	-	-	-	-
ARD	Ardebil	639.23 (99.56) *	721.74 (199.75) *	469.99 (238.57) *	266.10 (71.50) *	-	382.21 (45.49) *	12,326.48 (2628.71) *	13,212.93 (1788.62) *	-	-	1095.93 (213.70) *	-
BUS	Bushehr	164.48 (135.11) ***	111.06 (69.41) ***	1789.34 (513.42) *	-	-	-	18,956.24 (2623.89) *	-	1153.61 (721.00) ***	-	126.13 (78.83) ***	16,085.23 (2339.44) *
CHM	Chahar Mahall and Bakhtiari	222.51 (130.88) ***	459.21 (234.35) *	-	292.82 (54.66) *	-	597.04 (75.35) *	-	15,608.02 (1914.44) *	-	-	-	-
EAZ	East Azarbaijan	387.78 (150.01) *	990.42 (215.27) *	-	331.55 (43.60) *	306.93 (190.73) ***	380.67 (39.83) *	20,491.75 (2683.91) *	14,842.95 (1859.84) *	17,678.11 (2671.72) *	-	517.09 (217.63) *	20,474.54 (3430.24) *
ILM	Ilam	218.40 (136.26) ***	232.84 (122.54) **	−536.81 (275.29) **	188.45 (62.53) *	-	327.12 (65.93) *	1272.21 (795.13) ***	-	-	623.61 (218.66) *	140.67 (82.74) ***	19,107.47 (3016.10) *
ESF	Esfahan	186.28 (116.42) ***	1751.67 (292.01) *	2099.80 (480.05) *	234.49 (44.84) *	947.35 (142.52) *	416.29 (55.57) *	20,366.24 (2743.14)	14,746.41 (1991.57) *	30,393.90 (3632.51) *	-	1513.74 (247.63) *	20,499.08 (2637.61) *
FRS	Fars	136.39 (75.78) ***	789.48 (288.01) *	1785.87 (499.87) *	113.93 (51.15) *	432.11 (156.87) *	325.46 (53.89) *	31,288.56 (2838.36) *	7546.07 (1955.90) *	16,504.09 (3143.61) *	-	942.09 (218.67) *	15,905.97 (2549.33) *
GIL	Gilan	461.41 (223.36) *	-	-	-	-	16.75 (121.85)	-	17,514.08 (4417.52) *	-	-	-	6670.47 (3368.92) *
GOL	Golestan	954.77 (163.03) *	607.64 (293.22) *	318.78 (199.23) ***	-	-	312.76 (86.51) *	8902.02 (3063.27) *	2141.74 (1338.59) ***	-	192.89 (120.56) ***	750.09 (257.59) *	12,760.01 (3102.36) *
HAM	Hamadan	280.32 (116.87) *	1373.85 (233.23) *	2310.61 (468.68) *	221.38 (47.94) *	200.78 (125.48) ***	288.64 (56.17) *	17,623.94 (2754.43) *	19,706.23 (1898.36) *	-	-	1185.07 (228.63) *	21,982.84 (2593.30) *
HOR	Hormozgan	-	221.74 (123.19) ***	963.12 (495.04) *	-	-	-	10,944.12 (2541.08) *	15,631.80 (2802.31) *	5250.58 (2746.27) *	-	218.83 (110.52) **	5918.89 (2450.61) *
KOH	Kohgiluyeh and Buyer Ahmad	201.46 (111.92) ***	485.14 (312.90) ***	741.08 (376.18) *	268.52 (80.23) *	-	511.34 (84.28) *	1558.73 (974.20) ***	-	13,963.67 (4560.04) *	-	-	18,532.38 (3414.16) *
KER	Kerman	-	124.86 (63.38) **	1513.52 (475.69) *	-	718.35 (125.62) *	-	5906.26 (3028.85) **	9696.35 (1907.38) *	9866.16 (3399.20) *	-	-	14,337.10 (2586.03) *
KRD	Kordestan	301.84 (135.80) *	806.59 (233.37) *	1548.28 (682.07) *	52.62 (48.12) *	-	116.44 (56.36) *	2515.42 (1572.14) ***	13,773.89 (1925.17) *	1141.52 (713.45) ***	-	356.80 (209.88) ***	9580.82 (3245.69) *
KRM	Kermanshah	257.28 (125.54) *	1211.95 (282.20) *	1574.41 (500.79) *	189.71 (32.88) ***	-	-	13,135.53 (3017.10) *	2662.87 (2087.62) *	3310.78 (2069.24) ***	-	391.48 (230.28) ***	-

Table 4. *Cont.*

Abbr.	Crop	Wheat	Barley	Maize	Peas		Lentils	Tomato	Potato	Onion	Canola		Watermelon
	Region	**Rain-Fed**	**Irrigated**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Irrigated**	**Irrigated**	**Rain-Fed**	**Irrigated**	**Irrigated**
KHZ	Khuzestan	145.98 (82.01) ***	159.62 (93.90) ***	1289.78 (464.23) *	-	-	632.32 (85.93) *	17,239.31 (2651.88) *	9536.86 (1863.94) *	7129.97 (2961.85) *	144.22 (73.58) **	152.90 (85.50) ***	14,729.58 (2467.24) *
LRS	Lorestan	217.16 (109.67) **	30.42 (18.21) ***	1848.85 (511.18) *	198.74 (54.28) *	90.30 (54.07) ***	259.93 (54.16) *	1200.21 (718.70) ***	8634.78 (2042.19) *	-	-	167.58 (101.56) ***	20,270.74 (4172.69) *
MRK	Markazi	827.09 (175.05) *	1562.76 (262.62) *	2205.20 (474.365) *	-	-	-	18,995.09 (2516.86) **	17,226.32 (1944.965) *	30,393.9 (3632.51) *	-	-	-
MAZ	Mazandaran	822.30 (203.18) *	742.43 (357.04) *	-	-	-	146.83 (90.46) ***	4933.05 (4215.13) *	7668.62 (2787.22) *	25,726.26 (5669.57) *	-	-	15,713.85 (3700.82) *
NKR	North Khorasan	375.38 (162.61) *	182.80 (109.46) ***	-	149.49 (55.37) *	-	289.95 (49.92) *	13,321.84 (2921.88) *	9087.52 (2091.47) *	20,644.72 (2710.28) *	-	171.42 (107.13) ***	5480.32 (3242.74) ***
QOM	Qom	197.72 (105.17) ***	774.58 (259.42) *	-	-	-	-	-	-	-	-	799.28 (232.65) *	-
QZV	Qazvin	246.04 (117.20) *	716.85 (253.77) *	3265.71 (478.44) *	171.00 (49.57) *	-	176.53 (65.95) *	19,228.90 (2737.06) *	6700.52 (1907.27) *	-	-	999.00 (232.15) *	-
RKR	Razavi Khorasan	314.33 (112.03) *	598.93 (256.30) *	1426.91 (600.23) *	51.91 (31.03) ***	222.35 (133.14) ***	159.07 (65.82) *	18,363.82 (3066.07) *	14,302.08 (2083.65) *	20,040.48 (3099.55) *	-	370.98 (189.28) **	9433.59 (2707.73) *
SIS	Sistan and Baluchestan	-	129.65 (77.69) ***	467.41 (236.06) *	-	-	-	11,527.22 (2371.48) *	11,646.07 (2834.44) *	16,160.10 (2577.94) *	-	402.21 (205.20) **	10,927.99 (2224.71) *
SKR	South Khorasan	337.44 (129.62) *	321.13 (162.18) *	-	-	471.73 (211.57) *	-	534.66 (320.15) ***	3869.28 (1974.12) **	5731.15 (2924.06) **	-	-	8320.09 (2648.87) *
SMN	Semnan	555.44 (118.59) *	1055.15 (238.24) *	-	-	-	421.21 (51.32) *	9947.72 (2858.18) *	5903.01 (1876.29) *	-	-	-	4989.82 (2771.10) ***
THE	Tehran	309.06 (106.76) *	1315.73 (244.45) *	-	-	-	-	19,701.52 (2709.22) *	10,845.51 (1783.89) *	25,797.34 (4168.44) *	-	361.29 (184.33) **	15,026.99 (4096.34) *
WAZR	West Azarbaijan	414.59 (121.44) *	1052.98 (200.16) *	-	195.41 (44.78) *	23.47 (14.05) ***	173.71 (47.41) *	14,205.00 (2706.69) *	9032.89 (1795.97) *	7143.82 (3495.17) *	-	816.37 (298.45) *	17,318.75 (2454.50) *
YZD	Yazd	-	1045.21 (239.37) *	2151.67 (504.84) *	-	768.70 (197.42) *	-	14,216.37 (2727.38) *	12,318.72 (2190.62) *	35,673.81 (3320.70) *	-	-	12,302.64 (2577.66) *
ZNJ	Zanjan	219.43 (135.95) ***	541.68 (217.09) *	-	78.58 (45.57) ***	197.21 (116.70) ***	162.06 (46.73) *	11,194.78 (2666.36) *	13,406.53 (1767.37) *	5821.94 (3210.14) *	-	-	-

[1] Numbers in parentheses denote the standard deviations of the coefficients. * The coefficient is significant at the 1% level. ** The coefficient is significant at the 5% level. *** The coefficient is significant at the 10% level. [2] Crops shaded in grey are selected due to all their coefficients (rainfall, nitrate, square of nitrate) being statistically significant at either the 5% or 1% significance levels (Table 3). Source: Model results.

Following the determination of random and fixed effects (Table 2) and subsequent coefficient estimation (Tables 3 and 4), the calculation of the optimal nitrate application rate, as outlined in the methodology, became feasible (Figure 1). The results of the estimated quadratic yield response functions show that rice (with 1031 (kg/ha)), onion (with 800 (kg/ha)), and tomato (with 508 (kg/ha)) have the largest usage of nitrogen at the optimal point, and rain-fed wheat (with 168 (kg/ha)) and rain-fed canola (with 171 (kg/ha)) have the smallest. Figure 1 shows that across all crops, the optimal nitrate use exceeds the observed application rates in 2016. This discrepancy is more evident in rice in Iran. The lower-than-optimal nitrate use for rice in the north of Iran can be influenced by specific soil types prevalent in the region. Factors such as the presence of alluvial, clayey, or coastal soils may contribute to suboptimal nitrogen application. Limited awareness of soil characteristics, inadequate soil testing, and inefficient nitrogen management practices may further contribute to the disparity between actual and optimal nitrate use.

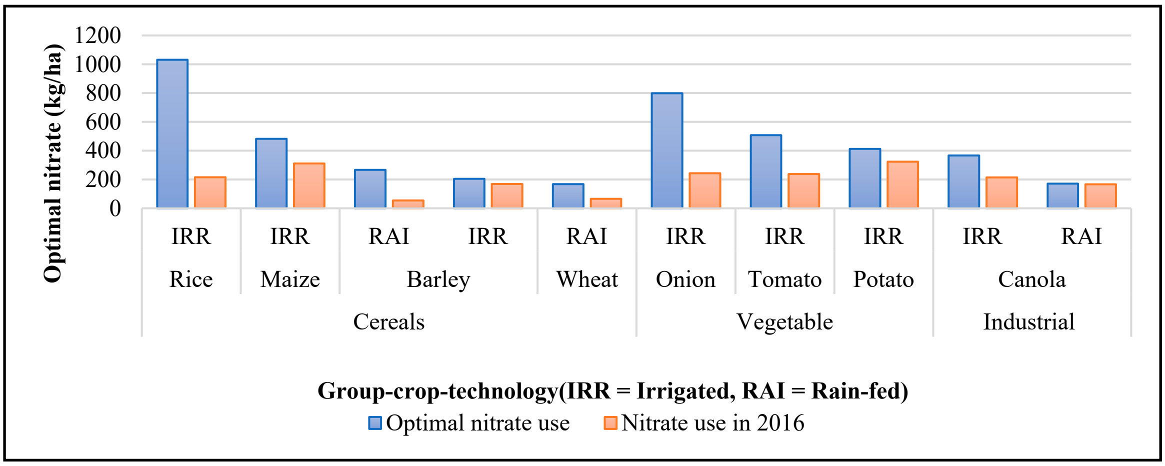

Figure 1. Optimal nitrate application (kg/ha) for crops under rain-fed and irrigated technologies in Iran. Source: model results.

The gap between estimated optimal nitrate use and actual application in Iran's agriculture stems from multiple factors. Firstly, economic constraints, limited fertilizer accessibility, and affordability issues notably contribute to farmers applying lower nitrate levels than the estimated optimal values. Despite government efforts to provide nitrate to farmers annually, the timely receipt of fertilizers, especially nitrate, remains a persistent challenge. Particularly for farms situated far from distribution centers, high transportation costs often prompt farmers to rely on leftover fertilizer from the previous year, which is suboptimal for their crops and results in consistently lower-than-optimal application rates [7]. However, accessibility and affordability are not the sole concerns. Recent high inflation rates and increasing nitrate prices on the market have prompted farmers to engage with intermediaries, creating a new market dynamic. Iranian farmers, generally earning modest incomes from their produce, view government-subsidized nitrate as an opportunity to make profits by selling it at higher rates in the free market [6]. This trend is prevalent in the agricultural sector, especially for cereal crops that receive higher subsidies compared to others. Consequently, farmers opt to store subsidized nitrate for resale at higher prices rather than using it for their current crops. This practice results in the recurrent underutilization of nitrate, leading to application rates consistently below the optimal threshold [4]. Secondly, diverse localized conditions and soil management practices in Iran influence actual nitrate use. Varied factors like soil types, crop needs, climate variations, and traditional farming practices create discrepancies between actual and optimal nitrate usage in agriculture. Soil differences affect optimal nitrate needs regionally, while crops may require varying nitrogen levels during growth, deviating from standard practices [10]. Climate disparities impacting water availability, along with traditional farming practices, may lead to either insufficient or excessive nitrate application compared to optimized levels [9]. Last but not least is the lack of access to updated research and the diverse responses of crops to varying nitrate levels. Limited access to the latest agricultural findings can lead farmers to rely on outdated or generalized guidelines, hindering the alignment of practices with the most current and optimized nitrate application strategies. Moreover, crops exhibit diverse responses to nitrate levels, and optimal usage can differ based on individual crop requirements, growth stages, and regional variations in soil types and climatic conditions. Without precise knowledge of these crop-specific responses and localized guidelines, farmers may apply nitrate levels that are insufficient, resulting in either suboptimal yields or inefficient resource utilization [40].

Our study utilized the quadratic yield response function to uncover insights into optimal nitrate use and yield determination. After comparing the 2016 nitrate application rates with the calculated optimal use, we focused on disparities between the optimal and actual yields for specific crops. It is important to note that our analysis focused on crops displaying significant coefficients, as indicated in Table 3. Based on the determination of the most appropriate specification between random- or fixed-effects estimation, the average yields corresponding to the optimal nitrogen usage level were computed. These computations were conducted either regionally or as an aggregate across all regions, and will be illustrated using GIS maps in the discussion section.

The estimated optimal yield for rain-fed barley is 1.29 t/ha, reflecting the random-effect nature of the analysis without individual regional specifications. Applying nitrate optimally could potentially increase yields by 176 kg/ha compared to the 2016 observed yield. For other crops with significant coefficients, specific optimal yields were determined for each region, considering their fixed effect. Rain-fed canola, limited to Ilam, Golestan, and Khuzestan, was not displayed separately due to its limited presence. However, a slight nitrate increase to reach optimal levels might potentially raise yields by approximately 400 kg/ha in Ilam and Khuzestan. Yet, in Golestan, due to distinct soil characteristics and nutrient balancing challenges, optimal nitrate use may result in a slight yield decrease of about 50 kg/ha.

Figure 2 displays rain-fed wheat's optimal and observed 2016 regional yield distribution across 31 regions. Rain-fed wheat data were unavailable for Alborz, Kerman, Hormozgan, Sistan and Baluchestan, and Yazd. Comparing the average observed yields in 2016 to the optimal yields shows a 31% increase in optimal yield. Most regions, with optimal nitrate use, indicate potential yield increases compared to 2016. Exceptions are Golestan and Mazandaran, showing slightly lower optimal yields, about 70 kg/ha less than in 2016. Gilan has the smallest optimal yield, just below 1 t/ha. Notably, Bushehr, South Khorasan, and Razavi Khorasan exhibit substantial increases in optimal yield, exceeding 60% compared to the 2016 yields.

Figure 3 showcases the regional yield distribution of irrigated barley at its optimal point compared to the 2016 yields, excluding Gilan due to data limitations. On average, the optimal yield displays a 9% increase compared to 2016. However, in Kermanshah, Kerman, South Khorasan, Mazandaran, North Khorasan, Tehran, Qazvin, and Qom, a slight decrease in optimal yield is observed. Conversely, other regions exhibit an increase in optimal yield over 2016. Markazi province leads with a 4.5-t/ha increase, while Sistan and Baluchestan has the lowest increase at 2 t/ha. Notably, Hormozgan shows a substantial 30% surge compared to 2016, while Hamadan experiences a mere 1% increase.

The maize crop, part of the cereal group, is observed to have a fixed effect. Figure 4 displays regions where data were available, indicating higher optimal yields compared to 2016 when using optimal nitrate levels. Qazvin, Lorestan, and Kohgiluyeh and Buyer Ahmad show the highest optimal maize yields, around 8.42 to 8.93 t/ha. Golestan and Markazi exhibit a notable percentage increase of approximately 25%, while Sistan and Baluchestan display the highest percentage change, approximately 20%, despite having the smallest optimal yield among the regions.

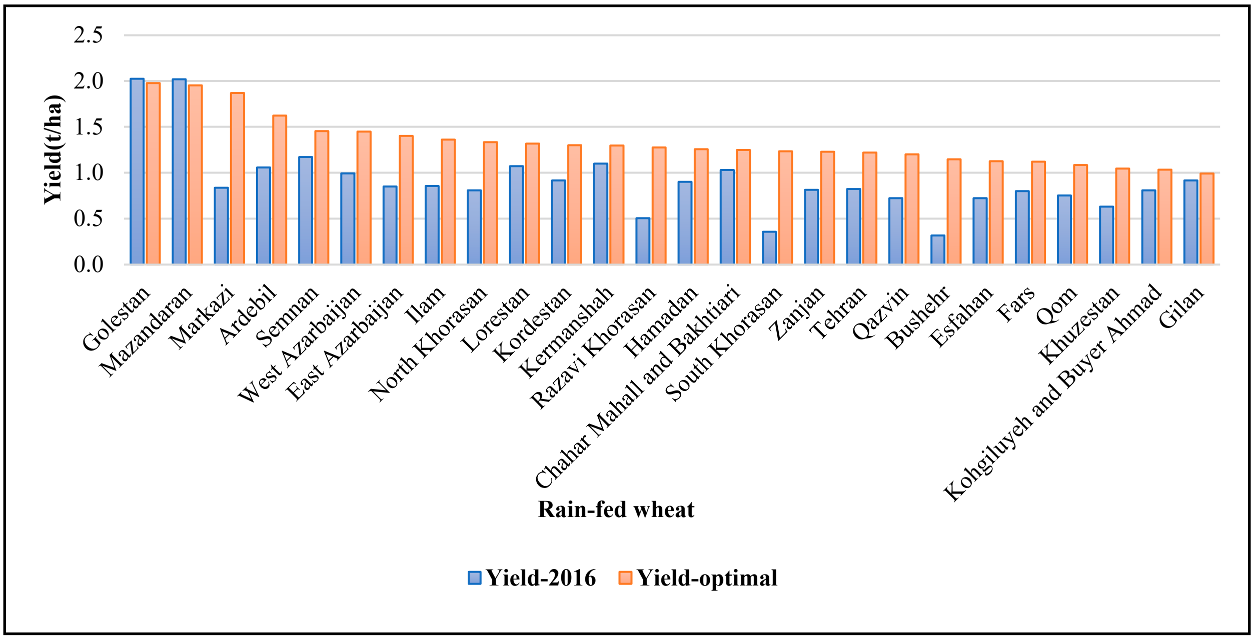

Figure 2. Optimal and observed 2016 regional yield distribution of rain-fed wheat in Iran.

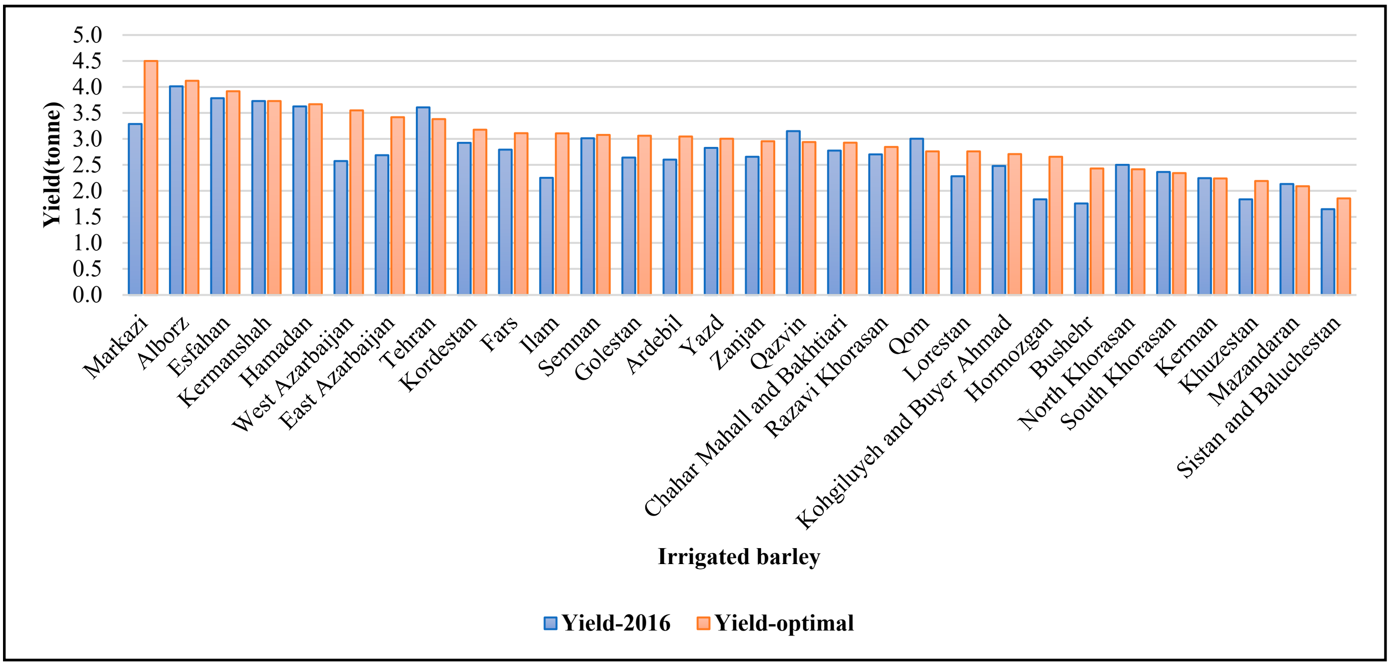

Figure 3. Optimal and observed 2016 regional yield distribution of irrigated barley in Iran.

Figures 5–7 display higher yields in the vegetable group compared to cereals. For tomatoes, potatoes, and onions, Figure 5 reveals 8%, 7%, and 18% increases in the optimal yield versus 2016. Fars, East Azarbaijan, and Bushehr top the regions with the largest optimal yield for tomatoes, with increases ranging from 40 to 52 t/ha. Conversely, South Khorasan, Kordestan, and Kerman exhibit smaller increases, around 16 to 24 t/ha. Hormozgan and Sistan and Baluchestan present the most significant percentage rises, approximately 25%. Unfortunately, data for tomatoes were unavailable for Alborz, Chaharmahal and Bakhtiari, Gilan, and Qom.

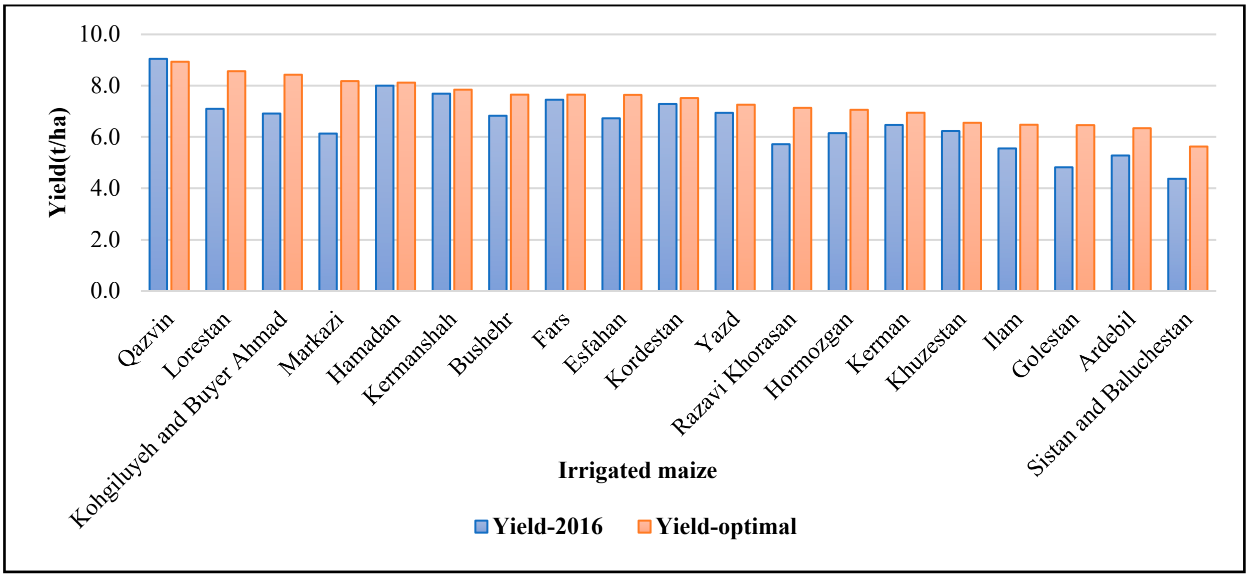

Figure 4. Optimal and observed 2016 regional yield distribution of rain-fed maize in Iran.

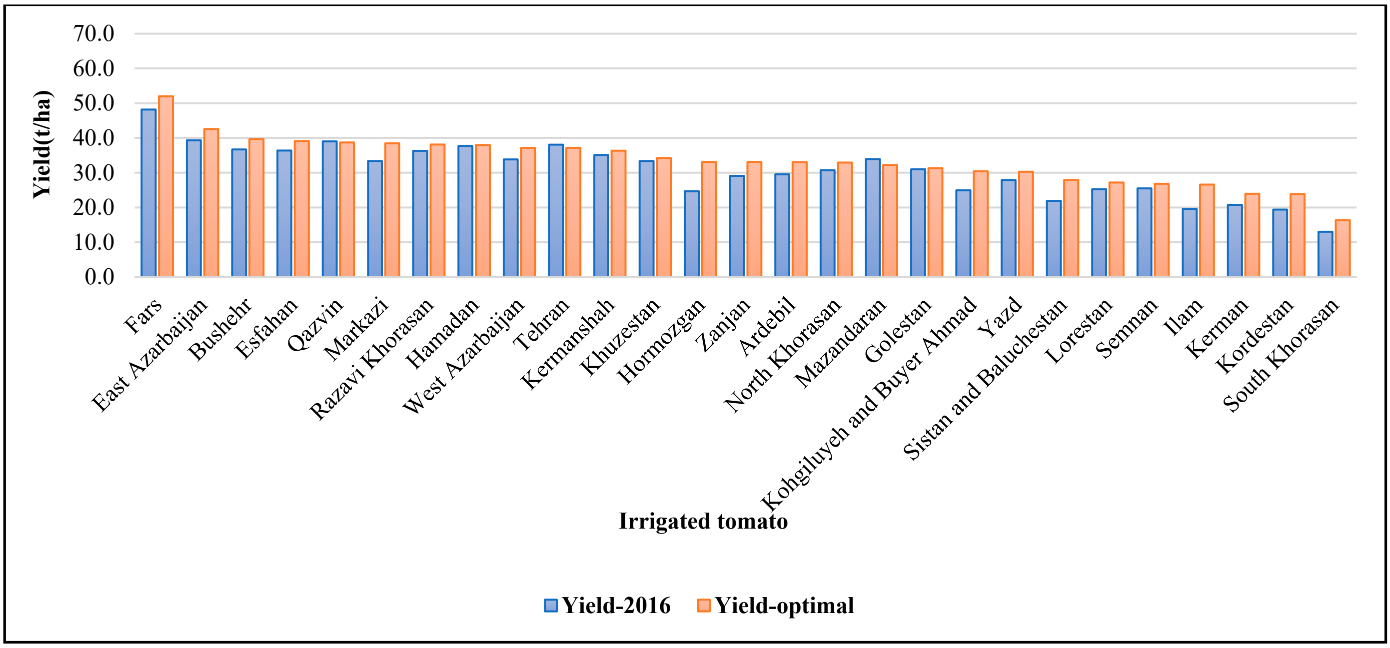

Figure 5. Optimal and observed 2016 regional yield distribution of irrigated tomato in Iran.

Figure 6 reveals that Hamadan has the largest potato yield increase at 35 t/ha, followed closely by Chahar Mahall and Bakhtiari with a 33 t/ha rise. Markazi and Esfahan present the most substantial percentage changes, around 20%, between their optimal and observed yields in 2016. Hormozgan stands out with both the highest optimal yield value and the highest percentage increase in potato yield compared to 2016. Conversely, except for Tehran, Mazandaran, and Golestan, which show decreased yields at the optimal level compared to 2016, Gilan has the smallest optimal yield value with a 15-t/ha increase, while Hamadan showcases the lowest percentage increase, less than 1%. Note that potato data were unavailable for Bushehr, Kohgiluyeh and Buyer Ahmad, Ilam, and Qom due to data limitations.

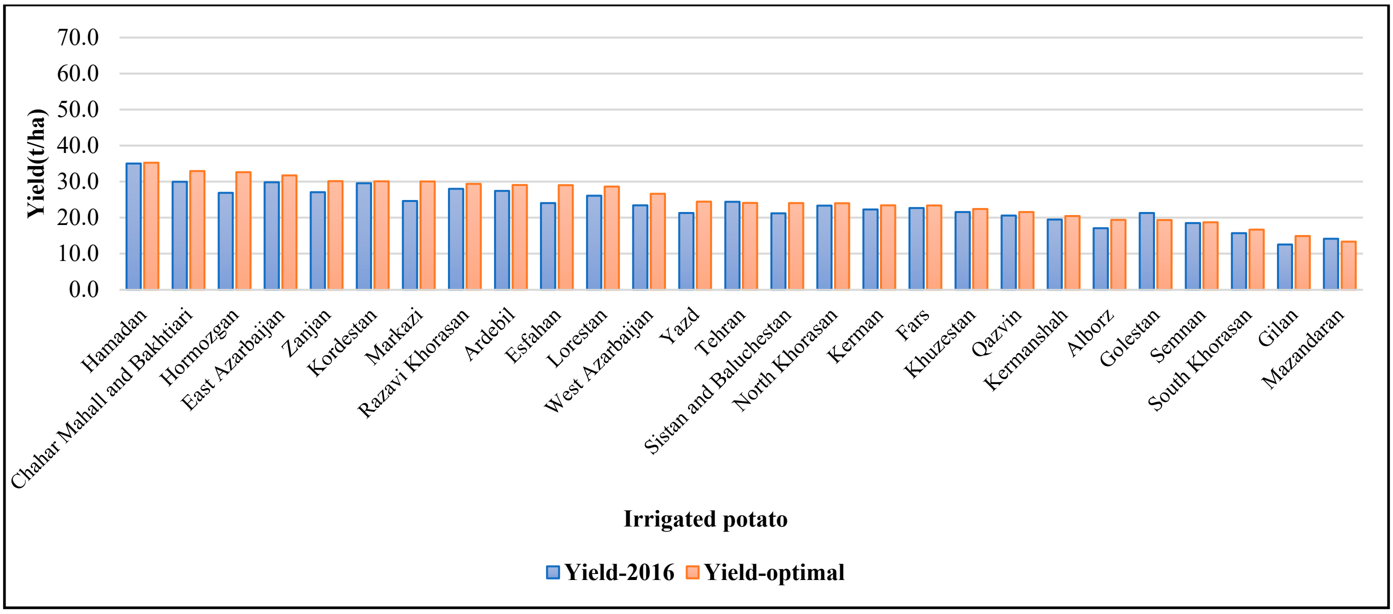

Figure 6. Optimal and observed 2016 regional yield distribution of irrigated potato in Iran.

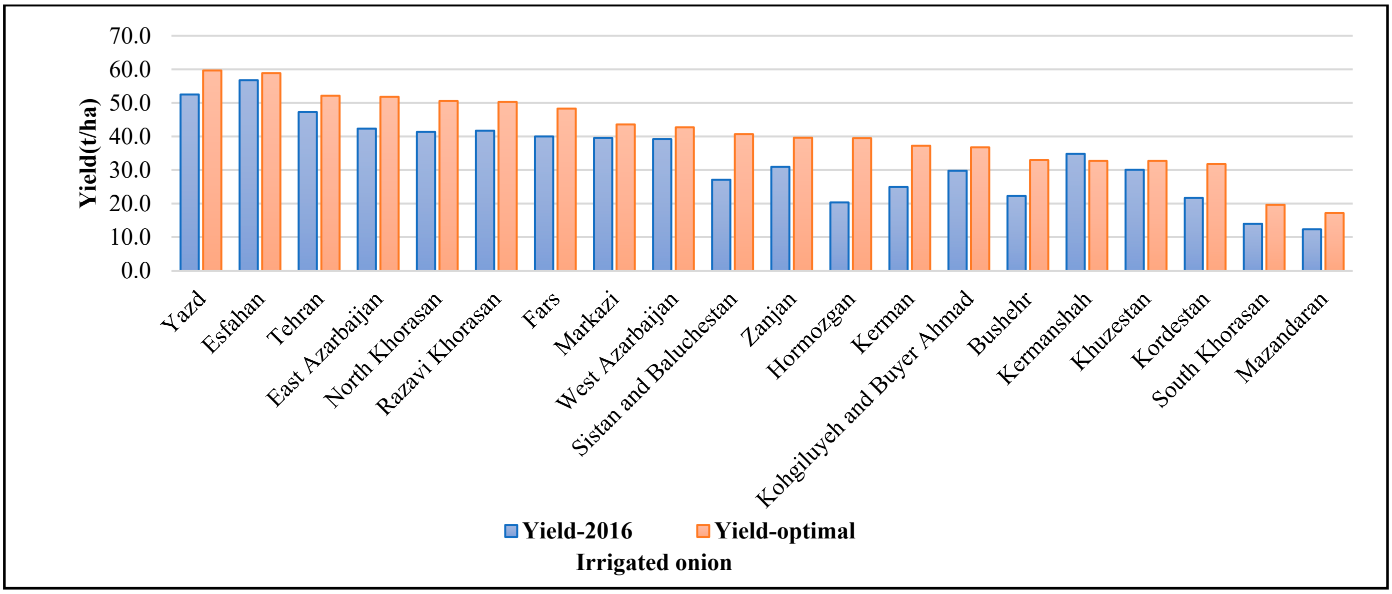

Figure 7. Optimal and observed 2016 regional yield distribution of rain-fed onion in Iran.

The analysis of onion, the final crop in the vegetable group, is presented in Figure 7. Yazd and Esfahan lead the pack, with yields of approximately 60 t/ha each as the regions with the largest optimal yields. Conversely, South Khorasan and Mazandaran exhibit the smallest optimal yields, around 20 t/ha each. However, the most intriguing aspect lies with Hormozgan. When comparing the percentage changes between its optimal yield and the observed yield in 2016, a striking increase of around 50% is observed.

Figure 8 shows the yield distribution of irrigated canola. Comparing the average observed yields in 2016 with the optimal yield, there is a 13% increase in the optimal yield. Esfahan leads with the largest optimal yield allocation, exceeding the others by 3 t/ha, while North Khorasan has the smallest at just 1 t/ha. Notably, Bushehr stands out with a significant 56% increase between the observed and optimal yields. However, both Qazvin and Tehran show lower optimal yields compared to 2016, in contrast to other regions.

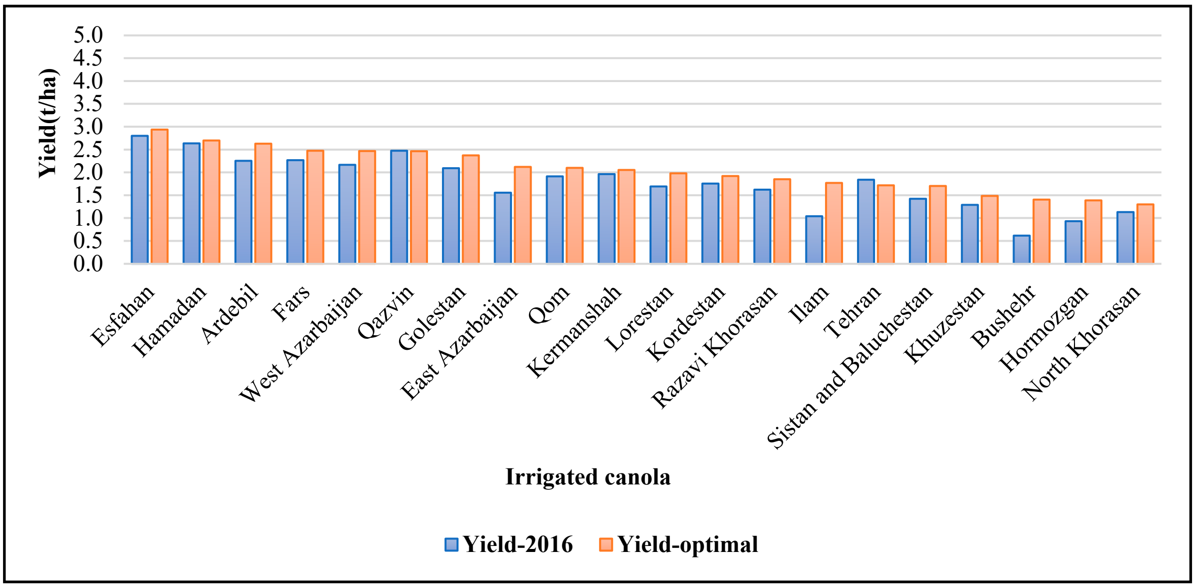

Figure 8. Optimal and observed 2016 regional yield distribution of irrigated canola in Iran.

4. Discussion

In our study, the incorporation of Geographic Information System (GIS) maps is instrumental for visualizing and understanding the relationships between cropping patterns, optimal yield distribution, and nitrate use at both regional and national scales. The overarching objective is to provide a roadmap that extends beyond the scientific community to policymakers, offering insights for the implementation of targeted policy reforms, specifically focusing on nitrate subsidies in Iran based on optimal applications and yield distributions. This distinctive feature sets our research apart from others in the realm of yield assessment and nitrate use. The utilization of GIS maps not only enhances the scientific discourse, but also positions our findings as a practical guide for policymakers, facilitating informed decisions and reforms to optimize agricultural practices, particularly in the context of nitrogen management.

In Iran, wheat and barley yields vary due to factors like climate and geography, despite some shared cultivation practices [41]. Wheat tends to flourish in temperate climates with cooler temperatures during growth and warmer weather during ripening, favoring well-drained, fertile soils and adequate moisture [42]. On the other hand, barley exhibits more adaptability to diverse climates, thriving in cooler conditions and tolerating drier periods, but benefitting from consistent moisture during crucial growth stages [43]. Both grains require ample sunlight for optimal growth, yet their specific soil preferences and moisture tolerances set them apart in terms of cultivation needs, a crucial understanding for effective agricultural practice selection [44]. In the context of Iran's regions, high rain-fed wheat yields in the northern areas, particularly Golestan and Mazandaran, stem from a blend of climatic nuances, soil quality, agricultural methods, and water access [45]. While Gilan benefits from a favorable temperate and humid climate, occasional waterlogging impacts wheat growth. In contrast, Golestan and Mazandaran strike a balance between rainfall and dry periods, fostering ideal conditions [46]. Central regions like Markazi and Semnan, with better soil quality and moderate rainfall, support robust wheat yields. Northwestern areas like Ardebil and East and West Azarbaijan benefit from ample rainfall and cooler temperatures, ideal for wheat cultivation. Conversely, southern regions like Kohgiluyeh and Buyer Ahmad, Khuzestan, and Fars grapple with water scarcity and high temperatures, posing challenges for rain-fed wheat cultivation [47] (Figures 9 and 10). Our results align with published studies, such as [48], highlighting regional variations in climate change impact on rain-fed wheat yield. The positive effects observed in northern regions mirror findings in Golestan and Mazandaran, while negative impacts align with southern areas like Khuzestan and Fars. Ref. [49] supports our study, emphasizing rain-fed wheat yield sensitivity to temperature and precipitation fluctuations. The consensus on anticipated yield decline in strategic crops due to climate change, including [50], aligns with our findings. Ref. [50] emphasizes increased rainfall needs in Southern Iran, coinciding with our identified challenges. Shared focus on adequate water resources for wheat crops strengthens alignment with existing literature. Ref. [50] predicts a marginal rise in wheat yield and income in Markazi's central region, echoing our projections.

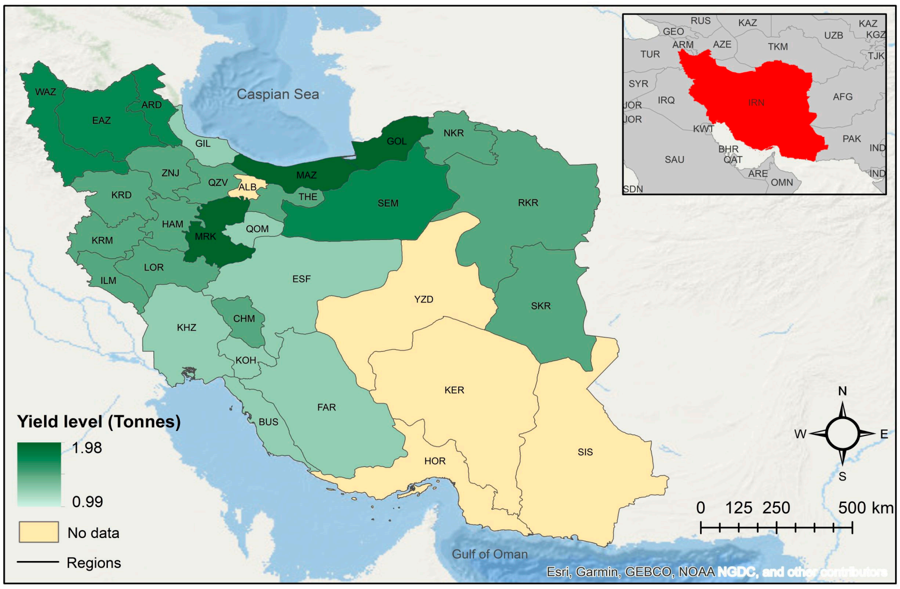

Figure 9. Optimal regional yield distribution of rain-fed wheat in Iran.

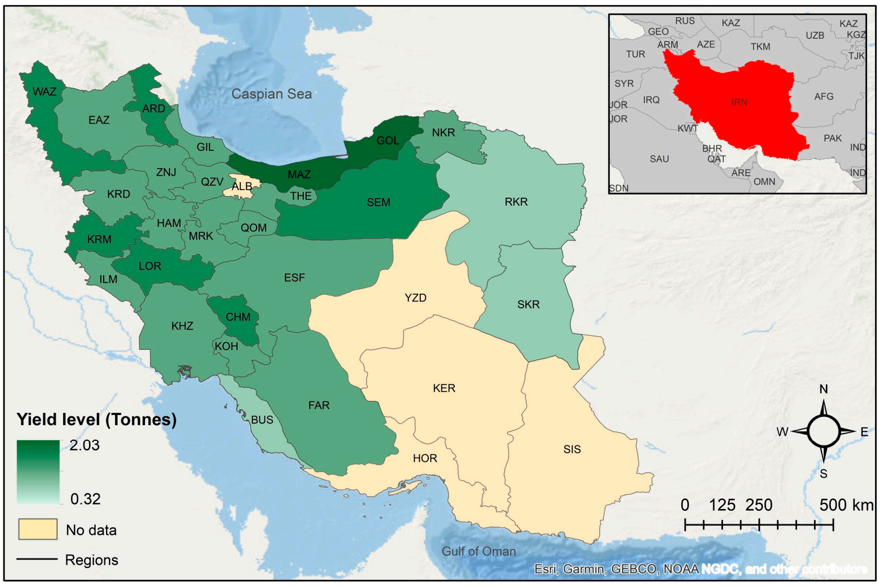

Figure 10. Observed 2016 regional yield distribution of rain-fed wheat in Iran.

Barley finds conducive conditions for cultivation in regions like Markazi, Alborz, East and West Azarbaijan, Kordestan, and Kermanshah, characterized by cooler temperatures and irrigation access, along with fertile soils. Barley's remarkable adaptability allows it to thrive even in semi-arid to arid climates like those found in Hamadan and Esfahan [51]. However, its cultivation in these regions is not solely due to climatic suitability. Centuries of historical cultivation have established barley as a staple, deeply rooted in the traditional agricultural practices of these areas. This historical precedence has led to the adaptation of traditional methods, favoring barley's growth specifically in Hamadan and

Esfahan [41]. Moreover, government support through subsidies and agricultural policies likely contributes notably to the continued cultivation of barley in these regions [4]. Conversely, arid regions or those with limited irrigation, such as Kerman, Khuzestan, and Sistan and Baluchestan, encounter challenges in achieving high barley yields due to water scarcity or unsuitable growing conditions [52] (Figures 11 and 12). Ref. [53] substantiates our research by illuminating historical, cultural, and political factors influencing barley cultivation. Our regional observations also resonate with its exploration of diverse barley species distribution.

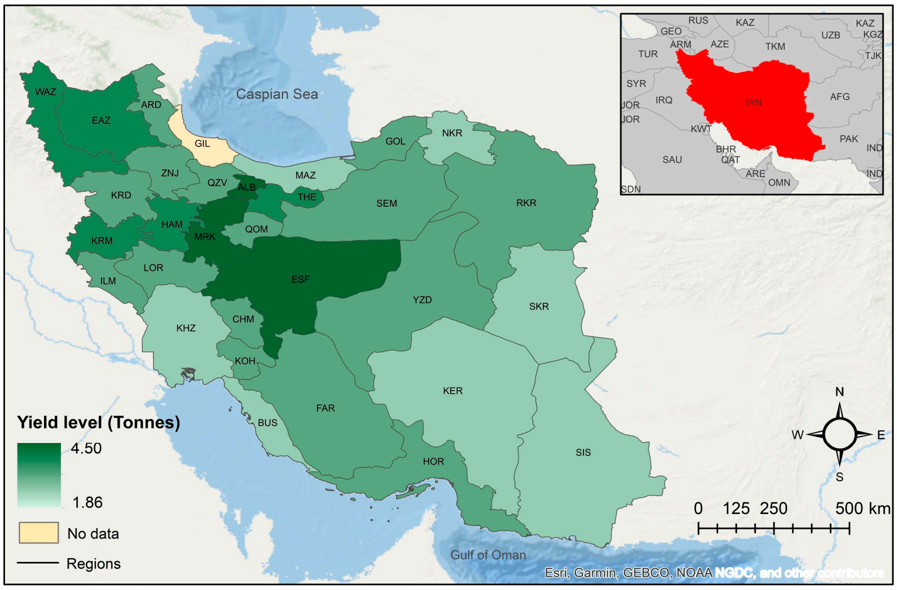

Figure 11. Optimal regional yield distribution of irrigated barley in Iran.

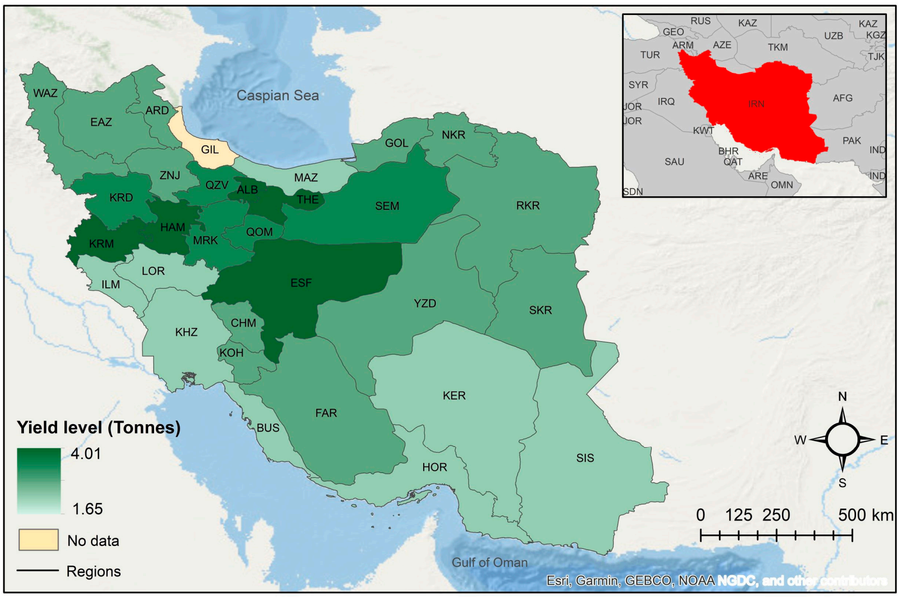

Figure 12. Observed 2016 regional yield distribution of irrigated barley in Iran.

Regions such as Qazvin, Lorestan, and Kohkiloyeh and Buyer Ahmad in the central–western area offer favorable climates for maize cultivation, characterized by sufficient rainfall, suitable temperatures, and extended growing seasons. Conversely, areas like Sistan and Baluchestan (southeast), Ardebil (northwest), and Golestan (northeast) face challenges due to aridity, extreme temperatures, or shorter growing periods, limiting maize productivity. Soil quality variations greatly impact yields; nutrient-rich soils with good drainage and suitable pH levels tend to support higher maize production [54]. Qazvin, Lorestan, and Kohkiloyeh and Buyer Ahmad potentially possess more fertile soils compared to regions like Sistan and Baluchestan or Ardebil. Adequate water supply is crucial for maize cultivation, favoring regions with better irrigation systems or access to water reservoirs [55]. Qazvin, Lorestan, and Kohkiloyeh and Buyer Ahmad likely benefit from better water availability and more developed irrigation systems compared to Sistan and Baluchestan, Ardebil, Golestan, and Ilam [56]. Disparities in farming practices, agricultural technologies, and access to modern farming techniques can substantially impact maize yields. Regions with advanced agricultural practices, better infrastructure, and technology adoption tend to achieve higher productivity. Areas with lower yields might lack access to modern farming techniques or face limitations in implementing efficient agricultural methods [57] (Figures 13 and 14). Our study reveals that maize cultivation in Iran is influenced by factors like climate, soil, water, and farming practices, varying across regions. Ref. [58] supports this, highlighting how management practices impact maize in semi-arid regions. Ref. [59] reinforces this, detailing maize diversity and adaptive cultivation in different climates. Our results show that favorable climates, fertile soils, water access, and advanced practices lead to higher maize productivity. Ref. [59] identifies traits linked to increased yield, while [60] highlights the benefits of early-maturing cultivars under climate change impacts.

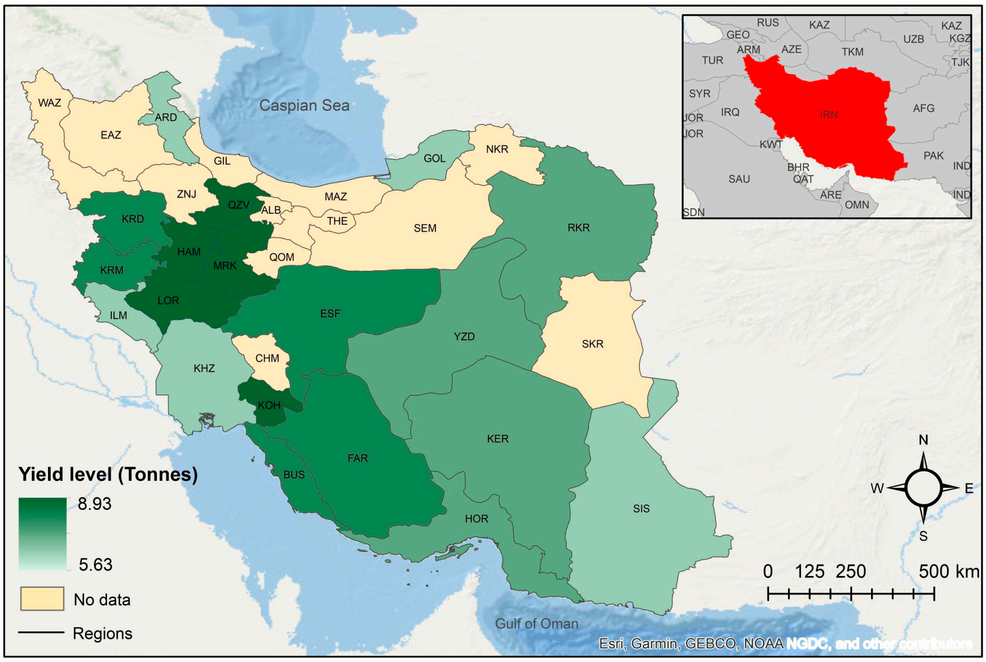

Figure 13. Optimal regional yield distribution of irrigated maize in Iran.

In Iran, vegetable crops often yield more than cereal crops. Shorter growing seasons allow multiple cultivation cycles per year, maximizing overall yields [61]. The intensive care and nutrient management required for vegetables, along with the potential suitability of local climates and soils, contribute to enhanced productivity. Farmers might prioritize vegetable cultivation due to higher market demand, better pricing, and the potential for increased profitability. They employ advanced agricultural practices that further optimize yields compared to traditional methods used for cereal crops [4].

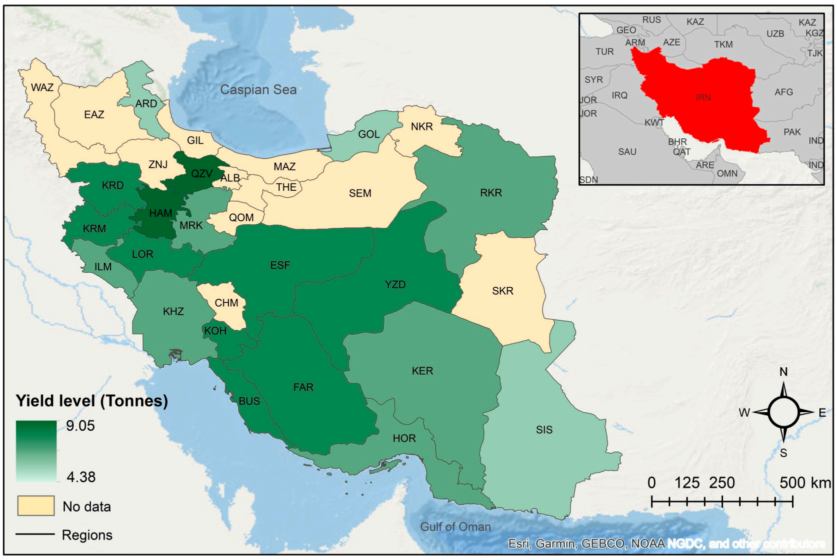

Figure 14. Observed 2016 regional yield distribution of irrigated maize in Iran.

Tomatoes thrive in warm climates (15 °C to 30 °C), needing well-draining, fertile soil with pH 6.0 to 6.8. They require consistent watering, ample sunlight (6–8 h/day), support, and spacing. Regions like Fars, East Azarbaijan, and Bushehr, meeting these conditions, excel in tomato cultivation. Conversely, in some inland regions like parts of south Khorasan, Kordestan, and Kerman, where arid or desert-like conditions prevail, tomato cultivation might yield lower outputs [62]. Limited water availability, high temperatures, and arid soils pose challenges, necessitating notable irrigation efforts and resource-intensive practices to sustain tomato crops, ultimately impacting yields negatively [63] (Figures 15 and 16). Our study aligns with [64], confirming the diverse influence of climate, soil, water, and farming practices on tomato cultivation. Ref. [64] reinforces our findings on optimal greenhouse conditions, showing that regions with favorable climates, fertile soils, sufficient water, and advanced practices achieve higher tomato productivity. These results also highlight the benefits of greenhouse cultivation in leading tomato-producing regions for both quality and quantity.

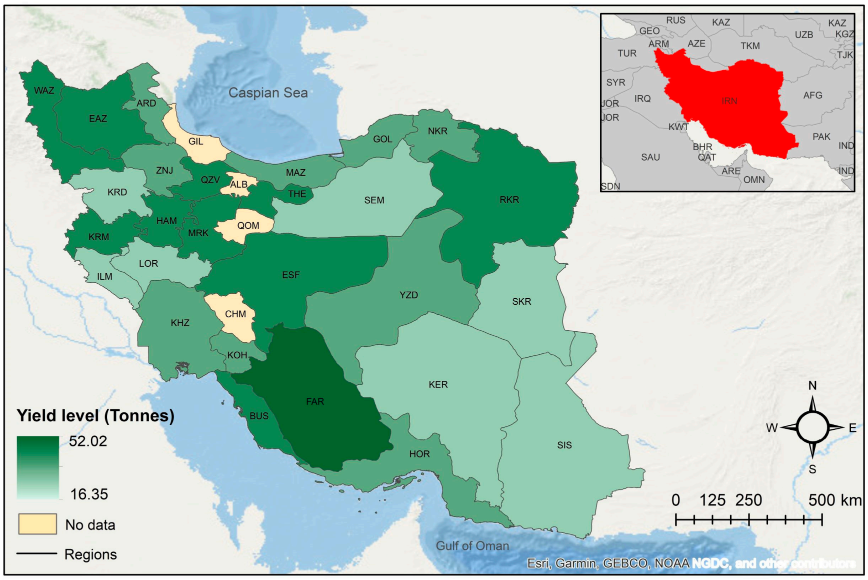

Figure 15. Optimal regional yield distribution of irrigated tomato in Iran.

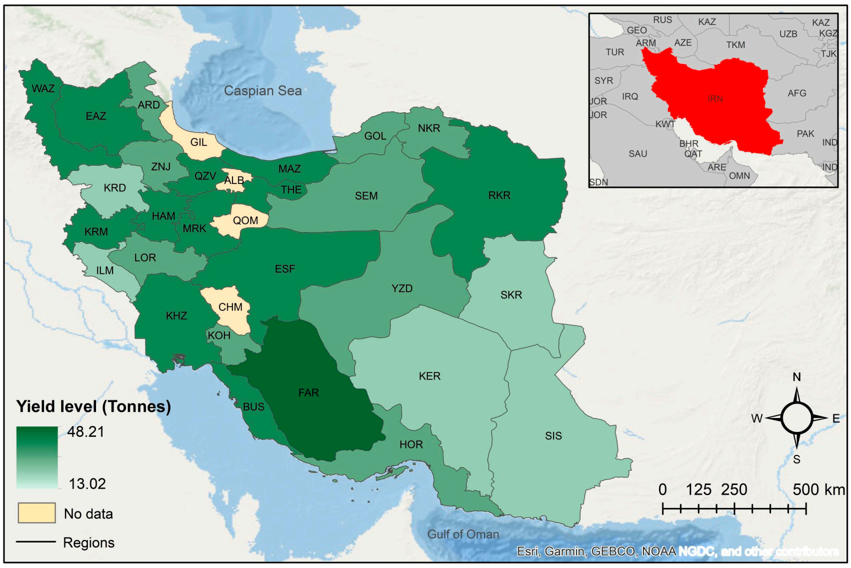

Figure 16. Observed 2016 regional yield distribution of irrigated tomato in Iran.

Unlike tomatoes, potatoes in Iran do well in cooler climates (15–20 °C) with well-drained soil and proper moisture. Hamadan enjoys a moderate climate with relatively cool temperatures, attributed in part to its elevation of around 1800 m (5900 feet), making it suitable for potato cultivation [65]. Adequate rainfall and supplementary irrigation methods maintain consistent moisture levels crucial for potato growth [66]. The fertile, well-drained loamy soils in Hamadan further contribute to optimal conditions, providing good drainage to prevent waterlogging and supporting healthy root development. Similarly, in Chaharmahal and Bakhtiyari, the mountainous terrain creates various microclimates suitable for potatoes. Climate variability due to the landscape offers milder temperatures in lower valleys and cooler conditions at higher elevations, enabling diverse potato varieties to thrive. The region's soils, often loamy or sandy loam, ensure proper drainage, crucial for preventing potato rot [67] (Figures 17 and 18). Refs. [68,69] support our findings on the variability of potato production in Iran, emphasizing the influence of resource and market dynamics. Both of these sources corroborate our observation of optimal conditions and practices for potato cultivation in Hamedan, with [69] addressing environmental and technical challenges. They agree on Hamedan and Chaharmahal and Bakhtiyari as leading potato producers, attributing their success to climatic advantages and modern technologies. However, Ref. [68] introduces a contrasting view, highlighting the environmental unsustainability of potato production in Hamedan. It suggests that reducing resource consumption can mitigate ecological impact and contribute to sustainability in this region.

Onions, much like tomatoes, thrive in cooler temperatures ranging from 13 °C to 24 °C, requiring well-draining, nutrient-rich soil, consistent moisture, and ample sunlight for optimal growth [70]. Yazd, known for its arid climate and well-drained sandy soils, provides an environment that prevents fungal diseases while offering adequate sunlight and moderate temperatures, fostering robust onion growth. Esfahan benefits from fertile soils like loam and clay loam, coupled with a moderate climate featuring distinct seasons, creating ideal conditions for successful onion cultivation [71]. Razavi Khorasan's geographical diversity, varying landscapes, soils, and altitude variations support the thriving of diverse onion varieties. Moreover, East and West Azarbaijan, with their moderate climates and rich agricultural heritage, facilitate successful onion farming, where traditional practices play a pivotal role in supporting cultivation [72]. These unique regional advantages contribute to the successful cultivation of onions across Iran's diverse landscapes (Figures 19 and 20). The study of the Yazd, Esfahan, Razavi Khorasan, and East/West Azarbaijan provinces reveals how onion cultivation is intricately influenced by climate, soil, water, and farming practices, creating optimal growth conditions. Ref. [71] supports this, illustrating onion production's diverse distribution in Iran based on resource availability. Additionally, Ref. [72] aligns with findings on common cultural methods, production statistics, and challenges. Our results highlight the productivity and profitability of onion cultivation utilizing arid climates, well-drained sandy and fertile soils, geographical diversity, and agricultural heritage. Ref. [71] identifies native onion cultivars and their optimal conditions, while [72] introduces challenges like a single annual production season, high bulb losses during storage, and the need for resistant cultivars and pest management. Ref. [71] suggests key research goals for Iran, including extending shelf life, reducing resource consumption, and improving pest control in onion cultivation.

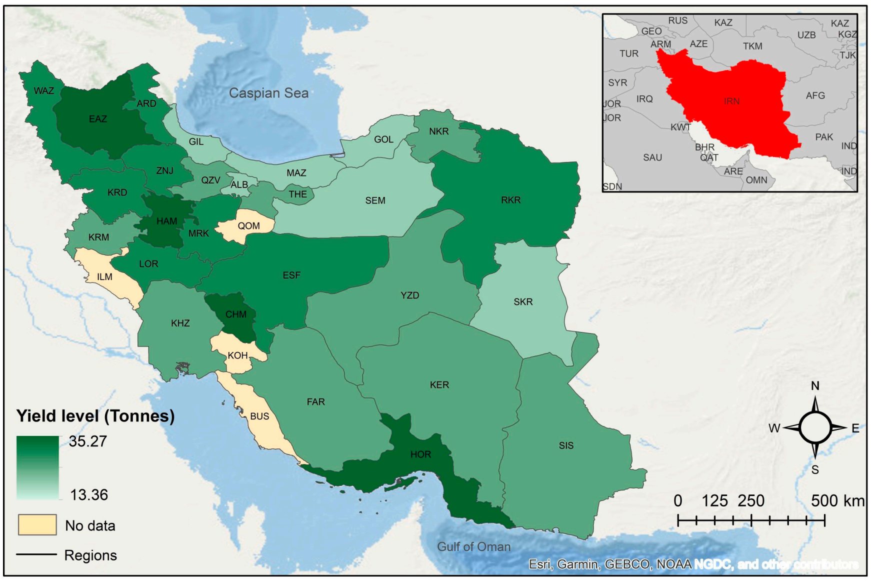

Figure 17. Optimal regional yield distribution of irrigated potato in Iran.

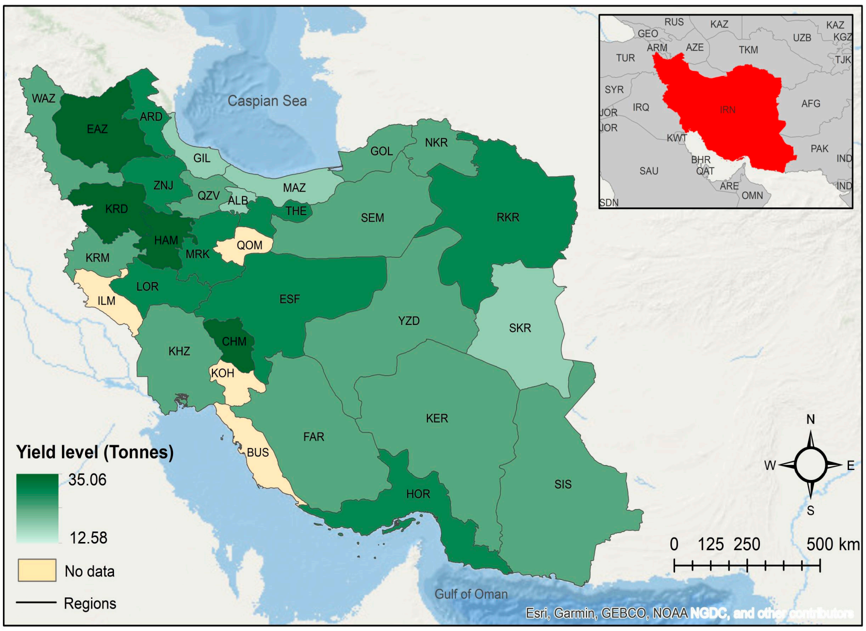

Figure 18. Observed 2016 regional yield distribution of irrigated potato in Iran.

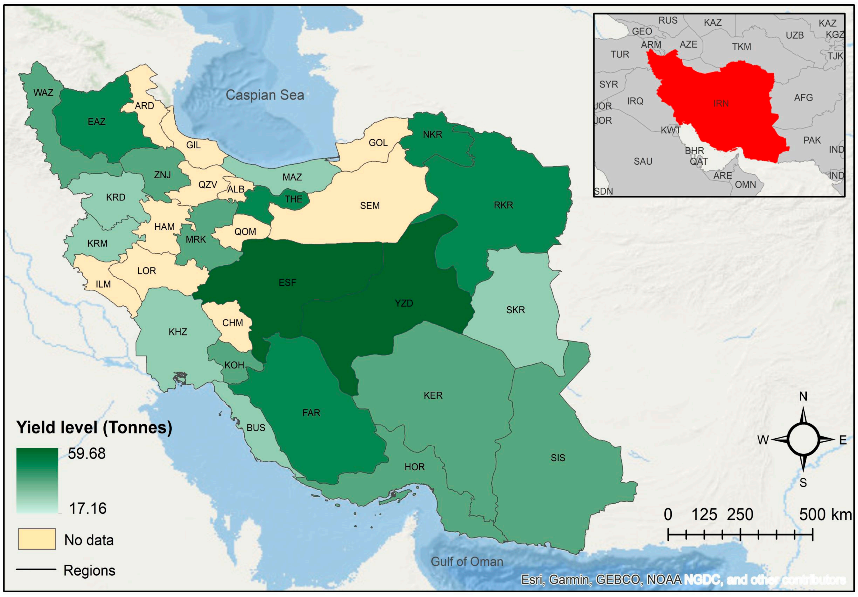

Figure 19. Optimal regional yield distribution of irrigated onion in Iran.

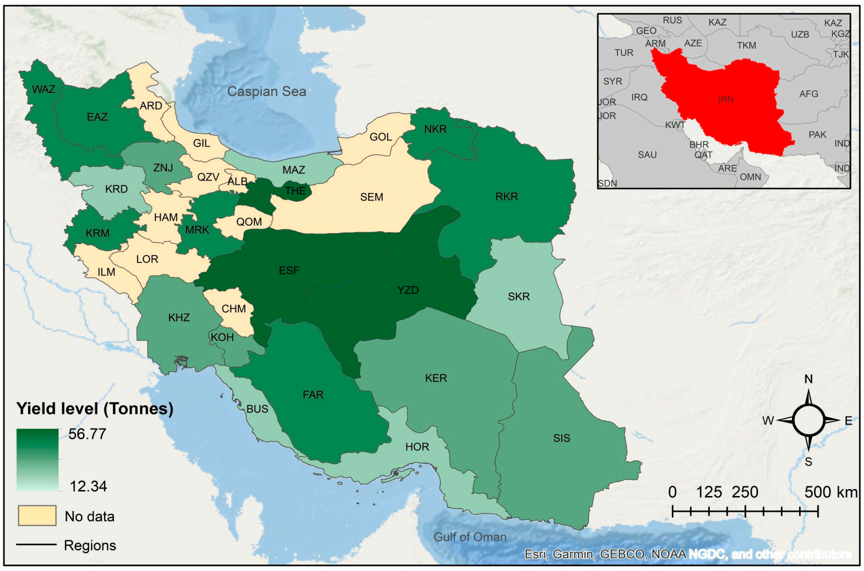

Figure 20. Observed 2016 regional yield distribution of irrigated onion in Iran.

In Iran, canola thrives in regions with moderate climates, adequate moisture, fertile soil, and proper farming practices [73], yielding well in areas around northwestern regions (Ardebil, West Azarbaijan) [74], and parts of the central plateau (Esfahan). High yields correlate with moderate temperatures, good soil quality, and sufficient water. Esfahan boasts a moderate climate complemented by the Zayandeh Rud River, offering optimal conditions for irrigated canola cultivation [75]. Hamadan, with its higher altitude, enjoys a cooler climate and abundant water resources, facilitating successful canola growth through irrigation. Ardebil, situated in the northwest, benefits from cooler temperatures and available water sources, creating a conducive environment for canola crops. Fars province, characterized by diverse geography, presents adaptable conditions and ample water reservoirs, fostering thriving canola cultivation. Meanwhile, West Azarbaijan, with its varied but often moderate climate, coupled with access to rivers and lakes, supports irrigated canola growth, contributing to its success in the region [75] (Figures 21 and 22). Canola cultivation in Iran thrives under the influence of climate, soil, water, and farming practices, as revealed in our study. Ref. [74] supports this, illustrating the impact of various factors on canola cultivation in Kermanshah province. Additionally, Ref. [75] highlights the diversity of canola cultivation in Iran, coupled with government support. Our results underscore the productivity and profitability of canola cultivation, crediting this success to moderate climates, fertile soils, sufficient water supply, and appropriate farming practices. Despite Iran's significant increase in canola production, Ref. [74] points out limitations in Kermanshah province, including low guaranteed prices, poor seed quality, and a lack of extension and credit services. The article suggests that enhancing canola adoption in the region requires addressing these challenges through increased guaranteed prices, improved seed quality, and better provision of extension and credit services.

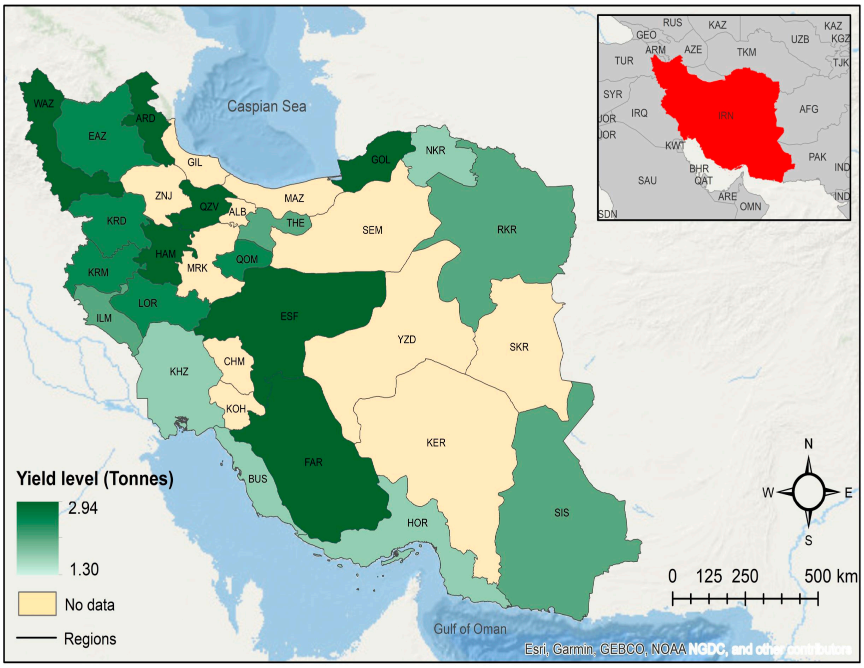

Figure 21. Optimal regional yield distribution of irrigated canola in Iran.

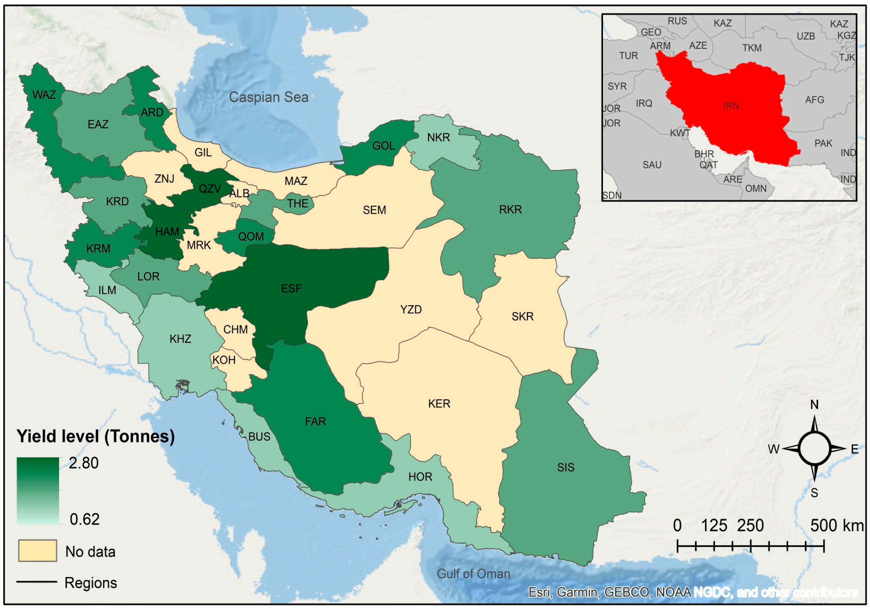

Figure 22. Observed 2016 regional yield distribution of irrigated canola in Iran.

Acknowledging the notable impact of economic constraints and soil management practices on the yield response function to nitrate, it is evident that economic factors play a pivotal role in shaping farmers' decisions on nitrogen fertilizer application, especially with rising input costs [76]. Understanding the complexities of resource allocation and the influence of economic considerations on farmers' prioritization of crops and regions within their fields leads to variations in nitrogen application rates, impacting the overall yield response. Highlighting soil management, the examination of soil characteristics, and organic matter content are crucial to comprehending their role in nitrogen efficiency and optimal crop yields [77]. Recognizing government policies and subsidies, an extended discussion will elaborate on their influence on farmers' decisions, including their potential impacts on fertilizer usage and their regulatory roles in mitigating environmental concerns related to nitrogen application [4].

The utilization of regional yield response functions in the context of nitrogen application, while presenting a convenient method, brings forth several limitations that require thoughtful consideration. Regional yield response functions often fail to adequately capture the variability in soil conditions, crop types, and climatic factors across different fields, potentially compromising the accuracy of predicting optimal nitrogen requirements. Additionally, these models may lack consideration for interactive effects with other nutrients and the temporal dynamics of nitrogen availability throughout the growing season. Despite the challenges associated with the time and cost of monitoring in field experiments, their practical conditions contribute notably to their superiority over relying solely on regional models. Furthermore, it is crucial to acknowledge that regional assessments may introduce biases in nitrogen–crop models, particularly in the presence of significant variations in technology adoption and farm sizes within a given region. Heterogeneity in technology use or farm sizes can lead to diverse agricultural practices, impacting the accuracy of regional models. The risk of overestimating or underestimating optimal nitrate levels and, consequently, optimal yields is heightened when these variations are not adequately accounted for. In such cases, field experiments become indispensable, providing the granularity necessary to discern the impact of diverse agricultural practices and farm structures on nitrogen response [14].

5. Conclusions

Given Iran's diverse climatic conditions and geological compositions and varying soil management practices, there exists a notable gap between the optimal utilization of nitrate and its practical implementation by farmers. This gap directly affects the difference between potential and actual yields in farming. To tackle this, accurately estimating the yield response function to nitrogen fertilizer becomes crucial, as it determines the most efficient application rates. The results of the estimated quadratic yield response functions show that rice (with 1031 (kg/ha)), onion (with 800 (kg/ha)), and tomato (with 508 (kg/ha)) have the largest usage of nitrogen at the optimal point, and rain-fed wheat (with 168 (kg/ha)) and rain-fed canola (with 171 (kg/ha)) have the smallest. Depending on whether the random or fixed-effects estimation is found to be the most suitable specification, the average yields corresponding to the optimal level of nitrogen use are calculated by region, or the average across all regions.

The GIS maps reveal how the varied geographical conditions across Iran's regions intricately influence the cultivation patterns and yields of different crops. As is also shown in the Iran yield gap atlas [78], the intricate interplay of factors such as temperature, rainfall, soil quality, and historical agricultural practices distinctly impacts the success and productivity of cereals like wheat and barley, alongside vegetable crops including tomatoes, potatoes, onions, and canola. Northern regions like Golestan and Mazandaran, with a balanced mix of rainfall and dry periods, are ideal for rain-fed wheat. Barley adapts well to semi-arid climates in Hamadan and Esfahan, driven by both climatic suitability and traditional practices. Maize thrives in Qazvin, Lorestan, and Kohkiloyeh and Buyer Ahmad, while limitations in Sistan and Baluchestan, Ardebil, and Golestan occur due to aridity. Tomatoes and potatoes succeed in Fars, East Azarbaijan, Hamadan, and Chaharmahal and Bakhtiyari, owing to specific climate and soil conditions. Onions, preferring cooler temperatures, find optimal growth in diverse regions like Yazd, Esfahan, Razavi Khorasan, and East and West Azarbaijan. Canola excels in moderate climates, flourishing in areas such as Esfahan, Hamadan, Ardebil, and Fars, benefiting from varied yet conducive environmental factors.

The nuanced regional disparities in climate, soil, and agricultural traditions underscore the importance of tailoring cultivation practices and embracing adaptive strategies. Understanding these regional intricacies is crucial for devising targeted agricultural interventions (e.g., subsidies), enhancing crop productivity, and ensuring food security amidst Iran's diverse landscapes. Therefore, the estimated yield response functions will be embedded into comprehensive agricultural–economic–environmental optimization models that facilitate assessing the impacts of different fertilizer policies on fertilizer use, land allocation, farm-household incomes and environmental externalities such as nitrate leaching and nitrate balance.

This study presents a novel contribution that explores policy implications related to fertilizer usage, particularly relevant for Iran and other developing nations struggling with inefficient agricultural practices. It stands out as the first of its kind, offering estimations of optimal nitrogen use and crop yield points across all regions in Iran through advanced GIS map visualization. While our findings present valuable insights, they warrant cautious interpretation. The choice of yield response function, transitioning from quadratic to alternative forms, can yield differing outcomes. Additionally, due to data constraints, our assumption regarding the fixed proportional application of phosphorus and potassium to nitrogen fertilizer, alongside the independent application rates of remaining inputs, such as pesticides and labor, by hectare, for each specific crop, may limit precision. Relaxing this assumption could lead to more accurate estimations of optimal nitrate application rates and subsequently refine yield distributions across regions. Acknowledging these limitations, our study marks a notable milestone as an inaugural exploration providing estimations for the optimal and most efficient points of nitrogen use and yields across all Iranian regions. Furthermore, it sheds light on the policy implications tied to fertilizer utilization, a matter of paramount importance not only for Iran, but also for numerous developing nations grappling with inefficient and unsustainable agricultural practices.

Author Contributions: Conceptualization, M.A.; Methodology, M.A.; Software, M.A. and C.D.; Validation, M.A.; Formal Analysis, M.A.; Investigation, M.A.; Resources, M.A.; Data Curation, M.A. and C.D.; Writing—Original Draft Preparation, M.A.; Writing—Review and Editing, M.A.; Visualization, C.D.; Supervision, M.A. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

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

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