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BAYESIAN REGRESSION MODEL'S ROLE IN MANAGING NEGATIVE EFFECTS OF SOIL AND WATER POLLUTION AND SOIL FERTILITY IMPACT ON CROP YIELD

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SUMMARY

Water pollution poses a foremost threat to crop productivity by degrading soil health. The latest study aimed to determine the impact of water quality and soil fertility on yields of chief cereal crops. Proposed data in corn, wheat, and soybeans used in Bayesian regression modeling helped determine crop-specific sensitivities to variations in water pollution and soil nutrients. The model estimates revealed that high water pollution levels reduced the average corn yields by 4.305 t ha^{-1}, wheat by 0.522 t ha^{-1}, and soybeans by 0.609 t ha^{-1} compared with the water with low pollution. In contrast, the well-fertile soil improved corn productivity by 1.306 t ha^{-1} and wheat and soybean yields by 0.52–0.61 t ha^{-1} versus medium fertility. The results highlighted the critical need for policies to control water pollution while improving soil quality to sustain crop yields. These policies include Water Quality Standards, Pollution Prevention Plans, Wastewater Treatment Regulations, Stormwater Management Regulations, and Environmental Impact Assessments (EIAs). Policies that lower surface and irrigation water contamination and enhance soil health require wider adoption to offset projected yield declines, especially given an expanding food demand.

Keywords: Water pollution, soil fertility and health, crop production, corn, wheat, and soybean yields

Key findings: The findings gave significant implications for agricultural practices and policymaking. The results emphasized the urgent need to launch policies and practices to control water pollution and improve soil quality to sustain crop yields, particularly in the face of an expanding global food demand. The quantitative evidence provided by the regression models emphasized specific yield losses associated with water pollution and the benefits of healthy soil in ensuring sustainable crop production.

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INTRODUCTION

By negatively affecting soil fertility and reducing crop yields, water pollution is a crucial threat to global food security. In irrigation water, extreme levels of contaminants, such as heavy metals, pesticides, and excess nutrients, can alter the soil's physical characteristic, which includes the soil texture, as it refers to relative proportions of sand, silt, and clay particles in the soil (Xia et al., 2020). Likewise, these influence the cultivated soil's chemical and biological properties. In soil health, this disruption deteriorates the soil quality and environment vital for optimal plant growth, resulting in a substantial crop productivity decline (Wang et al., 2018).

Therefore, understanding the relationship between water pollution, soil fertility, and crop yields is precarious, especially considering the strengthening of agriculture needed to feed the world's growing population (Çakmakçı et al., 2023). However, the magnitude of this impact varies considerably depending on the type of pollutant, crops grown, and existing environmental conditions (Drachal, 2019). Quantifying the crop-specific yield losses is essential for informing policymakers and prioritizing remedial strategies to safeguard global crop production (Aslam et al., 2021). The economic valuation of these projected yield impacts will highlight the urgent need for policies for controlling pollution to ensure long-term food security and sustainability (Alengebawy et al., 2021).

The key water quality indicators of interest are the levels of nitrogen, phosphorus, suspended solids, and heavy metals known to influence soil fertility directly. The models developed will determine the sensitivity of corn, wheat, and soybean crops to variations in each water pollutant while controlling other yield-impacting factors like climate, technology, and management practices (Cataldo et al., 2021). In irrigation water, the excess nitrogen and phosphorus can also lead to eutrophication and alter the soil pH, depleting oxygen, and disrupting the microbial communities beneficial for crop plants in the soil (Khaki et al., 2021).

Heavy metals, such as cadmium, lead, and arsenic, can accumulate in soils and inhibit plant growth through phytotoxicity (Menesi et al., 2022). Chief staple cereal crops exhibit differential sensitivity to water pollutants. In wheat, heavy metals affect photosynthesis and other metabolic processes severely affecting the growth and yield-attributing traits. The rice crop demonstrated the highest susceptibility to organic pollutants causing oxidative stress. The econometric analysis of the data better characterized the relationship between surface water-quality parameters and wheat crop yield (Han et al., 2020).

Maize crops have shown a moderate tolerance to heavy metals; however, their yield declines substantially with exposure to heavy metal mixtures like Zn+Ni and Cd+Zn. In general, most studies have evaluated crop response; however, the quantifying authentic yield losses at regional and national scales remains limited (Çakmakçı et al., 2023). The promising study aimed to provide an in-depth analytical investigation into the effects of water pollution on yields of three major staple grains, i.e., corn, wheat, and soybean. These investigations sought to quantify the crop-specific yield losses attributable to water pollution. The said analysis will also provide granular insights into the vulnerability of primary staple crops to different water contaminants, revealing which pollutants inflict the most damage and, hence require priority mitigation.

MATERIAL AND METHODS

Dataset description

Table 1 presents the data from 10 crop farms located in different regions, showing the relationship among the three important factors, i.e., water pollution levels, soil fertility rating, and the production of corn, wheat, and soybean crops.

Date collection

Generating the data utilized in this analysis ran statistical simulations designed to closely approximate real-world agricultural conditions (Falco and Zoupanidou, 2017). The figures present 10 farms of approximately equal area, with their production calculated on an annual basis. Based on standard reporting for crop yields, the units for the crop yield data in this dataset were tons or kg ha^{-1}.

Table 1. Datasets showing the relationship among water pollution levels, soil fertility ratings, and the production of corn, wheat, and soybean crops (t ha^{-1}).

Region	Water Pollution Level	Soil Fertility Rating	Corn Yield	Wheat Yield	Soybean Yield
1	Low	High	13.17	3.89	5.33
2	Medium	Medium	12.72	3.76	5.01
3	High	Low	11.59	3.44	4.70
4	Low	High	13.47	4.07	5.14
5	Medium	Medium	12.43	3.63	4.89
6	High	Low	10.78	3.44	4.39
7	Low	High	13.08	3.95	5.27
8	Medium	Medium	12.35	3.57	4.82
9	High	Low	11.22	3.19	4.51
10	Low	High	13.28	4.01	5.20

Study variables

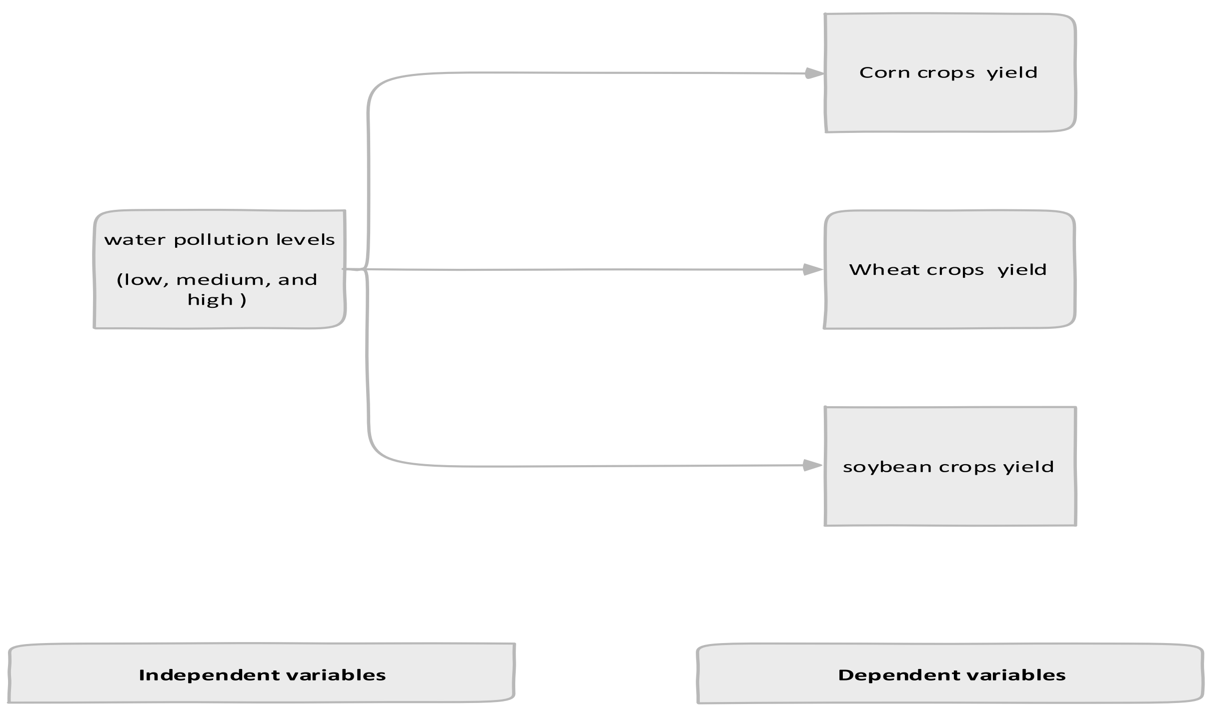

Figure 1. Study variables diagram.

Independent variables

In independent variables, the ratings for water pollution levels were low, medium, and high based on contaminant ppm (parts per million). The soil fertility ratings were low, medium, and high based on nutrient levels and organic matter.

Dependent variables

The yields from corn, wheat, and soybean crops were the dependent variables.

Data limitations

- Noteworthy in this study that the datasets used were dependent on simulated data designed to represent real-world agricultural conditions (Di Falco and Zoupanidou, 2017).
- Meanwhile, efforts sought to capture the variability in water pollution levels, soil fertility ratings, and crop yields, with the results interpreted within the context of the simulated datasets.

Ethical considerations

- The presented study adhered to ethical guidelines and ensured the privacy and confidentiality of the data collected.
- The research proceeded by the regulations and protocols of scientific research purposes.

Analytical approach

Performing the econometric analysis helped analyze the relationship between water pollution, soil fertility, and crop yields. The specific models developed aimed to determine the sensitivity of corn, wheat, and soybean crop yields to variations in each water pollutant while controlling other factors that may influence the yield, such as climate, technology, and management practices. The dataset analysis used SPSS software to identify patterns, correlations, and trends between the variables of interest. Descriptive statistics, such as means, standard deviations, and frequencies, also summarized all the datasets. Similarly, regression analysis and hypothesis testing characterized the relationship between water quality parameters and crop yields.

RESULTS AND DISSCUSION

The section presents the study results scrutinizing the effects of water pollution and soil fertility on crop yields from corn, wheat, and soybean production (Table 2). The analysis of datasets ran through the Bayesian regression modeling. The findings provide crucial insights for policymakers, agronomists, and the progressive farming community in ensuring future food security (Han *et al*., 2020).

The water pollution levels varied across the farms, i.e., 30% (high), 40% (low), and 30% (medium) pollution levels (Table 3). The soil fertility ratings also ranged from low to medium to high, with equal distributions of 40%, 30%, and 30% across the farms (Table 4). The study further revealed variations in water pollution levels, soil fertility ratings, and crop yields across different farms. Farm 1 was distinctive in low water pollution and high soil fertility, which attained the highest yields for all three crops. In contrast, Farm 5 notably showed high water pollution and soil fertility and experienced the lowest corn, wheat, and soybean crop yields. These variations highlight the significant impact of water pollution and soil fertility on these crops' productivity (Cataldo *et al*., 2021).

The quantitative analysis further supports the findings presented in Table 1. Bayesian regression modeling revealed that high water pollution levels led to average yield reductions of 4.305 t ha^{-1} for corn, 0.522 t ha^{-1} for wheat, and 0.609 t ha^{-1} for soybeans compared with low pollution conditions. Additionally, the high soil fertility conditions resulted in yield improvement of 1.306 t ha^{-1} for corn and 0.52-0.61 t ha^{-1} for wheat and soybeans compared with medium soil fertility levels. Conversely, low soil fertility led to yield reductions of 0.87-1.04 t ha^{-1} across all three crops (Çakmakçı *et al*., 2023).

Table 2. Soybean Yield * Water Pollution Cross Tabulation.

Soybean Yield * Water Pollution Level Cross Tabulation					
Count					
		Water Pollution Level			Total
		High	Low	Medium	
Soybean Yield	0.71	1	0	0	1
	0.74	1	0	0	1
	0.77	1	0	0	1
	0.79	0	0	1	1
	0.80	0	0	1	1
	0.82	0	0	1	1
	0.84	0	1	0	1
	0.85	0	1	0	1
	0.86	0	1	0	1
	0.87	0	1	0	1
Total		3	4	3	10

Table 3. Corn Yield * Soil Fertility Cross Tabulation.

Corn Yield * Soil Fertility Rating Cross Tabulation					
Count					
		Soil Fertility Rating			Total
		High	Low	Medium	
Corn Yield	1.76	0	1	0	1
	1.83	0	1	0	1
	1.90	0	1	0	1
	2.02	0	0	1	1
	2.03	0	0	1	1
	2.08	0	0	1	1
	2.14	1	0	0	1
	2.15	1	0	0	1
	2.17	1	0	0	1
	2.20	1	0	0	1
Total		4	3	3	10

Table 4. Wheat Yield * Soil Fertility Cross Tabulation.

Wheat Yield * Soil Fertility Rating Cross Tabulation					
Count					
		Soil Fertility Rating			Total
		High	Low	Medium	
Wheat Yield	0.51	0	1	0	1
	0.52	0	1	0	1
	0.56	0	1	0	1
	0.58	0	0	1	1
	0.59	0	0	1	1
	0.61	0	0	1	1
	0.63	1	0	0	1
	0.64	1	0	0	1
	0.65	1	0	0	1
	0.66	1	0	0	1
Total		4	3	3	10

The presented results further provide valuable insights into the specific effects of water pollution and soil fertility on crop yields, enabling policymakers and agricultural practitioners to develop targeted strategies for controlling water pollution and soil management. By implementing measures to reduce water pollution and enhance soil fertility, it is possible to mitigate different crop yield losses and ensure sustainable crop production to combat an increasing food demand (Wang *et al*., 2018; Amangaliev *et al*., 2023; Manzoor *et al*., 2024).

Moreover, the economic implication of a projected yield decline due to water pollution emphasized the need for practical policies and practices. The estimated yield losses translate into potential economic losses for the farming community and society. By prioritizing pollution control and adopting practices to improve soil health, policymakers can safeguard crop productivity and contribute to long-term food security (Menesi *et al*., 2022).

Effect of water pollution on crop yields

The evaluation of crop yields about different levels of water pollution revealed that high pollution had a significant negative impact on crop productivity. The cross-tabulation of crop yields against water pollution levels indicated a consistent trend across all three crops, i.e., corn, wheat, and soybean. The crop farms exposed to high water pollution consistently exhibited lower yields than those with low and medium water pollution levels (Alengebawy *et al*., 2021).

Cross-tabulating crop yields against water pollution levels vividly depict the negative influence of high water pollution on crop productivity (Tables 5–7). For corn, with high water pollution, yields ranged from 10.78 to 11.59 kg ha^{-1} compared with 12.36 to 13.49 kg ha^{-1} with low pollution conditions (Table 5). Wheat and soybean yields also exhibited a similar trend and the high water pollution consistently resulted in lowered crop yields than farms with low and medium pollution levels (Tables 6–7). The regression analysis quantifies the magnitude of these effects. The Bayesian model estimates that high water pollution reduced the average corn yields by 4.305 kg ha^{-1} compared with the baseline (Drachal, 2019).

For wheat and soybean crops, the losses were 0.38–0.44 t ha^{-1} with high water pollution vs. low pollution conditions. These findings exposed that higher water pollution considerably decreased grain yields of corn, wheat, and soybean crops. The models also suggested the positive impact of lower water pollution, with gains of 0.69–0.94 t ha^{-1} for these three crops under low vs. medium pollution levels (Khaki *et al*., 2021).

Effect of soil fertility on crop yields

The analysis also focused on exploring the relationship between soil fertility and crop productivity. The cross-tabulation of crop yields against soil fertility levels revealed an apparent positive trend, indicating that higher soil fertility correlated with increased yields of corn, wheat, and soybean crops.

The cross-tabulation of grain yield against soil fertility exhibited clear positive trends - higher soil fertility relates to increased crop productivity. For corn, wheat, and soybean crops, yields were lowest with low fertility and highest under high fertility conditions. The Bayesian regression model also quantifies the magnitude of these effects. Relative to medium fertility, high soil fertility enhanced corn yields by 0.94 t ha^{-1}. In wheat and soybean crops, the corresponding increments were 0.38–0.44 t ha^{-1} (Han *et al*., 2020).

Conversely, low compared to medium soil fertility reduced the yields by 0.87–1.04 t ha^{-1} across the three crops. These results also authenticated the beneficial effects of higher soil fertility and the detrimental impacts of low nutrient levels on crop productivity. In summary, the study results highlighted the negative effects of water pollution and the positive impact of soil fertility on corn, wheat, and soybean crop yields. Maintaining water quality and soil health emerged as the key factors in optimizing the productivity of these valuable cereal crops (Alengebawy *et al*., 2021).

Table 5. Bayesian estimates for corn yield.

Bayesian Estimates of Coefficients[a,b,c]					
Parameter	Posterior			95% Credible Interval	
	Mode	Mean	Variance	Lower Bound	Upper Bound
(Intercept)	199.333	199.333	8.806	193.403	205.264
Water Pollution Level = High	-20.667-	-20.667-	17.611	-29.053-	-12.280-
Water Pollution Level = Low	11.917	11.917	15.410	4.072	19.762
Water Pollution Level = Medium	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = High	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Low	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Medium	.[d]	.[d]	.[d]	.[d]	.[d]

a. Dependent Variable: Corn Yield
b. Model: (Intercept), Water Pollution Level, Soil Fertility Rating
c. Assume standard reference priors.
d. This parameter is redundant. Posterior statistics are not calculated.

Table 6. Bayesian estimates for wheat yield.

Bayesian Estimates of Coefficients[a,b,c]					
Parameter	Posterior			95% Credible Interval	
	Mode	Mean	Variance	Lower Bound	Upper Bound
(Intercept)	58.333	58.333	1.578	55.823	60.844
Water Pollution Level = High	-6.333-	-6.333-	3.156	-9.883-	-2.783-
Water Pollution Level = Low	5.167	5.167	2.761	1.846	8.487
Water Pollution Level = Medium	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = High	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Low	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Medium	.[d]	.[d]	.[d]	.[d]	.[d]

a. Dependent Variable: Wheat Yield
b. Model: (Intercept), Water Pollution Level, Soil Fertility Rating
c. Assume standard reference priors.
d. This parameter is redundant. Posterior statistics are not calculated.

Table 7. Bayesian estimates for wheat yield.

Bayesian Estimates of Coefficients[a,b,c]					
Parameter	Posterior			95% Credible Interval	
	Mode	Mean	Variance	Lower Bound	Upper Bound
(Intercept)	78.333	78.333	1.489	75.895	80.772
Water Pollution Level = High	-6.000-	-6.000-	2.978	-9.449-	-2.551-
Water Pollution Level = Low	5.167	5.167	2.606	1.941	8.393
Water Pollution Level = Medium	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = High	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Low	.[d]	.[d]	.[d]	.[d]	.[d]
Soil Fertility Rating = Medium	.[d]	.[d]	.[d]	.[d]	.[d]

a. Dependent Variable: Soybean Yield
b. Model: (Intercept), Water Pollution Level, Soil Fertility Rating
c. Assume standard reference priors.
d. This parameter is redundant. Posterior statistics are not calculated.

In the pertinent study, the findings detailed significant implications for agricultural practices and policymaking. The results emphasized the urgent need to launch policies and practices to control water pollution and improve soil quality to sustain crop yields, particularly in the face of expanding global food demand. The quantitative evidence provided by the regression models emphasizes the specific yield losses associated with water pollution and the benefits of healthy soil in ensuring sustainable crop production. The study highlights the importance of adopting practices that reduce surface and irrigation water contamination while simultaneously enriching soil health. By targeting mitigation strategies based on the identified crop-specific vulnerabilities, policymakers can better ensure future food security. Moreover, the economic valuation of the projected yield impact emphasizes the perseverance of the pollution control policies for long-term sustainability (Drachal, 2019).

Understanding the intricate relationship between water pollution, soil fertility, and crop yields is crucial for informed decision-making in agricultural and environmental management. The presented research significantly contributes to filling the knowledge gap by quantifying crop-specific yield losses attributable to water pollution. This granular analysis provides valuable insights into the vulnerability of major staple crops to different water contaminants, enabling the prioritization of mitigation efforts. The promising results also explored the detrimental effects of water pollution on crop yields and the positive impact of higher soil fertility. The findings emphasized the urgent need for policies and practices that target water pollution control and soil quality improvement to sustain crop productivity. By utilizing the pieces of evidence provided by the regression models and considering the specific relationship observed in the datasets, policymakers can make informed decisions to promote sustainable agricultural practices and ensure food security (Menesi *et al*., 2022).

CONCLUSIONS

The results demonstrated that high water pollution significantly reduced crop productivity, while higher soil fertility enhanced crop yields. Specifically, the high water pollution compared to low decreased corn, wheat, and soybean yields. In contrast, high soil fertility vs. medium enhanced the productivity of these crops.

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