THE REGIONAL EFFECTS OF WATERLOGGING AND SOIL SALINIZATION ON A RURAL COUNTY IN THE ARKANSAS RIVER BASIN OF COLORADO

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Abstract:

Rural counties along the Arkansas River of Colorado are being negatively affected as a result of irrigation induced waterlogging and soil salinization. Mathematical programming is first used to estimate the direct costs of these effects on agricultural production, then input-output analysis is used to estimate the indirect and induced impacts that are occurring. The average direct loss to agricultural production in Otero County Colorado was estimated to be approximately $68/acre. When the indirect and induced impacts are included, the total costs associated with waterlogging and soil salinization are estimated to increase by approximately 20% within this county.

Introduction

As lands are continually used in irrigated crop production the salinity levels in the soil and water table tend to increase. Over time, if there is inadequate drainage, the depth to the water table will decrease and a saline shallow water table is likely to develop. When a saline shallow water table exists, crop production can suffer as a result of waterlogging and/or excess soil salinity. Approximately 25-30% of irrigated lands in the United States have crop yields that are negatively affected by high soil salinity levels (Tanji 1990; Postel 1989; Ghassemi et al. 1995; Wichelns 1999). Estimates suggest that the worldwide crop production losses associated with salinity on irrigated lands are around $11 billion annually and increasing (Ghassemi et al. 1995).

The lower Arkansas River Basin of Colorado has been continuously irrigated since the 1870's and began to develop high saline water tables by the early part of the twentieth century (Miles 1977). Currently, the Arkansas River is one of the most saline rivers in the United States (Tanji 1990; Miles 1977). Although there is subjective evidence identifying waterlogging and soil salinity as threats to the viability of agriculture in the Arkansas River Basin, until recently there has not been adequate field data to appropriately quantify the phenomena. The objective of this paper is to estimate the economic impacts associated with waterlogging and soil salinization within a rural county located along the Lower Arkansas River of Colorado.

Description of Study Area

This research focuses upon approximately 65,000 acres of irrigated land located within Otero County Colorado (Figure 1).

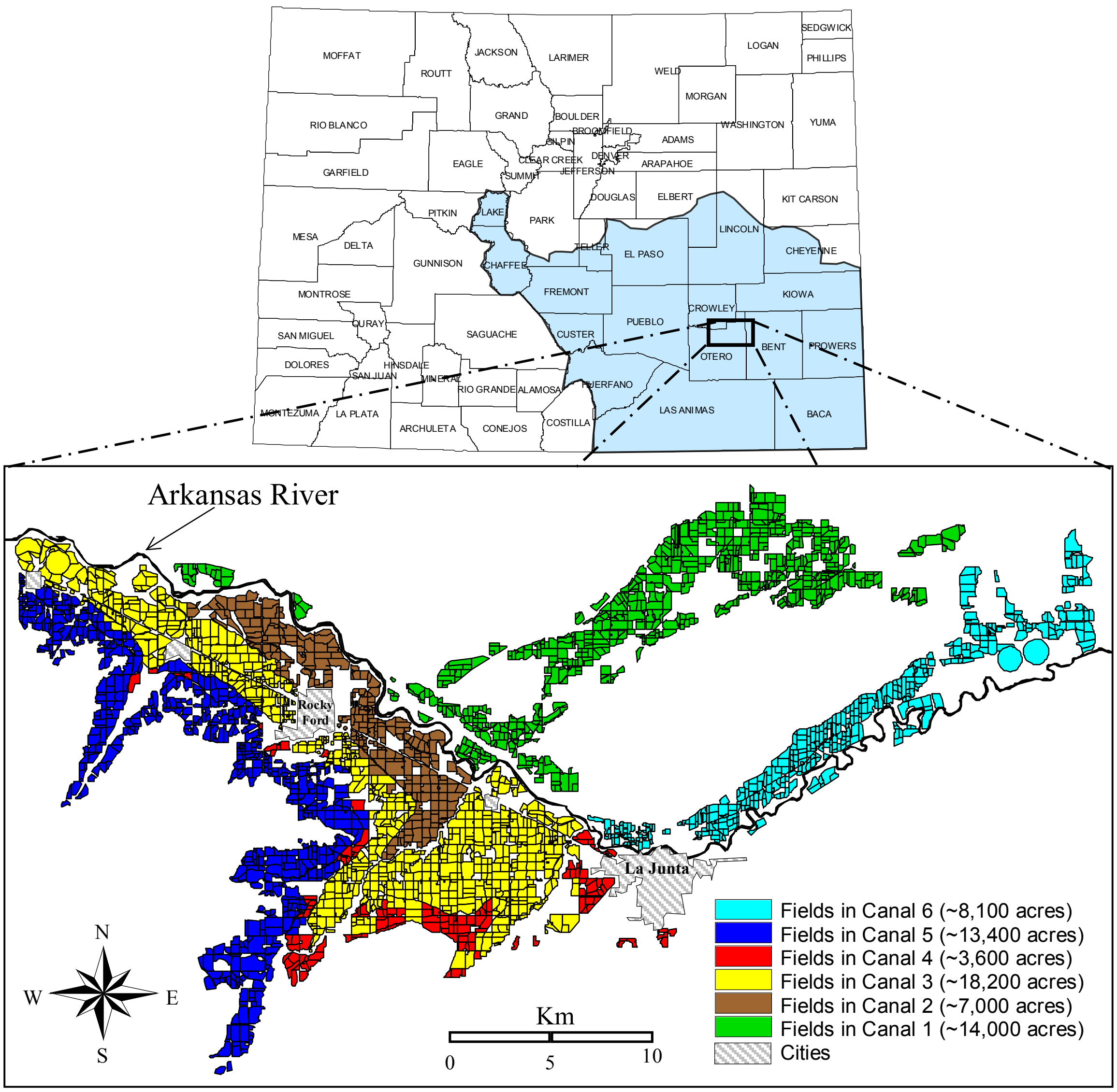

Figure 1: Map of Colorado Counties with Arkansas Basin Highlighted and Study Area Enlarged with Cities, River, and Irrigated Fields in each Canal Area Identified.

Impact of Soil Salinity and Waterlogging

A soil salinity problem exists when the build up of salts in a crops root zone is significant enough that a loss in crop yield results (Ayers and Westcot 1985). Many studies have been conducted to estimate the relationship between soil salinity levels and crop yield. Maas and Hoffman (1977) published an extensive review of the research examining these relationships. They concluded that crops are generally unaffected by salinity up to a threshold at which time yield will begin to decrease linearly as soil salinity levels increase. This type of two-piece linear relationship between relative crop yield (RY^S) and the electrical conductivity of the soil extract (*EC, a common measure of salt concentration)* can be described mathematically as follows:

(1) $$RY^S = 100 - b(EC - a) \qquad \text{for } EC \geq a$$

where, b is the slope of the yield response to salinity and a is the salinity threshold level at which crop yields begin to be affected. The thresholds and slope parameters presented by Maas and Grattan (1999) are used in this study to reflect the responsiveness of the relevant crops to salinity stressing (Table 1).

Table 1: Soil Salinity Ratings, Thresholds, and Slope Response Parameters.

	Rating	Threshold (*a*)	Slope (*b*)
ALFALFA	Moderately Sensitive	2.0	7.3
BEANS	Sensitive	1.0	19.0
CORN	Moderately Sensitive	1.7	12.0
GRASS	Moderately Sensitive	3.9	5.3
MELONS	Moderately Sensitive	1.0	8.4
ONION	Moderately Sensitive	1.0	8.0
SORGHUM	Moderately Tolerant	6.8	16.0
WHEAT	Moderately Tolerant	6.0	7.1

Waterlogging of agricultural lands occurs when there is inadequate oxygen available in the crops root zone as a result of excess water. Reduced oxygen supplies to a crops root as a result of a shallow water table reduces nutrient uptake, crop growth, and yield (Wesseling 1974). In general, when a shallow water tables exists the yields of most crops can be related to the depth of the water table. For most crops there exists an "optimum" water table depth, at which aeration, moisture, and nutrients are such that crop yields can be maximized. When the water table rises above this threshold, crop yields begin to decline (Evans and Fausey 1999).

Many studies have documented the negative effects of waterlogged soils on crop growth and yield. Williamson and Kriz (1970) presented a comprehensive review of the literature relating static (constant) non-saline water table depths to crop yield and included additional results from their own studies. Wesseling (1974) later compiled these findings and more recently Evans and Fausey (1999) have expanded upon these earlier studies. Table 2 reflects a summary of previous research examining the impact of waterlogging on the relevant crops in the study area.

Table 2: Relative Crop Yield (%) at Varying Water Table Depths.

			Water Table Depth, cm								
Crop	Code*		15-20	30	40-50	60	75	80-90	100	120	150
Alfalfa	1	5	37	63	100	-	-	-	-	-	-
	2	5	-	-	49	-	-	-	90	-	100
Beans	3	1	-	-	79	84	-	90	-	94	100
Corn	4	3	45	55	67	70	-	100	-	-	-
	5	3	-	-	-	59	-	87	-	100	-
	6	3	20	31	-	67	-	67	-	100	-
Grass	7	4	51	100	-	-	-	-	-	-	-
Melon(Squash)	8	4	21	48	58	65	78	90	100	-	-
Onion	9	6	-	-	63	109	-	-	-	-	-
Sorghum	10	2	-	34	-	48	-	100	-	-	-
Wheat	11	3	-	-	-	91	-	100	-	-	-

*Code numbers refer to author and soil type respectively.
First Number: 1 = Rai, S.D., D.A. Miller, and C.N. Hittle (1971), 2 = Benz, L.C., E.J. Doering, and G.A. Reichman (1985), 3 = Van Hoorn, J.W. (1958), 4 = Goins, T.J. Lunin, and H.L. Worley (1966), 5 = Chaudhary, T.N., V.K. Bhatnagar, and S.S. Prihar (1975), 6 = Kalita, P.K., and R.S. Kanwar (1992), 7 = Gilbert, W.B., and D.S. Shamblee (1959), 8 = Williamson, R.E., and G.J.. Kriz (1970), 9 = Harris, C.R., H.T. Erickson, N.K. Ellis, and J.E. Larson (1962), 10 = Hiler, E.A., R.N. Clark, and L.J. Glass (1971), 11 = Chaudhary, T.N., V.K. Bhatnagar, and S.S. Prihar (1974).
Second Number: 1 = Clay, 2 = Clay Loam, 3 = Silty Clay Loam, 4 = Loam, 5 = Sandy Loam, 6 = Muck.

Although no data was available for the response of melons, personal communication with a local crop scientist suggested that the data for squash be used in its place since they are both in the *Cucurbitaceae* family. The soils within the study are primarily made up of silty clay loam surface layers and loam to sandy loam substrata (USDA 1972a, 1972b). For some crops there was no information available for the relevant soil type, in this case the next closest soil type was used.

To estimate the losses associated with waterlogging it was necessary to estimate the functional form explaining the relationship between crop yield and water table depth. After analyzing the data, it was found that a segmented linear relationship identifying a water table depth threshold and response coefficient for each crop would be appropriate. Gates and Grismer (1989) used a similar approach to explain the variation in cotton yield as a function of water table depth. To identify the crop specific thresholds and slope parameters, data from Table 2 was plotted and ordinary least squares regressions were estimated (Figure 3).

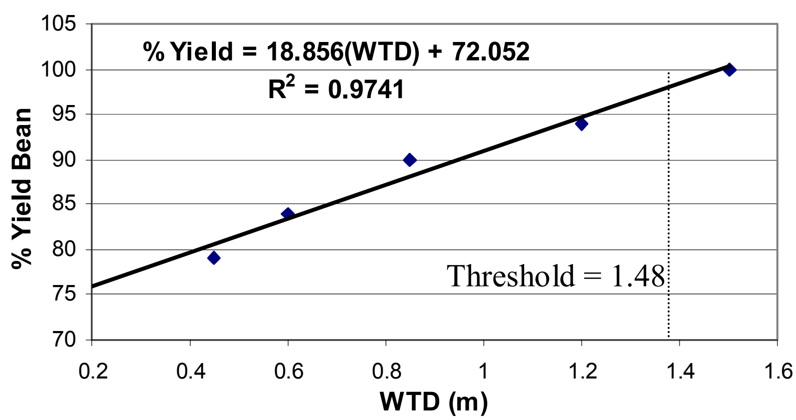

Figure 3: Relationship Between Relative Bean Yield and Depth of Water Table.

For some crops, there was more than one study available that identified the relationship between crop yield and water table depth. In these cases, the data sets were combined and the same regression techniques were used. This can be seen for corn in Figure 4, which uses the data from three separate studies.

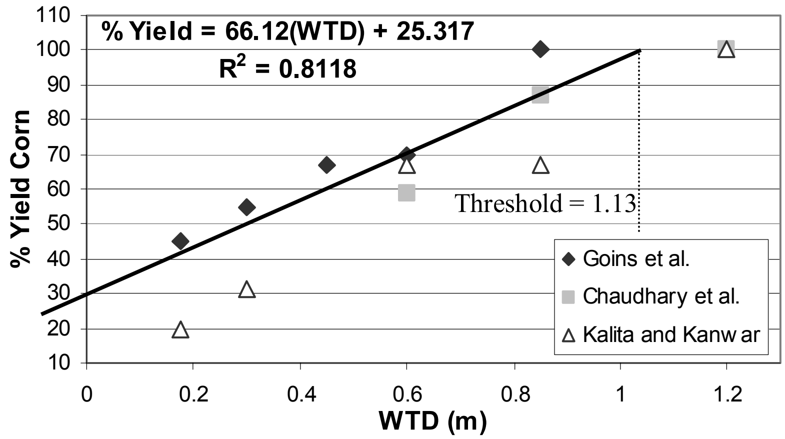

Figure 4: Relationship Between Relative Corn Yield and Depth of Water Table.

This segmented linear relationship can be shown mathematically in a similar manner as the relative yield concept for soil salinity. Where the relative yield as a result of water table depth (RY^{WTD}) can be shown as follows:

(2) $$RY^{WTD} = 100 - d(c - WT) \qquad \text{for } \; 0 \leq WT \leq c$$

Where, d is the slope of the waterlogging response curve, WT is the depth to water table, and c is the water table depth threshold level at which crop yields begin to be affected. The estimated thresholds and slope parameters for all of the relevant crops can be seen in Table 3.

Table 3: Estimated Values of Waterlogging Thresholds and Slope Parameters.

	Threshold (m)	Slope	P-Value of Slope Coefficient	R^2
ALFALFA	1.34	38	0.11339	0.505
BEANS	1.48	19	0.00178	0.974
CORN	1.13	66	0.00003	0.812
GRASS	0.30	392	0.00000	1.000
MELONS	1.00	84	0.00006	0.970
ONION	0.56	230	0.00000	1.000
SORGHUM	0.96	110	0.20431	0.901
WHEAT	0.85	36	0.00000	1.000

Little or no field data has been analyzed in order to better understand the combined effects of both soil salinity and waterlogging on crop yields (Christopher and TeKrony 1982). However, most field observations describe the effects of soil salinity on crop production to be increased when waterlogging conditions are present (West and Taylor 1980). Kahlown and Azam (2002) also observed the combined effect of waterlogging and soil salinity to be more harmful to crop yields than the individual effect of waterlogging. Due to the complexity associated with these interactions only a few studies have tried to account for the relationship between these impacts, typically assuming the interaction to be additive (Grieve et al 1986) or multiplicative (Christopher and TeKrony 1982; Gates and Grismer 1989). This study will follow the method developed by Christopher and TeKrony (1982) and later applied by Gates and Grismer (1989). These studies related the total relative yield factor (RY) for each crop to be the product of the relative yield associated with soil salinity (RY^S) and the relative yield associated with waterlogging (RY^{WTD}) as follows:

(3)
$$RY = RY^{S} * RY^{WTD}$$

Analytical Framework

The economic approach that is used in this study is to use mathematical programming to estimate the profitability of agriculture within the study section of the Lower Arkansas Basin given the current distribution of waterlogging and soil salinity. The model allows for the estimation of the direct impact of waterlogging and soil salinization on agricultural production. Once these direct estimates have been made, input-output analysis is used to approximate the additional indirect and induced effects that are occurring within Otero County.

The set of equations identified in equation (4) represents how total profits are estimated across all crops (*k=1,..,8*), irrigated fields (*I, avg.= 470/canal*), and canal areas (*c=1,…,6*) for each of the years.

$$\Pi = \sum_{c=1}^{C} \sum_{i=1}^{I} \sum_{k=1}^{K} \left[(P_k - HC_k) * Y_{cik} * A_{cik} - NHC_k \right]$$

(4) Where:

$$Y_{cik} = Y_k^p * RY_{cik}^S * RY_{cik}^{WTD}$$

$$RY_{cik}^S = 100 - b_k (EC_{ci} - a_k) \quad \text{for } EC_{ci} \geq a_k$$

$$RY_{cik}^{WTD} = 100 - d_k (c_k - WT_{ci}) \quad \text{for } WT_{ci} \leq c_k$$

Total profits (Π) are calculated by first identifying the difference between crop price (P_k) and per unit harvest costs (HC_k) which are multiplied by the estimated yield on each canal area field for each crop (Y_{cik}). This per unit crop return is then multiplied by the quantity of acres of each crop on each canal area field (A_{cik}). Finally, the per acre non-harvest costs for each crop (NHC_k) are subtracted. As mentioned above, the estimated yield of each crop represents the multiplicative effect of both salinity ($RY^S{}_{cik}$) and waterlogging ($RY^{WTD}{}_{cik}$) which is multiplied by the potential yield for each crop (Y_k^P). The above model will be estimated under current conditions and then again assuming a total reduction in soil salinity and waterlogging effects, thus identifying the total impact of the two effects. The model was written and solved using the General Algebraic Modeling System (GAMS).

To estimate the model above, the current cropping patterns and distribution of water table depths and soil salinity were identified. The area specific cropping parameters that needed to be identified are as follows: field acreage, field crop type, field location, current crop yields, regional crop prices, regional costs, irrigation technologies, and typical management practices.

Information concerning the size, crop type, and location of each field within the study area was identified using Farm Service Agency records for each of the three years (FSA 1999-2001). Average crop yields for Otero County and ten-year average crop prices were collected from Colorado Agricultural Statistics. Crop budgets from Colorado State Universities Cooperative Extension were used as a reference point from which to develop a complete set of area specific cropping budgets. All of the budgets reflect the costs of an open-ditch gravity irrigation system, which was identified as the typical water application method used in the region.

The current distribution of soil salinity and water table depths over the three-year period that was modeled were estimated by the Department of Civil Engineering at Colorado State University through the use of sophisticated hydrologic modeling. This hydrologic model has been calibrated through the use of extensive field data that was collected between 1999 and 2001. The hydrologic model applies a numerical finite-difference technique to simulate groundwater flow and salinity transport throughout the study area using a three dimensional grid containing 16,188 active cells (Burkhalter 2003, Gates et al. 2002). To estimate the on field impact associated with waterlogging and soil salinity, the engineering grid output needed to first be converted into a data set that reflected the weighted average condition on each field within the study area for each year.

To convert the grid data, the data was imported into ArcView GIS 3.2 and was placed under a layer that identified the borders of all irrigated fields within the study area. The software was then used to calculate the weighted average value for both soil salinity and water table depth on each field for each year[1]. (Figure 6)

[1] The hydrologic model was found to over predict soil salinity levels in the last two time periods. The average overestimate was calculated by comparing the modeled levels on approx. 67 fields for which field data had been collected. This average over prediction was then subtracted from all observations.

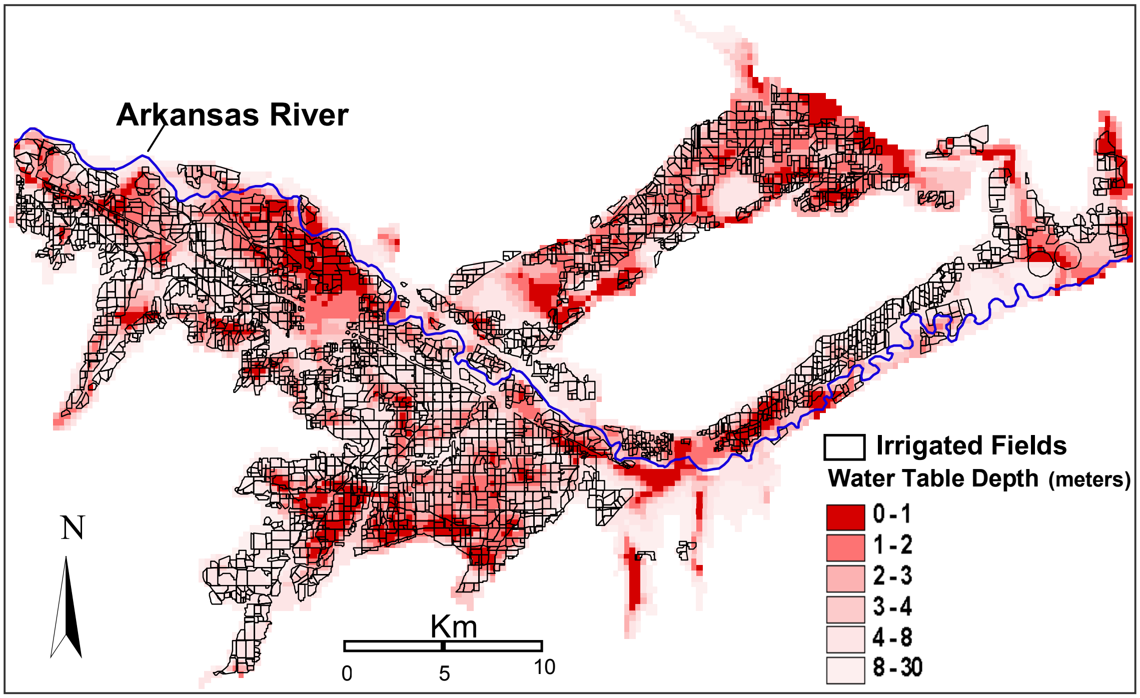

Figure 6: Image of Irrigated Fields Over Water Table Depth Grid Output (1999).

Results

Using the crop yields estimated under the current conditions for each field and year, the baseline profit levels were estimated. Table 8 shows the baseline profit levels within the study area for each year.

Table 8: Total Annual Profits and Profit per Acre under Current Conditions.

	Total Profit	Profit/Acre
1999	$10,124,177	$157.56
2000	$11,995,677	$192.21
2001	$10,952,782	$171.45
Average	$11,024,212	$173.74

The distribution of the baseline profit levels can also be seen graphically for each year in figure 7.

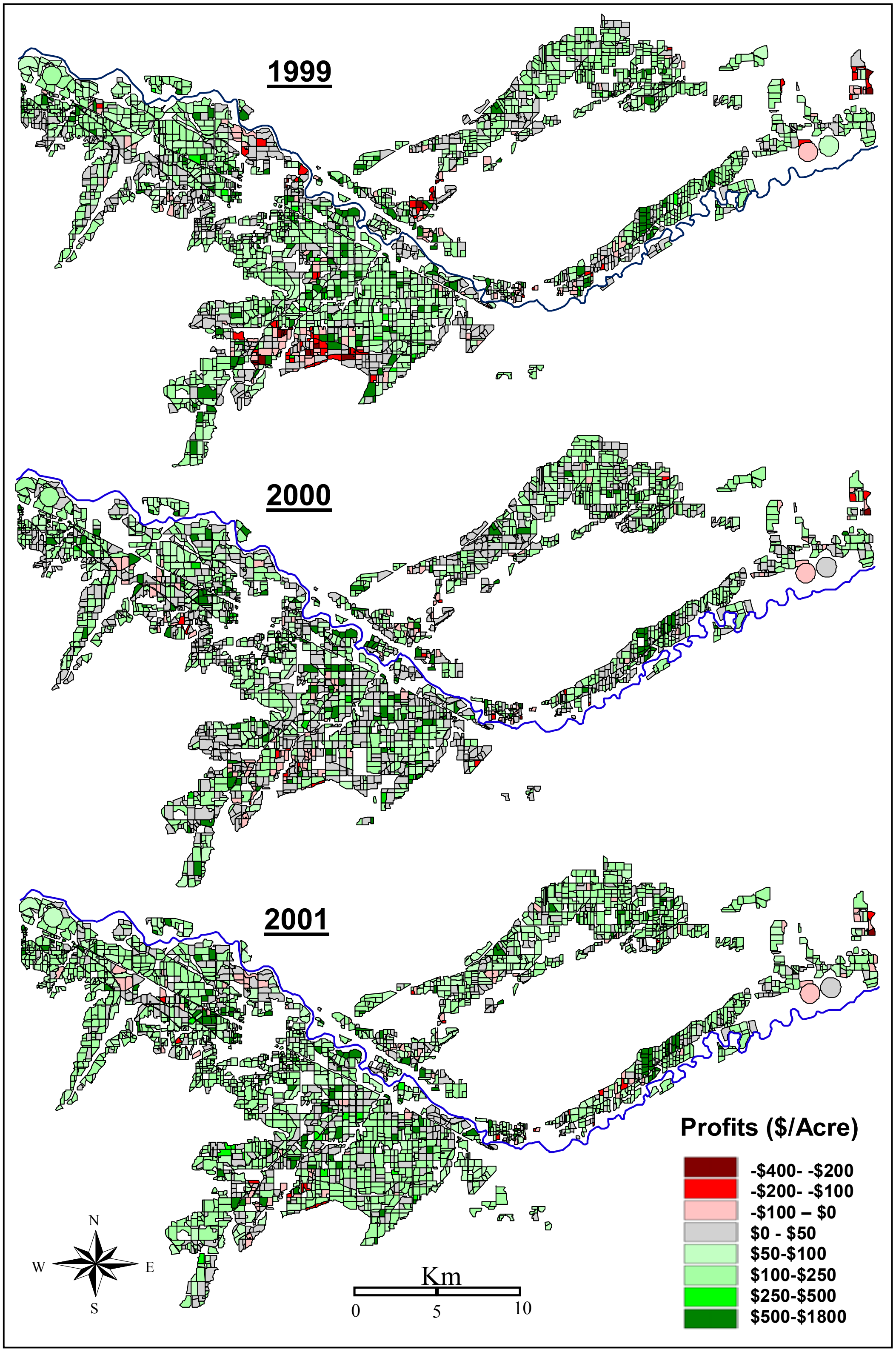

Figure 7: Average Baseline Profit Levels per Acre for each Field and Year under Current Conditions.

Cost of Salinity and Waterlogging

The total direct cost imposed on agricultural production was estimated by comparing the current baseline profitability levels with the level of profitability associated without yield reductions from soil salinity and waterlogging. The total value of forgone profitability as a result of soil salinity and waterlogging is estimated to range from approximately $3.1 to $5.4 million annually, averaging just over $4.3 million/year (Table 9).

Table 9: Forgone Profit Associated with Current Salinity and Waterlogging Levels for each Year.

	Total Foregone Profits	Foregone Profits/Acre
1999	$5,354,923	$83.34
2000	$3,121,125	$50.01
2001	$4,529,644	$70.90
Average	$4,335,231	$68.08

In addition, figure 8 shows how the damage associated with soil salinity and waterlogging varied across fields from year to year. The average annual direct loss as a result of current soil salinity and waterlogging is estimated to be $68.08/acre, which reflects the difference between the current average profit level of $173.74/acre and the potential profit level of $241.82/acre. This difference represents the opportunity of increasing profits from agricultural production by approximately 39% if the effects of waterlogging and soil salinity could be removed. In addition to these direct effects upon agricultural production, the indirect and induced impacts upon Otero County must also be taken into consideration.

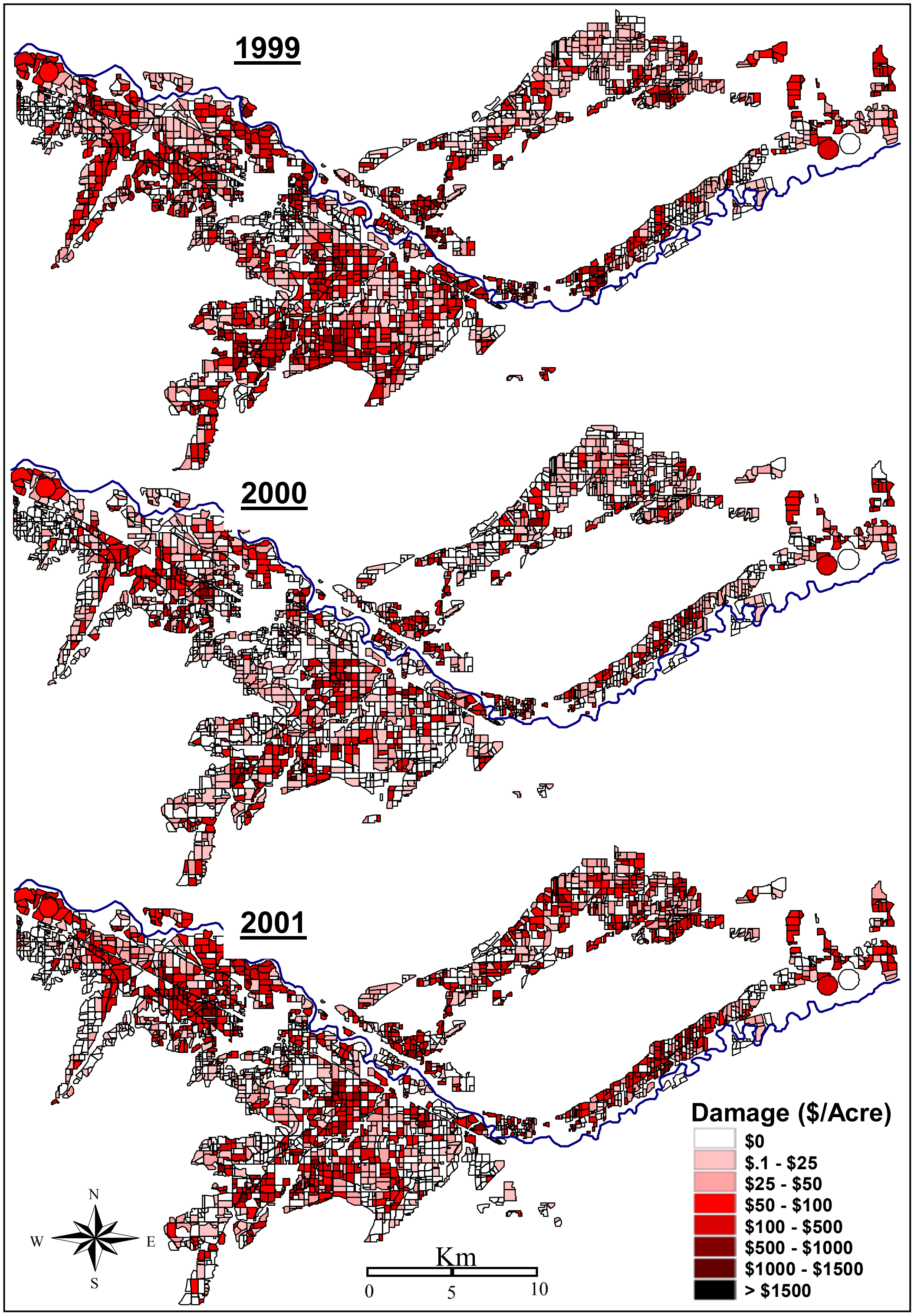

Figure 8: Direct Cost per Acre of Waterlogging and Soil Salinization on each Field and Year Given Current Conditions.

IMPLAN was used to estimate the indirect and induced impact that will occur as a result of the direct impact of waterlogging and salinity. This was done by entering the estimated average annual cost of salinity and waterlogging as direct impacts upon the three sectors of the Otero County economy that would be affected (Table 10). This distribution of the average direct impacts was developed by aggregating the impacts across the relevant crop types.

Table 10: Direct Impacts on Otero County Economy by Agricultural Sector.

	Direct Impacts to Otero County
Vegetables	$2,015,219
Hay & Pasture	$999,306
Feed Grains	$1,320,721
Total	$4,335,247

As a result of these direct impacts to the Otero County economy the following indirect and induced impacts were estimated to occur (Table 11).

Table 11: Direct, Indirect, and Induced Impacts on Otero County as a Result of Current Waterlogging and Soil Salinity Conditions.

	Otero County Impacts
Direct	$4,335,247
Indirect	$614,241
Induced	$267,951
Total	$5,217,439

This indicates that waterlogging and soil salinization imposes an additional cost of nearly $900,000 annually upon the Otero County economy as a result of the estimated $4.3 million of direct impact to agricultural production. Therefore, for each dollar directly lost from agricultural production due to waterlogging and soil salinization there is an additional cost of $.20 within this county.

Conclusions

The results of this study indicate that the direct production losses and associated forgone profits as a result of waterlogging and soil salinization are significantly impacting farmers located within the study area. The direct average forgone profit in agricultural production was estimated to be approximately $4.3 million annually (approx. $68/acre per year). In addition to these significant direct losses to agricultural production, the additional indirect and induced losses that have been estimated to occur within the overall Otero County economy indicate an even bigger problem.

Although water management practices for dealing with irrigation induced waterlogging and soil salinization have been well documented over time, it is critical to determine whether they are economically justified within this region. Future research will need to evaluate the alternatives available for improving the current conditions in the basin. By estimating both the costs and benefits associated with the alternatives aimed at reducing waterlogging and soil salinization, appropriate future actions can be identified.

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