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Irrigated agriculture and human development: a county-level analysis 1980–2010

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Abstract
As policy is developed to manage the declining Ogallala Aquifer, it is imperative to understand and manage the relationship between irrigated agriculture and human well-being in the High Plains region. We use a path analysis model to estimate the impact of the gallons of groundwater extracted for agricultural use and the percentage of irrigated farmland on Human Development Index scores for 234 High Plains counties between 1980 and 2010. Controlling for population, state, and the previous decade's Human Development Index score, we find that the prevalence of irrigated agriculture on the High Plains, as measured by the percentage of farm acres irrigated and the number of gallons of groundwater extracted, has a negligible impact on county-level human development, as measured by the Human Development Index. This suggests that policymakers may employ a range of strategies for managing irrigation withdrawals from the Ogallala Aquifer without harming the well-being of area residents.

Keywords Ogallala Aquifer · Human Development Index · High Plains · Irrigation policy · Groundwater management · Community capitals framework

1 Introduction

Agricultural production in the High Plains region of the USA is heavily dependent on groundwater from the Ogallala Aquifer (Smidt et al. 2016). The Ogallala Aquifer underlies 450,000 km^2 in portions of eight states (Qi and Christenson 2010) and contained 3750 km^3 of water in 2012 (Haacker et al. 2016). Irrigated agriculture in the High Plains is two to four times more productive relative to dryland farming (Smidt et al. 2016). Beginning in

Research impact statement: County-level human development on the High Plains is resilient across varying levels of irrigated agriculture between 1980 and 2010, indicating that there is space for experimentation by policymakers.

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the 1960s, access to Ogallala Aquifer groundwater for irrigation transformed the High Plains region from dust bowl to breadbasket (Opie et al. 2018).

However, the Ogallala Aquifer is being exploited unsustainably. By the 1990s, widespread groundwater withdrawals for irrigation had depleted at least one-third of the total water available (Opie et al. 2018). The Ogallala Aquifer recharges slowly, and while both the rate of recharge and saturated thickness—a measure of how much groundwater is available in storage—vary greatly across the High Plains region, continuing current rates of use would exhaust most groundwater supplies by 2070 (Smidt et al. 2016).

A sudden shift to dryland farming due to groundwater depletion could have profoundly negative consequences for agricultural livelihoods and rural communities in the region (Opie et al. 2018; Roberts and Emel 1992; Farmer et al. 2015; Sanderson and Frey 2015). At the same time, policymakers and local residents know that the current system of irrigated agriculture cannot endure much longer (Opie et al. 2018).

As policies are implemented to manage a transition away from widespread irrigation, it is important to understand any relationship between irrigated agriculture and human development in the region (Morton 2015). A stronger relationship between irrigated agriculture and human development would indicate that the transition must be managed more carefully to avoid greater regional stresses or harms, while a weaker relationship would indicate that there is potentially more leeway for policy experimentation. With this urgent question of policy in mind, we use the Human Development Index (HDI) to assess the extent to which irrigated agriculture is associated with human well-being in counties overlying the Ogallala Aquifer between 1980 and 2010.

Figure 1 shows changes in groundwater level in the Ogallala Aquifer in 2013 relative to predevelopment in the 1950s (McGuire 2017).

2 Background

2.1 Theoretical Framework

We use the community capitals framework (CCF) (Flora et al. 2015) to situate the relationship between groundwater depletion and HDI in the Ogallala Aquifer region. "Capitals" are assets that can be reinvested to generate additional assets. The CCF identifies seven types of capitals: natural, cultural, human, social, political, financial, and built. Each type of capital consists of both a stock of assets available to the community, and a flow component, whereby assets are drawn down and reinvested. One type of capital can be reinvested to increase a different type of capital, as when financial capital in the form of a community endowment fund is invested to provide entrepreneurial training for youth, thereby increasing the community's human capital (Flora et al. 1997).

The CCF was initially developed to better understand how communities achieve sustainable development outcomes in rural areas and has since been applied widely throughout the world (cf Gasteyer and Araj 2009; Gutierrez-Montes et al. 2009; Sseguya et al. 2009). Key insights include that some forms of capital reinvestment are more effective than others at generating sustainable development (Flora et al. 1997) that an over-emphasis on any one form of capital tends to decrease stocks of the other capitals thereby harming overall sustainability (Flora et al. 2015), and that a focus on reinvesting capitals within the community is conducive to sustainable development (Emery and Flora 2006; Flora et al. 1997, 2015). A study of rural communities in Nebraska suggests that properly mobilizing

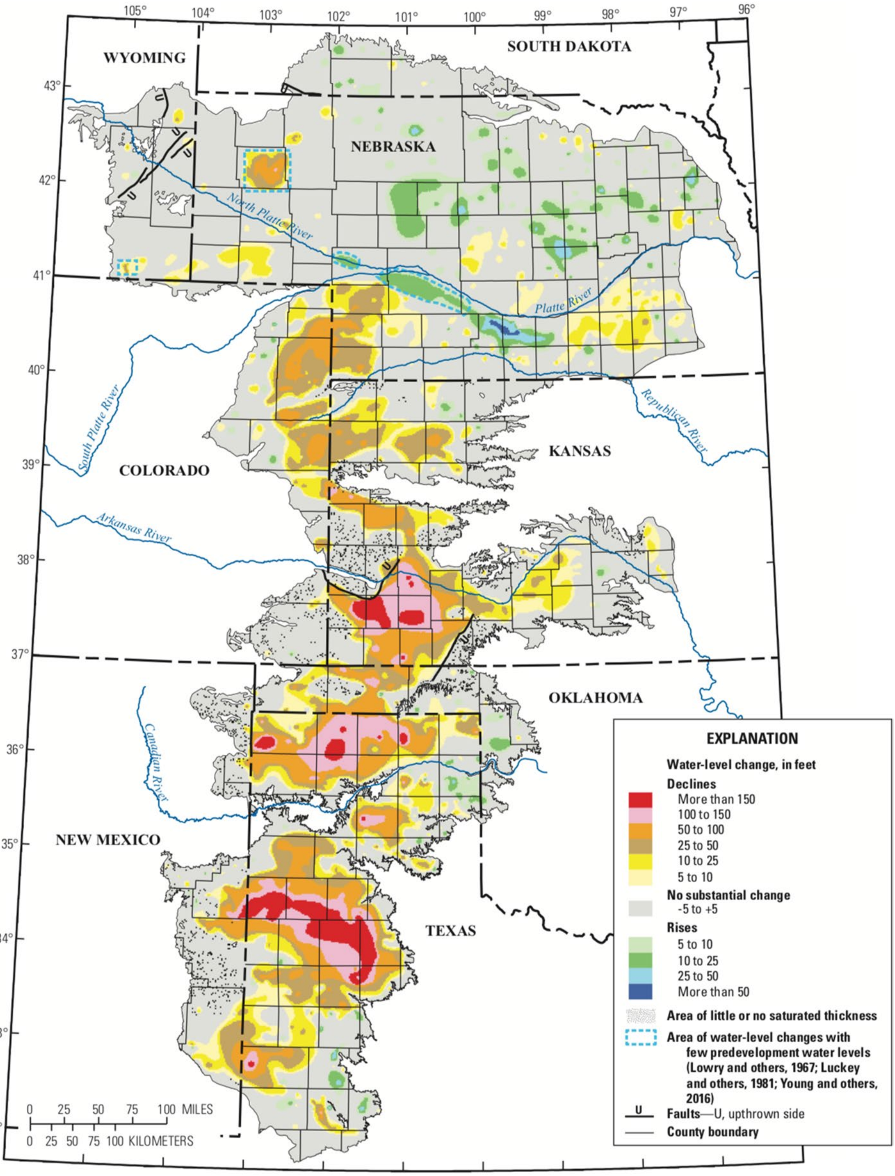

Fig. 1 Changes in groundwater in the Ogallala Aquifer predevelopment-2013 (McGuire 2017)

and reinvesting capitals locally can lead to a virtuous cycle, "spiraling up" toward a better future (Emery and Flora 2006). On the other hand, an excessive focus on reinvesting capitals outside of the community tends to harm community viability over the medium to long term (Emery and Flora 2006).

Our study focuses on three types of capital: natural, human, and financial. The exploitation of the Ogallala Aquifer can be seen as a drawdown of a natural capital stock. The HDI aggregates indicators of human capital (health and education) and financial capital (income). If the drawdown of groundwater, a natural capital stock, is reinvested into local human and financial capitals, we would expect to see greater HDI scores in counties with higher rates of drawdown.

2.2 Research consistent with a positive relationship between groundwater depletion and HDI

There is empirical evidence supporting the proposition that groundwater drawdown is reinvested, in this sense, into local financial capital and local human capital. Regarding financial capital, most studies find that access to irrigation has a sustained positive impact on the agricultural economy within the High Plains region (Hornbeck and Keskin 2015; Torell et al. 1990). Albrecht and Murdock (1986) found that irrigation increases gross farm sales, and together, higher gross farm sales from irrigation increased population size, numbers of farms, farm energy use, and farm wage expenditures relative to areas with less irrigation among non-metro counties on the High Plains between 1940 and 1980. More recent research indicated that agricultural incomes and farm-sector jobs remain positively associated with access to irrigation in the Texas Panhandle (Almas et al. 2004) and throughout the High Plains region (Parton et al. 2007).

There is also evidence on the reinvestment of groundwater drawdown into local human capital, especially as it relates to the relationship between irrigated agriculture and population growth. The most comprehensive inquiry into the relationship between irrigated agriculture and population growth on the High Plains was conducted in the early 1990s by geographer Stephen White.

White found that the population of the High Plains aggregates in counties with access to groundwater for irrigated agriculture (White 1992). Specifically, White found a statistically significant correlation between irrigated acreage and population growth across the High Plains between 1980 and 1990 (White 1992). Focusing on Kansas from 1980 to 1990, county-level population growth was most strongly positively correlated with the population size of the largest census place in the county, followed by a significant positive correlation with groundwater use per square mile (White 1994). White (1992, 1994) argued that population in the High Plains is redistributing to “Ogallala Oases” with over 500 people who depend on the benefits of groundwater exploitation in their hinterlands.

More recent research involving the entire High Plains region is consistent with White’s “Ogallala Oasis” hypothesis (Parton et al. 2007). Parton et al. (2007) found that population decreased from 1940 to 2000 in dryland, non-metro counties, but increased in irrigated, non-metro counties and in metro counties. The proportion of elderly residents over age 65 and over age 55 increased across all counties in the High Plains region between 1940 and 2000, but increased fastest in dryland, non-metro counties (Parton et al. 2007). An aging population is a challenge for policymaking due to the difficulty in accessing specialized medical care and handicap-accessible transportation in rural areas.

2.3 Research consistent with a negligible relationship between groundwater depletion and HDI

By contrast, a negligible relationship between groundwater depletion and HDI could be indicative of at least three possibilities, which are not mutually exclusive. First, the drawdown of natural capital in the form of groundwater use may not be reinvested locally. Non-local, or extra-local, reinvestment is consistent with the theory of ecological unequal exchange, whereby transfers of ecological resources from a more peripheral area to a more core area are not fully compensated by transfers of resources from core to periphery (Bunker 1985; Rice 2007; Jorgenson 2009).

There is evidence that ecological unequal exchange occurs not only across international income gradients (i.e., between countries of differing development levels), but that it also occurs across income gradients within countries (i.e., between rural and urban areas), and in the High Plains in particular. For example, Sanderson and Frey (2015) demonstrated that aggregate personal income in the rural counties of southwest Kansas remained stagnant from 1969 to 2011 in real terms, despite a dramatic increase in irrigated agricultural production. Furthermore, the gap in real aggregate personal income between southwest Kansas and urban Kansas increased significantly from 1969 to 2011 (Sanderson and Frey 2015). Taken together, these findings indicated that residents in rural, agricultural regions of the High Plains may not be reaping the full benefits of irrigated agriculture.

Second, the drawdown of natural capital in the form of groundwater might be reinvested locally but be a highly inefficient way of increasing local human and financial capital stocks. Prior research provides some evidence consistent with this hypothesis. Hornbeck and Keskin (2012) found no sustained benefit to the non-farm economy from increased access to irrigation. Indeed, there is some evidence that increased access to irrigation can be detrimental the non-farm economy over the long term, as resources and investments are shifted toward the farm economy (Hornbeck and Keskin 2012).

Locally inefficient reinvestment is consistent with the treadmill of production theory (Cochrane 2003; Schnaiberg 1980). A treadmill of production involves structural imbalances that encourage producers to debt-finance investments in infrastructure to increase their production capacity. This in turn forces producers to further deplete the natural resource stock to pay off the debt (Carolan 2012; Cochrane 2003).

Variants of treadmill theory have been applied to understand the context of farming and agriculture in the American Midwest (cf. Arbuckle and Kast 2012; Gasteyer and Carrera 2013; Gasteyer 2008; Sanderson and Hughes 2018). In a production treadmill, farmers continually deplete a natural capital stock, increasing built capital while maintaining a constant level of human and financial capital (Carolan 2012). This treadmill is further exacerbated by ecological unequal exchange (Sanderson and Frey 2015) and supported by the farm subsidies (Sanderson and Hughes 2018). The structure of federal farm subsidies encourages debt-financed investments into increasingly water-efficient irrigation infrastructure, which are then paid off through further groundwater extraction. The result is that groundwater depletion persists despite increased irrigation efficiencies, while farm incomes remain relatively stagnant, locking farmers into in a continual effort to "get ahead" through technology adoption and extension, which further depletes the resource base on which their incomes depend.

Third, the drawdown of natural capital in the form of groundwater might be reinvested locally into other forms of capital. For example, one would not necessarily expect a relationship between groundwater depletion and HDI if groundwater drawdown is primarily reinvested into increased cultural, social, or political capital.

A review of social science literature pertaining to irrigation from the Ogallala Aquifer (Lauer et al. 2018) suggests that the impact of Ogallala irrigation on "non-market values," which include cultural, social, and political capitals, is understudied. Nevertheless, there is some evidence that groundwater drawdown has increased local social, cultural, or political capital, at least in certain areas. Regarding social capital, Williams and Bloomquist (1997, p. 283) found that groundwater irrigation in Haskell County, Kansas, between 1940 and 1993 provided a "more stable social environment" in which communities became socially "integrated." These changes may be indicative of an increase in social capital in Haskell County.

Regarding cultural capital, Gray and Gibson (2013) found that farmers in southwest Kansas see irrigation as a means of preserving the farm profitability on which their culturally valued rural lifestyle depends. Regarding political capital, Griggs (2017) demonstrates that groundwater irrigation has increased political clout among farmers in areas with access to the Ogallala Aquifer, albeit at the expense of surface-water irrigators elsewhere in the High Plains.

We emphasize that these three explanations for a negligible relationship between groundwater depletion and HDI are not mutually exclusive. For example, a study of farm families in rural Iowa (Arbuckle and Kast 2012) found that subjective quality of life (a measure of cultural capital) is positively associated with community cohesion (social capital) and negatively associated with measures of exposure to a production treadmill. To the extent that groundwater irrigation improves community cohesion in the High Plains, one might speculate that a portion of the natural capital acquired from groundwater irrigation in the High Plains is similarly invested into local social and cultural capital, while another portion is inefficiently invested into local built capital through a production treadmill.

2.4 The present study

High Plains residents are the most immediately impacted by the depletion of the Ogallala Aquifer and by changes to its management. At this point, transitioning away from the present system of widespread irrigation is unavoidable. As policies are implemented to manage this transition, it is important account for the impacts of irrigation on human development in the region.

We are not aware of any prior research that explicitly examines the relationship between irrigation and human development in the region. It is clear, however, that the previous research into the impacts of irrigation on *aspects of* human development in the region remains inconclusive. For example, the previous research indicates that irrigation provides a sustained benefit to the local agricultural economy but only a temporary boost to the non-farm economy (Hornbeck and Keskin 2012). While population growth concentrates in counties with access to irrigation, there is evidence that increased irrigation has not produced an increase in aggregate real personal income (Sanderson and Frey 2015).

Given these inconclusive findings, there is need for additional research into the relationship between irrigated agriculture and well-being among High Plains residents. This study fills a gap in our knowledge about the impacts of Ogallala groundwater on human well-being by ascertaining the relationship between HDI and irrigated agriculture from 1980 through 2010 across the counties overlying the Ogallala Aquifer.

2.4.1 Research question

Is there a relationship between the prevalence of irrigated agriculture on the High Plains, as measured by the percentage of farm acres irrigated and the number of gallons of groundwater extracted, and county-level human development, as measured by the HDI?

3 Method

3.1 Sample

We began with 235 counties in eight states that are underlain at least in part by the Ogallala Aquifer and its associated groundwater formations. These counties were obtained from the Natural Resources Conservation Service of United States Department of Agriculture (Gollehon and Winston 2013).

We excluded Oglala Sioux County in South Dakota from our analysis because it is located entirely within the Pine Ridge Indian Reservation. Due to the lingering effects of historic injustices, Oglala Sioux County follows a very different development trajectory from other counties in the Ogallala Aquifer region. Native American populations have the lowest HDI scores of any racial or ethnic demographic in the USA (Lewis and Burd-Sharps 2010), and Native Americans in South Dakota have particularly low HDI scores (Lewis and Burd-Sharps 2010).

While widespread irrigation began in the Ogallala region in the 1950s (Opie et al. 2018), data limitations constrained our analysis to the period from 1980 through 2010. Specifically, the 1980 census is the first to contain county-level data on a critical component of the HDI: life expectancy at birth.

The unit of analysis is the county. There were no missing data in our sample. We used publicly available secondary data that were originally collected by the US Census Bureau, the US Geological Survey, and the US Department of Agriculture. We accessed these data through various database managers that contract with the Federal Government to clean and store the data. The specific source of each dataset is described in the Measures section of this paper. After accessing the necessary datasets, we built a single, integrated database in MS Excel and imported it into the *R* statistical program for analysis.

3.2 Measures

3.2.1 Human development

The Human Development Index (HDI) provides a robust metric of the health, education, and economic welfare of populations around the world (UNDP 2010; Zambrano 2014). Debuted in 1990 by the United Nations Development Program, the HDI measures indicators of basic capabilities for living a good life (Stanton 2007). The HDI focuses on health, education, and income as three of the most basic necessities for human development in all societies around the world. The HDI is a more comprehensive measure of development and is intended as a complement to more narrow measures of economic output, such as gross national product.

Pioneering work by the Social Science Research Council adapts and applies the HDI to states, counties, and congressional districts within the USA through the “Measure of America” initiative (Lewis and Burd-Sharps 2014). “Measure of America” research was cited by the United Nations Development Program in their 2010 Human Development Report (UNDP 2010). Except where noted otherwise, we followed the methods of the Social Science Research Council in calculating the HDI.

We calculated HDI by taking the mean value of three indices measuring health, education, and income. The Social Science Research Council multiplies the mean by a constant of ten. We instead multiplied by a constant of 100 because the measure of irrigated farmland in our model is expressed as a percentage. The choice of scalar has no substantive impact on our results

$$\text{Human Development Index}_i = 100 \times \left(\frac{\text{Health Index}_i + \text{Education Index}_i + \text{Income Index}_i}{3} \right). \tag{1}$$

3.2.2 Health Index

The Health Index measures life expectancy at birth, scaled using the ratio of minimum and maximum values observed among Ogallala counties between 1980 and 2010

$$\text{Health Index}_i = \frac{\text{life expectancy}_i - \text{life expectancy}_{\text{MIN}}}{\text{life expectancy}_{\text{MAX}} - \text{life expectancy}_{\text{MIN}}}. \tag{2}$$

County-level data on life expectancy at birth at the 1980, 1990, 2000, and 2010 US Censes were acquired through the Institute for Health Metrics and Evaluation (IHME 2017).

3.2.3 Education Index

The Education Index combines a subindex measuring educational attainment, weighted at two-thirds and a subindex measuring educational enrollment, weighted at one-third. Educational attainment for each county was determined by dividing the population with at least a high-school diploma by the total population over the age of 25. Consistent with Social Science Research Council methodology, educational enrollment for each county was determined by dividing the total population of any age enrolled in school by the total school-age population of 3–24 years old (inclusive). Both subindices were scaled using the ratio of minimum and maximum values observed among all Ogallala counties between 1980 and 2010

$$\begin{aligned} \text{Education Index}_i = &\frac{2}{3}\left(\frac{\text{Attainment}_i - \text{Attainment}_{\text{MIN}}}{\text{Attainment}_{\text{MAX}} - \text{Attainment}_{\text{MIN}}} \right) \\ &+ \frac{1}{3}\left(\frac{\text{Enrollment}_i - \text{Enrollment}_{\text{MIN}}}{\text{Enrollment}_{\text{MAX}} - \text{Enrollment}_{\text{MIN}}} \right). \end{aligned} \tag{3}$$

County-level data on population with a high-school diploma, total population over the age of 25, population enrolled in school, and total school-age population of 3–24 years old at the 1980, 1990, 2000, and 2010 US Censes were acquired through the National Historical Geographic Information System of the Minnesota Population Center (2011).

3.2.4 Income Index

We calculated the income index using the log of per-capita income, scaled using the minimum and maximum values observed in any county between 1980 and 2010. Our approach differs from the Social Science Research Council, which instead uses the log of median earnings as an indicator of economic welfare. Median earnings give greater weight to the economic welfare of individuals at the lower end of the income distribution and are arguably a better measure of the effect of income on human well-being (Lewis and Burd-Sharps 2014). However, median earnings are not available at the county level for the year 1980. Per-capita income is used by the United Nations Development Program in their calculation of the HDI and is available at the county-level for all census years of interest. We believe that per-capita income is a justifiable measure of economic well-being but urge caution when comparing our results to the “Measure of America” project

$$\text{Income Index}_i = \frac{\text{per capita income}_i - \text{per capita income}_{\text{MIN}}}{\text{per capita income}_{\text{MAX}} - \text{per capita income}_{\text{MIN}}}. \quad (4)$$

County-level data on per-capita income at the 1980, 1990, 2000, and 2010 US Census were acquired through the National Historical Geographic Information System of the Minnesota Population Center (2011). Per-capita income was adjusted for inflation using the online Consumer Price Index calculator of the Bureau of Labor Statistics (BLS 2017).

3.2.5 Percent irrigated farmland

We obtained one measure of the prevalence of irrigated agriculture within each county by calculating the percentage of irrigated farmland acres relative to the total number of farmland acres in that county

$$\text{Percent irrigated farmland}_i = 100 \times \left(\frac{\text{irrigated farmland}_i}{\text{all farmland}_i}\right). \quad (5)$$

County-level data on the number of acres of irrigated farmland and the total number of acres of farmland were generated by the Census of Agriculture during the years 1978, 1987, 1997, and 2007. We acquired the data through the National Agricultural Statistics Service of the United States Department of Agriculture (NASS 2017).

3.2.6 Groundwater extraction

We obtained a second measure of the prevalence of irrigated agriculture within each county by summing groundwater withdrawals in Mgal/d for irrigation and livestock at the county level in 1985, 1995, and 2005

$$\text{Groundwater extraction}_i = \left(\text{irrigation withdrawals}_i + \text{livestock withdrawals}_i\right). \quad (6)$$

County-level data on groundwater withdrawals in Mgal/d for irrigation and for livestock were generated by the United States Geological Survey. We acquired the data through the United States Geological Survey online data repository (U.S. Geological Survey 2018).

3.2.7 Population

We obtained US Census data on population at the county-level, in thousands, through the United States Geological Survey online data repository (U.S. Geological Survey 2018).

3.2.8 Log population

Because county-level population is not normally distributed, we used a log base ten transformation of county-level population in our model.

3.3 Analytic plan

The purpose of our study is to clarify the relationship between HDI and irrigated agriculture from 1980 through 2010 across the counties overlying the Ogallala Aquifer, thereby determining whether the depletion of natural capital in the High Plains region is effectively reinvested, or transformed, into increases in local human and financial capitals. We use a path analysis model to predict county-level HDI scores for each decade using the most recent past measures of percent irrigated farmland and groundwater extraction for that county, controlling for each county's contemporary population, the state in which it is located, and its HDI score from the previous decade. While path analysis models are most often used with latent variables, they are also appropriate for models using only manifest variables (Kline 2016). We use a path analysis model because it estimates all modeled parameters simultaneously, thereby reducing the likelihood of Type I errors (Kline 2016). Models were estimated using the lavaan package in *R* (Rosseel 2012).

4 Results

The primary goal of the analyses is to examine the relationship between two measures of the prevalence of irrigated agriculture and HDI scores over time at the county level. Table 1 provides the means, standard deviations, and ranges of each study variable.

We used a path analysis model to determine how HDI scores changed over time. Figure 2 shows the results of the model. The model explains 47.7% of the variation in 1980

Table 1 Model variables: descriptive statistics ($N=234$)

Variables	Unit	*M*	SD	Range	Skew	Kurtosis
HDI 1980	Score	53.96	5.48	17.00 to 60.91	−1.44	4.91
HDI 1990	Score	59.43	5.53	21.51 to 65.90	−1.34	4.73
HDI 2000	Score	73.40	5.93	36.10 to 76.81	−1.08	1.98
HDI 2010	Score	71.82	6.42	35.08 to 76.88	−.94	1.22
Irrigated farmland 1978	% total	12.35	23.12	1.34 to 88.81	1.59	2.15
Irrigated farmland 1987	% total	11.21	22.10	1.20 to 84.65	1.46	1.76
Irrigated farmland 1997	% total	13.09	19.64	.88 to 78.72	1.49	1.95
Irrigated farmland 2007	% total	14.39	17.95	2.21 to 78.33	1.70	2.85
Groundwater extraction 1985	Mgal/d	70.71	79.40	.12 to 401.24	1.68	2.63
Groundwater extraction 1995	Mgal/d	74.20	88.98	.11 to 543.88	1.84	3.99
Groundwater extraction 2005	Mgal/d	76.60	87.69	.17 to 421.08	1.60	2.27
Population 1980	Thousands	15.66	33.13	.51 to 366.53	6.71	58.38
Population 1990	Thousands	15.90	36.60	.46 to 403.66	6.75	58.42
Population 2000	Thousands	17.24	42.29	.44 to 452.87	6.58	54.26
Population 2010	Thousands	18.58	48.83	.46 to 498.37	6.30	48.02
Log population 1980		.87	.48	−.29 to 2.56	.47	.66
Log population 1990		.84	.50	−.34 to 2.61	.54	.71
Log population 2000		.84	.52	−.35 to 2.66	.57	.71
Log population 2010		.82	.55	−.34 to 2.70	.62	.72

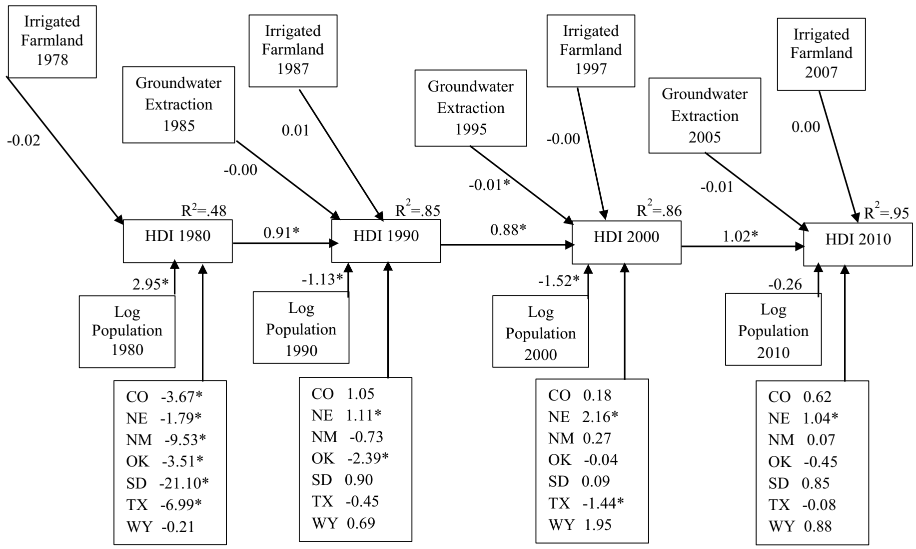

Fig. 2 Unstandardized path coefficients for variables explaining Human Development Index (HDI) scores in counties underlain in part by the Ogallala Aquifer ($N=234$). *$p<.05$ (two-tailed)

HDI scores ($R^2=.48$), rising to 85.4% in 1990 ($R^2=.85$), 86.2% in 2000 ($R^2=.86$), and 95.3% in 2010 ($R^2=.95$). The path analysis model has a good fit to the data: $\chi^2(36)=89.51$, $p<.001$; CFI = .97; TFI = .94; RMSEA = .08 (90% confidence interval [.06, .10]); SRMR = .01. Although the model fit indicated a significant Chi-square test, significant Chi-square tests often occur when utilizing large sample sizes (Hooper et al. 2008).

Table 2 shows the unstandardized coefficients, standardized coefficients, and p values for each path in the model.

There is no statistically significant relationship between decadal county-level HDI scores and percentage of irrigated farmland acres at the immediately preceding Census of Agriculture. Overall, there is no statistically significant relationship between decadal county-level HDI scores and measures of groundwater extraction taken 5 years prior. The sole exception is that HDI scores in 2000 had a statistically significant, negative relationship with groundwater extraction in 1995. These are findings with important theoretical and practical implications that we discuss later on.

Among the control variables, we find that county-level HDI scores in each decade have a positive, statistically significant relationship with that county's HDI score in the previous decade. This is an unremarkable finding, given that social and economic development tends to build upon itself over time.

We find that the log of county population in 1980 has a positive, statistically significant association with county-level HDI scores in 1980. One possible explanation for this association may be that counties with higher populations provide greater access to healthcare, educational opportunities, and a greater variety of employment options, thereby increasing HDI scores. Alternatively, counties with higher HDI scores may be more attractive destinations for people to live in, facilitating a higher population as more people are induced to move in and fewer leave. Because measures of HDI scores and of population were both taken at the time of the decennial census, we are not able to determine whether one causes

Table 2 Unstandardized, standardized, and significance levels for model in Fig. 2

Parameter estimate	Unstandardized	Standardized	p
Irrigated farmland 1978 → HDI 1980	− .02	− .04	.49
Log population 1980 → HDI 1980	2.95	.23	< .01
CO → HDI 1980	− 3.69	− .15	< .01
NE → HDI 1980	− 1.79	− .14	.02
NM → HDI 1980	− 9.53	− .32	< .01
OK → HDI 1980	− 3.51	− .11	.03
SD → HDI 1980	− 21.10	− .55	< .01
TX → HDI 1980	− 6.99	− .47	< .01
WY → HDI 1980	− .21	− .01	.91
Irrigated farmland 1987 → HDI 1990	.01	.03	.48
Groundwater extraction 1985 → HDI 1990	− .00	− .04	.29
HDI 1980 → HDI 1990	.91	.90	< .01
Log population 1990 → HDI 1990	− 1.13	− .09	< .01
CO → HDI 1990	1.05	.04	.13
NE → HDI 1990	1.11	.09	.02
NM → HDI 1990	− .73	− .02	.41
OK → HDI 1990	− 2.39	− .08	< .01
SD → HDI 1990	.90	.02	.48
TX → HDI 1990	− .45	− .03	.39
WY → HDI 1990	.69	.02	.49
Irrigated farmland 1997 → HDI 2000	− .01	− .01	.78
Groundwater extraction 1995 → HDI 2000	− .01	.10	.01
HDI 1990 → HDI 2000	.89	.81	< .01
Log population 2000 → HDI 2000	− 1.52	− .12	< .01
CO → HDI 2000	.18	.01	.80
NE → HDI 2000	2.16	.16	< .01
NM → HDI 2000	.27	.01	.78
OK → HDI 2000	− .04	− .00	.97
SD → HDI 2000	.09	.00	.94
TX → HDI 2000	− 1.44	− .09	< .01
WY → HDI 2000	1.95	.05	.07
Irrigated farmland 2007 → HDI 2010	− .01	− .03	.28
Groundwater extraction 2005 → HDI 2010	.00	.01	.61
HDI 2000 → HDI 2010	1.02	.95	< .01
Log population 2010 → HDI 2010	− .26	− .02	.20
CO → HDI 2010	.62	.02	.18
NE → HDI 2010	1.04	.07	< .01
NM → HDI 2010	.07	.00	.90
OK → HDI 2010	− .45	− .01	.43
SD → HDI 2010	.85	.02	.25
TX → HDI 2010	− .08	− .01	.81
WY → HDI 2010	.88	.02	.19

$N = 234$

$\chi^2(36) = 89.51$, $p < .001$; CFI = .97; TLI = .94; RMSEA = .08; SRMR = .01

the other. Furthermore, we find that the association between contemporaneous measures of population and HDI scores becomes statistically insignificant in subsequent decades.

Using Kansas as a reference state, we find that there are statistically significant differences in HDI scores among states in the region. Given differences in economic realities and legal and regulatory structures, finding that HDI scores differ among counties in these states is not particularly surprising. Notably, in 1980, counties in Kansas had higher HDI scores than counties in all other states except Wyoming, where the difference is not statistically significant. Over time, however, there are fewer differences in HDI scores among states, and HDI scores in Kansas counties fall below HDI scores in Nebraska counties. By 2010, Nebraska counties have higher HDI scores on average than Kansas counties and this is the only significant difference among the states. This leads us to believe there has been some convergence, albeit at a lower level, in HDI among counties over time, except in Nebraska, where HDI scores tend to be higher than in Kansas. This might be due to increasing economic and regulatory convergence. It is also possible that the diminishing influence of the state variable is attributable to the increasing explanatory impact of the previous decades' HDI scores as additional decades are incorporated into the model.

5 Discussion

Our finding of a small, statistically nonsignificant relationship between human development and irrigated agriculture is consistent with earlier findings showing that irrigated agriculture is not associated with increases in aggregate incomes (Sanderson and Frey 2015), provides few long-term benefits to the non-farm economy (Hornbeck and Keskin 2012), and that the benefits of irrigated agriculture for the agricultural economy (Hornbeck and Keskin 2015; Parton et al. 2007) only weakly translate into measures of population-wide human development. This finding is also consistent with the hypothesis that groundwater drawdowns are not effectively translating into increases in local human and financial capitals.

The mechanisms for ineffective reinvestment of natural capital declines into local human and financial capitals are a promising avenue for future research. We can only speculate here, as these data do not allow more precise elaborations. We offer two such speculations. First, ineffective reinvestment could be a result of inefficient local reinvestment into farm equipment, irrigation systems, and other forms of built capital that do not materially enhance human development to the degree that human and financial capitals do. Research that further explores and perhaps even quantifies the relative benefits of various human capitals in groundwater-dependent agricultural regions would be very useful, as such research is very limited.

Second, we note that the community capitals framework and the treadmill of production theory have not been integrated before. One intriguing, but still unexplored, possibility is further synthesis of these two frameworks, which might help explain more precisely the lack of a stronger, more positive relationship between groundwater depletion and human development. Again, the community capitals framework views Ogallala groundwater as a stock of natural capital, and the HDI includes indicators of human capital (health and education) and financial capital (incomes). If the drawdown of the natural capital stock of groundwater is being effectively reinvested into local human and financial capitals, counties with a higher rate of drawdown should have larger HDI scores. If, however, an agricultural production treadmill dynamic is at work, it is reasonable to believe that higher rates of groundwater drawdown may actually limit human development gains.

There are two mechanisms motivating an agricultural production treadmill in this region: a technology-irrigation infrastructure mechanism and an income-subsidy mechanism (Sanderson and Hughes 2018). Either, or both in combination, might limit the extent to which capital can be effectively reinvested, or translated into, human development. As irrigation technology increases water use efficiency, farmers use these gains to spread the water over more acres, increasing irrigation infrastructures in a rebound effect. Simultaneously, groundwater pumping generates federal subsidies, which support farm incomes and exacerbate over-production and lower commodity prices. Either alone, or in combination, the existence of these dynamics could constrain the translation of natural capital drawdown (groundwater depletion) into human development. Underlying both of these dynamics is ecological unequal exchange stemming from the undervaluation of groundwater at the point of diversion (the well) and the "adding of value" during the agricultural production process, which ensures that most of the financial gains from groundwater depletion are not captured locally, but are instead displaced into large, transnational corporations at the center of global agro-food commodity chains (Sanderson and Frey 2015; Sanderson and Hughes 2018). Because groundwater is undervalued locally, and because transnational agro-food corporations can capture "added value" by transforming water into processed goods (beef, etc.), community natural capital is effectively being transferred out of the region, limiting local communities' abilities to reinvest in capitals that could enhance human development. Along these lines, further research attempting to integrate treadmill theory with the CCF could be especially illuminating.

Future research could also focus on overcoming three main limitations of this study. First, work to collect data with higher spatial resolution would enable modeling of additional explanatory variables and potentially meaningful within-county variation in HDI scores. Second, research into possible spillover benefits to HDI from higher irrigation to lower irrigation counties would reveal the possible existence and magnitude of any human and financial capital reinvestments that are extra-local regarding county boundaries but still local to the High Plains region. Third, we anticipate theoretical and policy benefits from future research that determines which combinations of extra-local investment, inefficient local investment, and local investment into cultural, social, or political capitals are responsible for our finding that groundwater extraction is not being invested into local human and financial capitals in the High Plains region.

Research to collect data with higher spatial resolution would overcome the biggest constraint facing this study: that comprehensive longitudinal data are not available at higher resolution than the county level. The Ogallala Aquifer is highly spatially heterogeneous (Smidt et al. 2016), and we would expect to see large variations in access to irrigation within as well as between counties. A further limitation of county-level data is the fact that we are limited to a sample size of 234 counties. This small sample size limits the number of explanatory variables that we are able to incorporate into our model. For example, we are unable to control for the percentage of population employed in agriculture when modeling changes in human development over time as a function of the prevalence of irrigated agriculture. This control would be theoretically meaningful given the differential impact of irrigation on the agricultural versus non-farm economies of the region (Hornbeck and Keskin 2012, 2015). We, therefore, encourage future research to gather data with higher spatial resolution in order to capture within-county variation and model how theoretically meaningful variables such as percentage of agricultural employment, population density (White 1994), racial composition (Solis 2003), and age structure of the population (Parton et al. 2007) interact with irrigated agriculture to explain variations in human development among counties in the High Plains region.

There is also a need for additional research into the possibility that counties with less irrigation may be acquiring spillover benefits to HDI from irrigation in nearby counties. In particular, the larger and younger populations associated with irrigated "Ogallala Oases" (Parton et al. 2007; White 1992, 1994) may support healthcare services, rural schools, workplaces, and cultural amenities that also serve people in nearby counties with less access to irrigation. Using subjective quality of life rather than HDI as a measure of well-being, Arbuckle and Kast (2012) provide evidence for an association between population, community amenities, and subjective quality of life in rural Iowa. Further research is needed to untangle the complex social and economic connections that seldom follow county lines (Opie et al. 2018).

Finally, we recommend additional inquiry into the precise reasons for the ineffective reinvestment of natural capital declines into local human and financial capitals. One promising avenue of future research may be a comparative-historical analysis of the governance differences between High Plains states in the context of the CCF.

6 Conclusion: implications for groundwater management

We find that the prevalence of irrigated agriculture on the High Plains as measured by the percentage of irrigated farmland and by groundwater withdrawals has an insignificant impact on county-level human development, as measured by the HDI. However, we caution against extending these findings to situations where insufficient groundwater remains to support residential and non-agricultural economic activities.

As a measure of human development, the HDI compliments economic indicators such as personal income and gross domestic product by considering health and education in addition to income. Our findings indicate that the impact of irrigated agriculture on this broader measure of human development is very small. This suggests that policymakers may experiment with a range of strategies for managing irrigation withdrawals from the Ogallala Aquifer without harming the well-being of area residents. We recommend that policymakers focus first on collective groundwater management strategies that will avoid the economic shock that an abrupt collapse of irrigated agriculture brought on by a fully depleted local aquifer.

We further recommend that policymakers take a positive deviance approach (Green 2016) to planning for an eventual future without widespread irrigation. By experimenting and learning from counties that currently have little irrigation but high scores on the HDI, policymakers can put the High Plains in the best position to harness the "next big thing" after irrigation. Our finding that human development on the High Plains is resilient across varying levels of prevalence of irrigated agriculture suggests that there is political space to take risks and dream big.

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