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Race to the Bottom (of the Well): Groundwater in an Agricultural Production Treadmill

Matthew R. Sanderson[1] and Vivian Hughes[2]

[1]Kansas State University, [2]Florida State University

ABSTRACT

Groundwater from the Ogallala-High Plains Aquifer supports one of the most productive agriculture regions in the world. Yet, despite nearly 40 years of policies designed to conserve and sustain this vital resource, the Aquifer continues to be depleted at an unsustainable rate. We integrate propositions from treadmill of production theory and ecological modernization theory to develop a structural model, focusing especially on the role of technological modernization as a key mechanism motivating depletion. A time-sequenced path analysis of all counties in the Ogallala Aquifer region reveals that groundwater depletion has a strong internal momentum characteristic of an agricultural production treadmill. Technological modernization promotes depletion through Jevon's Paradox. Increases in water efficiency—more crop per drop—are associated with less groundwater consumption, but more extensive deployments of irrigation infrastructures overwhelm the beneficial effects of increased water efficiency. An income-subsidy mechanism supports the treadmill dynamic. Agricultural production and increased water efficiency do not influence incomes. Instead, incomes are influenced mainly by expansions of irrigation technologies, which generates subsidies, and this dynamic puts further "spin" on the treadmill. The implications of the findings for theory and policy are discussed.

KEYWORDS: water; agriculture; treadmill; environment; modernization.

Underlying nearly 174,000 square miles across parts of eight states in the United States—South Dakota, Wyoming, Nebraska, Colorado, Kansas, Oklahoma, Texas, and New Mexico—the High Plains-Ogallala Aquifer is the second-largest freshwater aquifer in the world, trailing only Australia's Great Artesian Basin in size. Groundwater supplies 82 percent of the drinking water for people living in the region (Maupin et al. 2014) and the Aquifer supports a very significant proportion of global agricultural production (Gleeson et al. 2012). Irrigated agriculture accounts for approximately 90 percent of withdrawals from the Ogallala Aquifer (McGuire 2011), and the region produces one-quarter of total agricultural production in the United States (DHS 2015). The beef industry in the southern portion of the region alone, including Kansas, Oklahoma and Texas, generated nearly $30 billion in 2010 (Guerrero, Amosson, and McCollum 2013).

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Across most of the region, the Ogallala Aquifer is being depleted (McGuire 2014). The Aquifer's original source—winter runoff carried by streams from the Rocky Mountains—no longer replenishes it, making water from the Aquifer essentially a nonrenewable resource over a human time horizon (Opie 2000). The advent of deep-well pumps and center-pivot irrigation technologies in the post-World War II period allowed agriculture to exploit a once-inaccessible resource on an unprecedented scale (White and Kromm 1992). Since the 1950s, nearly 132 trillion gallons (500 km^3) of groundwater—an amount that would fill Lake Erie—have been pumped from the Ogallala Aquifer (Basso, Kendall, and Hyndman 2013). The Aquifer is near a tipping point. The U.S. Department of Homeland Security (2015) projects that 30 counties in Kansas have less than 100 years of groundwater remaining, and 18 face complete depletion in less than 25 years. Region wise, the most recent estimates indicate that the Aquifer will be 70 percent depleted by 2070 (Steward et al. 2013).

Depletion of the Ogallala Aquifer garnered significant national attention during a drought that began in 2010. Yet the problem of depletion is not a newly discovered problem, at least not for the inhabitants of the region. In Kansas, for example, where the Aquifer recharges at approximately one-half of one inch each year, but withdrawals can exceed one foot each year (Hecox et al. 2002), groundwater depletion has received attention from the highest levels of state government for nearly 40 years:

> . . . certain aspects of our water resource problems have a degree of predictability about them. Most notable is the rapid depletion of our valuable groundwater resource . . .
>
> Kansas Governor Robert Bennett, 1977

> Without enough water of adequate quality, we have no foundation on which to build and maintain our economic development efforts . . . We must take steps now to protect the environmental legacy we leave to our children and grandchildren.
>
> Kansas Governor Michael Hayden, 1989

> To achieve long-term viability of Kansas' communities, industries and agricultural producers, I support the recommendation made by my Task Force on Water: by 2020 we stop depletion of our state's precious aquifers.
>
> Kansas Governor William Graves, 2001

> A regret I have is that more has not been done to preserve the Ogallala Aquifer . . . We have no future without water.
>
> Kansas Governor Sam Brownback, 2012

> . . . we are expending the liquid capital of our state.
>
> Kansas Governor Sam Brownback, 2014

These statements, spanning nearly four decades, illustrate the urgent, but still unmet need to address the problem of depletion. State-level recognition of the problem in Kansas and elsewhere is informed by an array of state and federal programs, all of which explicitly target depletion as a problem in need of a solution. Along with these programs, there have been substantial public and private investments in irrigation technologies, weather modification programs, along with a range of economic incentives and political institutions to manage groundwater more effectively (Opie 2000). However, depletion persists despite such prominent attention and considerable investment of resources.

The goal of this article is to empirically identify the drivers of groundwater depletion in the Ogallala Aquifer region. Unsustainable consumption of such a crucial natural resource over such a long period of time, despite widespread recognition of the problem and considerable investments to address it, raises important questions about the mechanisms motivating groundwater depletion. We draw upon treadmill of production theory (Gould, Pellow, and Schnaiberg 2004; Schnaiberg 1980) to generate propositions about these mechanisms. Treadmill theory is commonly counterposed against ecological modernization theory (Mol and Sonnenfeld 2000; Mol and Spaargaren 2000; Spaargaren and Mol 1992), which is used to generate alternative hypotheses. Ecological modernization theory has several "core themes," (Mol and Spaargaren 2000:5), but technological innovation has been the focus of much of this research because it is the "lynchpin of the argument" (Fisher and Freudenberg 2001:702): environmental problems can be solved through technological advances that dematerialize economic production. Empirical treatments then demonstrate the veracity of the theoretical frameworks by assessing the relative explanatory power of variables drawn from each framework (cf. York, Rosa, and Dietz 2003).

Although it has been useful in other contexts, the strategy of comparing the relative explanatory power of variables drawn from each framework is not as appropriate for explaining groundwater depletion in the Ogallala Aquifer region. Groundwater depletion in this region persists *in the presence of* long-term technological modernization. One would be hard-pressed to find another agricultural region where modernization is broader or deeper. Agriculture in this region is at the vanguard in adoption rates of the most advanced, efficient production technologies (Colaizzi et al. 2009; Wagner 2012). Thus, selecting between propositions derived from treadmill theory and ecological modernization theory to explain groundwater depletion in this region risks a false dilemma. The question is not whether ecological modernization is associated with depletion—both have co-existed in the region for over 40 years—it is *how* ecological modernization is associated with depletion. Indeed, this question is the crux of a contradiction experienced by individual producers, as they continually adopt more efficient technologies while seeing groundwater levels decline:

> In Grant County, Kansas, Clay Scott parked his Dodge pickup on a county road and reached for his iPad. A few hundred feet away, a solar panel planted in a field of wheat powered a probe that measures soil moisture at different depths. The probe told Scott's iPad that he could hold off watering the field . . . In addition to the soil moisture probes linked to his iPad, Scott consults satellites and radar data to track every shift in the weather and drop of rain that falls in his fields so he can minimize irrigation. He uses low-till techniques to preserve the soil and experiments with genetically engineered drought-resistant corn. He installed more efficient nozzles on his center pivot sprinklers. And he's trying out a new device called a "dragon line" that drags perforated hoses behind a center pivot to deposit water directly on the ground, reducing pooling and evaporation. Scott's version of high-tech farming would be unrecognizable to his great-grandfather, who homesteaded in nearby Stanton County around the turn of the century.
> Still, despite all his efforts, Scott knows there will come a day—sooner rather than later if nothing is done—when irrigation is no longer viable in this part of Kansas. The effects of the depleted aquifer already can be felt on Scott's farm, where he has had to reduce irrigation by 25 percent. Some of his two dozen wells are pumping just 150 gallons per minute now, down from thousands of gallons per minute when they were first drilled . . . "People think that we waste our water out here," Scott said, "and we just kind of grin because we work so hard to use that water" (*Kansas City Star* 2015).

Answering the question of *how* ecological modernization is associated with depletion requires *integrating* technological modernization into a treadmill of production framework. Rather than juxtaposing variables from treadmill of production and ecological modernization theories in a model, we use treadmill variables to explain technological modernization, and then we assess how technological modernization influences groundwater consumption. We begin by describing technological modernization, focusing especially on the role of the state in technological modernization, and using Kansas as an exemplar for broader trends in the region.

ECOLOGICAL MODERNIZATION: IRRIGATION TECHNOLOGY AND THE STATE IN THE OGALLALA REGION

Although it has been adapted and refined since it was first introduced in the 1980s, the basic tenet of ecological modernization theory remains: "the only way *out* of the ecological crisis is by going further *into* the process of modernization" (Mol 1995:42; emphasis in original). Ecological modernization entails a series of "social and institutional transformations," (Mol and Sonnenfeld 2000:6), but technological innovation is the center of the theory. Advances in technology should enhance the efficiency of economic production, allowing increased production and reduced environmental withdrawals: "Science and technology not only are judged for their role in the emergence of environmental problems, but also valued for their actual and potential role in curing and preventing them" (Mol and Sonnenfeld 2000:6). Technological modernization is not new in the Ogallala Aquifer region. Rapid and widespread adoption of irrigation technologies have become routine in this region over the past 40 years.

The state—from the federal to state and local levels—has played a key role in diffusing irrigation technologies. In practice, technological modernization is closely associated with state efforts to decentralize control over groundwater, which is viewed as "political modernization" in ecological modernization theory: "More decentralized, flexible, and consensual styles of governance emerge, with less top-down, national command-and-control environmental regulation—often referred to as political modernization (Mol and Sonnenfeld 2000:6). Technological and political modernization are thus closely related in the Ogallala region, making it difficult to disentangle technological and political modernization as distinct trends. Across the region, myriad policies have been developed to slow the decline of the Ogallala Aquifer. For much of the past 40 years, these policies have been oriented toward the individual agricultural producer. State-level government still plays a key role in water governance, but there has been gradual devolution of control from the state level to the individual producer, and with it, a shift in policy emphasis from regulation of groundwater use to incentivizing voluntary conservation.

In Kansas, political modernization is perhaps close to an apex if devolution is an indicator. Groundwater policies must comply with law, and Kansas water law protects individual property rights (Sophocleous 2012). In Kansas, and throughout much of the western United States more generally, water law follows the doctrine of prior appropriation, otherwise known as "first in time, first in right," stipulated in the Kansas Water Appropriation Act of 1945 (the Act) (Peck 2003). The Act gave the Chief Engineer of the Kansas Division of Water Resources- Department of Agriculture the authority to administer a system of water rights. Anyone seeking the right to appropriate water for non-domestic use must obtain a permit. Following prior appropriation, more senior water rights holders are given priority over junior water rights holders in any conflicts or impairments resulting from use. Individual water rights are real property rights under Kansas law: "Water right . . . is a real property right appurtenant to and severable from the land on or in connection with which the water is used and such water right passes as an appurtenance with a conveyance of the land by deed, lease, mortgage, will, or other disposal, or by inheritance" (K.S.A. 82a-701(g)).

Within the context of individual property rights, key aspects of groundwater management in Kansas have been devolved from the state to groundwater management districts (GMDs), quasi-governmental units. Although GMDs are *de jure* collective organizations that implicitly recognize the inability of individual-level policies to stem depletion of a common pool resource, they have had a *de facto* individual orientation. The individual orientation of these collective management organizations is in fact codified in the Groundwater Management District Act of 1972, which created the GMDs:

> It is the policy of this act to preserve basic water use doctrine *and to establish the right of local water users to determine their destiny with respect to the use of the groundwater* insofar as it does not conflict with the basic laws and policies of the state of Kansas (K.S.A. 82a-1010; emphasis added).

State efforts to address groundwater depletion in Kansas focus mainly on voluntary, incentive-based policies. Over the past five years, Kansas Governor Sam Brownback spearheaded a long-term plan to address water problems in the state. The individual-level focus is clearly identified in "guiding principles" of the plan: "Voluntary, incentive, and market-based water conservation and land management activities are the preferred tools for ensuring a reliable statewide water supply" (Kansas Water Office 2015:10).

The plan is consistent with most policy efforts to date, which incentivize producers to transition land out of irrigation or encourage technological modernization by incentivizing producers to adopt water-conserving irrigation technologies through cost-sharing arrangements. Examples of the former include the Water Right Transition Assistance Program (WTAP), through which the state pays producers to permanently retire irrigation water rights, and the Conservation Reserve Enhancement Program (CREP), a federal-state partnership that pays irrigators to shift irrigated land into grassland. Perhaps more importantly, government at both the state and federal levels plays an active role in the adoption of irrigation technologies, demonstrating the close connections between political and technological modernization. Indeed, subsidies for irrigation technologies are the most common policy to reduce groundwater depletion (Johnson, Revenga, and Echeverria 2001). The state of Kansas, for example, subsidizes the costs of converting from flood irrigation to center pivot sprinkler systems and irrigation water management technologies through the Water Resources Cost-Share Program (K.A.R. 11-1-6). This program is complemented by the federal Environmental Quality Incentives Program (EQIP), administered by USDA-NRCS, which provides subsidies for implementing water conservation practices.

Irrigation technologies in Kansas have become much more efficient at delivering water and minimizing water loss to evaporation. The most significant technological modernization occurred with the diffusion of center pivot sprinkler systems in the 1970s (Opie 2000). Prior to center pivot systems, most irrigators used flood systems in which water was released from a pipe through a gate and allowed to flow on the soil surface down furrows where it would seep into the soil root zone (Rogers and Aguilar 2012). Flood systems in Kansas were usually about 65 percent efficient: 35 percent of water diverted to the field was lost, or otherwise unusable by the plant (Rogers and Aguilar 2012). Center pivot sprinklers achieve at least 85 percent efficiency rates. Center pivot irrigation systems are now widely adopted throughout the Ogallala Aquifer region. In Kansas, only 18 percent of all irrigated acres were center pivot sprinklers in 1970; today, over 90 percent of all irrigated land in Kansas is under center pivot irrigation systems (Rogers and Aguilar 2012).

If stable, non-declining, groundwater supplies are a marker of success, modernization has not been successful. Groundwater levels continue to decline in Kansas and throughout much of the region. Groundwater management institutions have long been recognized as inadequate (U.S. NRC 2001, 2004). The more fundamental question is *why* modernization has been so ineffective.

That groundwater depletion persists for so long despite many attempts to stem it suggests the existence of a production treadmill dynamic in which technological modernization may actually promote groundwater depletion through a self-reinforcing feedback loop. To investigate this possibility, we integrate technological modernization into a production treadmill framework.

THE TREADMILL OF PRODUCTION

The treadmill of production theory links ecological consumption ultimately to competition for profits among capital owners (Schnaiberg 1980:230). Competition motivates capital owners to increase demand for natural resources mainly through the application of capital-intensive technologies to the production process (Gould et al. 2004). Capital owners are strongly incentivized to adopt more capital-intensive, labor saving technologies because they expand production and lower costs of production per unit (economies of scale), both of which raise gross profits and net incomes (Cochrane 2003). Expanded production requires increased withdrawals from the ecosystem (depletion) and increased additions to the environment (pollution). Higher levels of production, at lower per-unit costs, gives these organizations a distinct competitive advantage in the market, allowing them to lower prices for their products and drive out competitors from the market (Gould et al. 2004). The next round of production therefore includes fewer, but larger capital owners, who apply even more capital-intensive technologies to production because they can reinvest some portion of their accumulated capital into these production technologies. This subsequent round is merely the next round on a treadmill: more capital intensification, more production, and more ecosystem depletion and pollution.

Agriculture in the Treadmill of Production

The historical point of departure for treadmill of production theory is the immediate post-World War II period during which there was a massive expansion in production that motivated subsequent rounds on the treadmill. Perhaps because it uses the post-World War II manufacturing expansion as an historical starting point, much research employing treadmill of production theory focuses on the nonfarm sectors of the economy (Buttel 2004; Givens and Jorgenson 2011; Hooks 2005; Jorgenson and Clark 2011, 2012; Jorgenson et al. 2012; McKinney et al. 2010; Shandra, Esparza, and London 2012; Shandra et al. 2010). Agriculture, however, like other extractive activities (cf. Bunker and Ciccantell 2005) allows an even clearer understanding, in one conceptual model, of the key mechanisms driving the treadmill of production. First, because agriculture directly extracts natural resources, it is closer to the ecosystem in the production process. The original elaboration of the theory gives agriculture prominent attention. For example, agriculture is used to illustrate the first discussion of ecosystem withdrawals and additions—the two "environmental problems" of the treadmill:

> Societal production entails environmental additions and withdrawals, which in turn may disorganize biospheric systems . . . Modern agriculture, for example: 1. Adds pesticides, herbicides, and fertilizer to land and water; 2. Adds new animal species and new plant species; 3. Adds animal wastes to land and water (through run-off); 4. Withdraws existing flora (trees, weeds); 5. Withdraws existing predators and rodents (hunting, trapping); 6. Withdraws water (by intensive irrigation) . . . We could readily classify the six environmental impacts of agriculture into *pollution* (1-3) and *depletion* (4-6) effects" (Schnaiberg 1980:24; emphasis in original).

Second, not only is agriculture closer to the ecosystem than nonfarm sectors, agriculture illustrates more clearly how capital motivates the self-exploitation of labor, making labor ever-more dependent on production and accumulation as the treadmill spins.

Treadmill of production theory makes analytical distinctions among three key constituencies: capital, labor, and the state. The distinction between (wage) labor and capital is not as clear in the agricultural sector (Lobao 1990). Many farmers are both capital owners and laborers. As laborers, their incomes and (self-)employment depend on the continual expansion of farm production, just as wage laborers in manufacturing firms are dependent on the expansion of production. As capital owners, however, farmers are responsible for the very decisions about the allocation of capital (and labor) to production technologies—decisions that will tend to decrease labor inputs, raise capital intensity, lower per-unit costs, expand production, and generate profits and income, while increasing ecosystem withdrawals and additions. In the nonfarm sectors, labor does not play such a direct role in environmental depletion and pollution. Thus, applying the theory to agriculture allows a more undiluted view of the key mechanisms driving the treadmill because agriculture is situated at the original point of production—the extraction of ecosystem resources—and merges the roles of capital and labor in the same, decision-making unit of analysis—the farm.

There is a growing body of research employing treadmill of production, and close variants of the theory, to understand agriculture, and raw material extraction more generally (Arbuckle and Kast 2012; Bunker 2005; Clark, Jorgenson, and Auerbach 2012; Clark and Jorgenson 2012; Clausen, Clark, and Longo 2015; Diamond 2013; Driscoll and Edwards 2015; Gasteyer and Carrera 2013; Gunderson 2011; Horlings and Marsden 2011; Jorgenson and Kuykendall 2009; Konefal and Mascarenhas 2005; Leguizamon 2014; Novek 2003; Obach 2007; Shriver, Adams, and Longo 2015; Ward 1993). However, the mechanisms linking agricultural production and water consumption in the treadmill of production theory remain underdeveloped. We draw on treadmill theory to develop a series of propositions linking groundwater consumption to treadmill dynamics, focusing specifically on the role of irrigation technologies.

GROUNDWATER IN AN AGRICULTURAL PRODUCTION TREADMILL

Conceptually, the treadmill of production theory begins with the ecosystem as the source of withdrawals that feed production (Schnaiberg 1980). A conceptual model of an agricultural treadmill should therefore begin with the most important natural resource for agriculture: water. Water is the basis of agricultural production everywhere, but it is especially important in the semiarid High Plains region, where groundwater is used to produce products with higher market values such as corn and cattle.

Before it is transformed into agricultural commodities, groundwater is administered to field crops through capital-intensive forms of irrigation technologies, including deep well pumps and center pivot irrigation systems. As farmers extend irrigation infrastructures across more land, production can be expanded, potentially raising income. The more extensive use of capital-intensive irrigation also allows water to be used more productively, or efficiently, in market terms. That is, irrigation technology allows farmers to expand the market value of production by increasing the total production and by producing commodities with higher market values (i.e., irrigated corn versus dryland wheat). Higher levels of market value production raise the productivity of water for every given level of water used as an input into the production, raising the productivity, or efficiency, of water use. Farmers that use water more productively should generate higher incomes because they are producing more "crop per drop" (FAO 2003).

These investments in irrigation technology are an important part of the agricultural treadmill. Irrigation infrastructures are capital-intensive technologies, requiring significant investments between $500 and $1,000 per acre in installation costs alone. Once these systems are in the field, they are sunk costs that must be paid for by further expanding production, increasing the productivity of water, or both. The more extensive application of irrigation technology thus places farmers on a production treadmill that requires higher levels of water withdrawals to generate a given level of income.

The treadmill is exacerbated by overproduction (Schnaiberg 1980). As competitors adopt irrigation systems, production levels increase, supply can exceed demand, and prices decline in a phenomenon labeled the "product-price" treadmill (Cochrane 2003:chapter 2). Because of this dynamic, neither expansions in production nor more productive use of water may provide incomes for farmers that are sufficient to cover the full costs of production. As a result, farmers are strongly incentivized to deplete groundwater supplies to maintain incomes.

The state plays a key role in the treadmill of production, especially in agriculture. Across all sectors, the state has an active interest in promoting production expansion and private capital accumulation because these provide the revenues, through taxation, that support the state (Schnaiberg 1980:242). In the agricultural sector, the connection between the state and the treadmill of production is not implicit: the state—at both the federal and state levels—explicitly fosters the agricultural

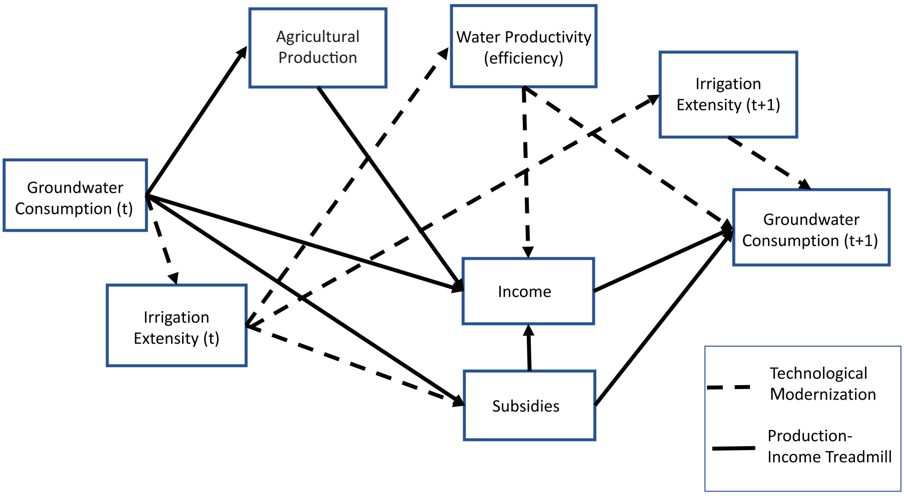

Figure 1. Conceptual Model of the Agricultural Production Treadmill

production treadmill by providing subsidies directly to farms in the form of income supports and support for irrigation technology. We described state-level support for irrigation technology adoption above. The state also supports the treadmill of production at the federal level. For example, under Title 1 of the 2002 Farm Bill (in effect until 2007 and formally titled the Farm Security and Rural Investment Act [PL 107-171]), the U.S. federal government made payments directly to farmers to support production of the main agricultural commodities: wheat, corn, barley, grain sorghum, oats, cotton, rice, oilseeds, peanuts, sugar, and dairy products. Subsidies under this program effectively guaranteed a minimum level of income for farms by setting a price floor (Bruckner 2016).

The state's role is crucial for understanding the agricultural production treadmill. By supporting farm incomes, subsidies promote groundwater depletion by encouraging more extensive irrigation systems and the expansion of production, and decreasing the sensitivity of farmers' decisions to groundwater depletion (Lee and Lacewell 1990). That is, in the absence of subsidies, groundwater depletion would be more likely to encourage farmers to conserve water, by allocating capital towards crops that require less water, for example, or by reducing the expansion of irrigation infrastructures. Subsidies, in this sense, distort the information farmers receive from the ecosystem while promoting capital-intensive expansions in production, putting further "spin" on the treadmill.

Together, the relations between capital-intensive irrigation technology, farm income, and state subsidies motivate an agricultural production treadmill that depletes groundwater in the Ogallala Aquifer. Figure 1 is a simplified illustration that indicates the key mechanisms in an agricultural production treadmill. This conceptual framework captures a dynamic familiar to many famers—one of appearing to "get ahead" one year while actually remaining in the same position the next year, with stagnant or even declining living standards drawn from exhausting a nonrenewable resource. To date, however, the agricultural production treadmill remains more of a heuristic tool (Levins and Cochrane 1996).

The model depicted in Figure 1 integrates technological modernization into a treadmill of production framework, allowing us to assess *how* modernization is associated with groundwater depletion. Instead of testing the explanatory power of modernization and treadmill variables against one another, this approach allows us to examine their respective roles *together* in a system of socio-ecological relations. As specified by treadmill of production theory, the model begins and ends with ecosystem (groundwater) withdrawals, with technological modernization and treadmill of production dynamics as mediating factors in a socio-ecological system. Groundwater consumption sets in motion technological modernization and treadmill of production dynamics, indicated in the figure by dashed

Table 1. Variables and Measurements

Variable	*Description*	*Source*
Groundwater consumption, 2005, 2010	Gallons of groundwater used for agriculture	U.S. Geological Survey & USDA Census of Agriculture
Net income per farm, 2007	Total net farm income/total number of farms	USDA Census of Agriculture
Direct payments per farm, 2007	Total direct payment subsidies/total number of farms	USDA Census of Agriculture
Market value of production per farm, 2007	Total market value of commodities/total number of farms	USDA Census of Agriculture
Water productivity (efficiency) per farm, 2007	Total market value of production per farm/total gallons of groundwater used for agriculture per farm	U.S. Geological Survey & USDA Census of Agriculture
Irrigated acres per farm, 2005, 2010	Total acres irrigated/total number of farms	U.S. Geological Survey
Annual precipitation, 2010	Total annual precipitation for the county	PRISM Climate Group

line pathways and solid line pathways, respectively. Drawing on ecological modernization theory, we assess the role of two key aspects of technological modernization (indicated by dashed lines): the diffusion, or extensity, of capital-intensive irrigation technologies across acreages, and the efficiency of irrigation technologies in terms of water efficiency, or productivity—the ratio of market value of production to the amount of groundwater consumed. Drawing on treadmill of production theory, we include a production-income-subsidy mechanism (indicated by solid lines) through which agricultural production and subsidies support incomes that allow more groundwater consumption. We empirically test these pathways, and their relations, in the Ogallala Aquifer region.

DATA AND METHODS

We employ path analysis to test the model. Path analysis is an extension of multivariate regression that allows analysis of multiple endogenous (dependent) variables through simultaneous equations. Path analysis is a special case of structural equation modeling that only includes observed variables, each of which has one indicator. An important advantage of path analysis is the ability to assess direct and indirect, or mediating, effects among variables in the same model, allowing a closer, more rigorous, test of the specified relations in the conceptual framework. The path analysis tests the general hypothesis that the covariance matrix of the variables in the model is a function of the set of parameters in the model (Bollen 1989). The model specifies a series of causal relations linking the variables. Path analysis, like all other empirical analyses, cannot prove causality, but it can provide more robust evidence of the tenability of these relationships (Bollen 1989).

Table 1 describes the variables used in the model. The county is the unit of analysis. Complete data on the variables included in the model are available for 177 of the 181 counties identified by the U.S. Geological Survey as comprising the Ogallala Aquifer Region (White 1994). All of the variables are standardized on the number of farms in each county in order to compare effects across the variables in the model. All of the variables are log-transformed (ln) in order to assess the relationships in terms of percentage change regardless of the units measured (i.e., gallons, dollars, etc.).

We specify a time-sequenced path analysis linking variables measured at three time points: 2005, 2007, and 2010. Data on agricultural water use are from the U.S. Geological Survey, which provides information on water use at the county level in five-year intervals (i.e., 2005, 2010, etc.). Data on the

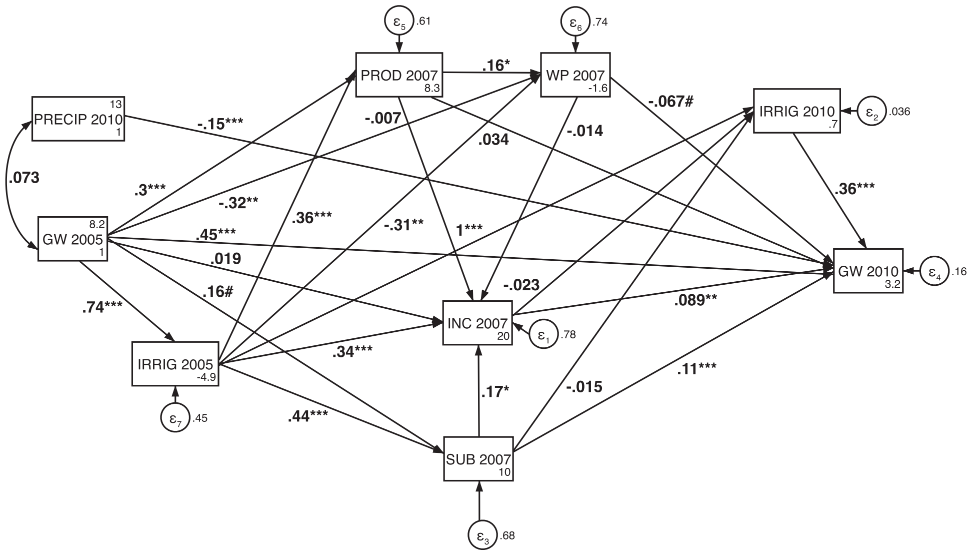

Figure 2. Empirical Model of the Agricultural Production Treadmill

number of farms is gathered by the U.S. Department of Agriculture in five-year intervals that do not coincide with the U.S. Geological Survey's data collection on water (i.e., 2002, 2007, 2012, etc.). Thus, to standardize water withdrawals on the number of farms in 2005 and 2010, we applied linear interpolation to identify values for the number of farms in 2005 and 2010, using 2002 and 2007 as the beginning and end values, respectively for the 2005 measure and using 2007 and 2012 as the beginning and end values, respectively for the 2010 measure. The same procedure was applied to measure irrigated acres per farm in 2005 and 2010, as the U.S. Geological Survey also measures these data in 2005 and 2010.

The model fits the data very well according to the standard tests of model fit (Kline 1998). The model explains 84 percent of the variance in agricultural groundwater consumption per farm in 2010 and 76 percent of variation in all the endogenous variables in the model. The likelihood ratio test for the Pearson's chi-square statistic is statistically significant (x^2 [12] $= 21.9$, $p = .04$), indicating a weaker model fit. Removing just one nonsignificiant path results in a nonsignificiant chi-square value, indicating a better fit, but we retain these paths because they are important conceptually. All the other tests indicate the model fits the data very well. The standardized root mean square residual (SRMR) is .03, the root mean square error of approximation (RMSEA) is .06, the comparative fit index (CFI) is .99, and the Tucker-Lewis Index (TLI) is .98 (cf. Hu and Bentler 1999). We use the SEM routine in Stata, version 14 to estimate the model.

RESULTS

Figure 2 displays the path model with standardized coefficients for each of the paths. Direct effects (unstandardized and standardized) are reported in Table 2 and total effects (standardized) are reported in Table 3. Again, the path coefficients are interpreted as percent changes, or elasticities, because the variables are log-transformed (ln).

As expected, groundwater consumption demonstrates a strong internal momentum characteristic of a production treadmill, as groundwater consumption in 2005 (*B*, standardized total effect = .85) is the strongest predictor of groundwater consumption in 2010. The unstandardized path coefficient, however, is less than 1.0 ($b = .39$), indicating that higher levels of consumption in 2005 are not associated with proportional increases in consumption in 2010. Instead, for example, farms that consumed 10 percent more groundwater in 2005 consumed only about 4 percent more water in 2010.

Table 2. Maximum Likelihood Estimates of Direct Effects

Endogenous		*Exogenous*	*Estimate*	*Critical Ratio*	*Std. Coefficient*	R^2
Irrigated acres 2005	←	Groundwater consumption 2005	.071***	14.75	.74	.55
Market value of production 2007	←	Groundwater consumption 2005	.247***	3.48	.31	
Market value of production 2007	←	Irrigated acres 2005	3.058***	4.14	.36	.39
Water productivity 2007	←	Market value of production 2007	.256*	1.96	.16	
Water productivity 2007	←	Groundwater consumption 2005	−.410***	−3.21	−.32	
Water productivity 2007	←	Irrigated acres 2005	−4.160***	−3.09	−.31	.26
Farm income 2007	←	Market value of production 2007	−.002	−.08	−.01	
Farm income 2007	←	Water productivity 2007	−.003	−.18	−.01	
Farm income 2007	←	Subsidies 2007	.104*	2.14	.17	
Farm income 2007	←	Irrigated acres 2005	1.104***	3.00	.34	
Farm income 2007	←	Groundwater consumption 2005	.006	.17	.02	.22
Subsidies 2007	←	Irrigated acres 2005	2.387***	4.72	.44	
Subsidies 2007	←	Groundwater consumption 2005	.082	1.70	.16	.32
Irrigated acres 2010	←	Farm income 2007	−.007	−1.42	−.02	
Irrigated acres 2010	←	Subsidies 2007	−.003	−.89	−.02	
Irrigated acres 2010	←	Irrigated acres 2005	1.004***	55.77	1.00	.96
Groundwater consumption 2010	←	Irrigated acres 2010	3.221***	7.12	.36	
Groundwater consumption 2010	←	Precipitation 2010	−.736***	−4.79	−.15	
Groundwater consumption 2010	←	Market value of production 2007	.037	.88	.03	
Groundwater consumption 2010	←	Water productivity 2007	−.045†	−1.94	−.07	
Groundwater consumption 2010	←	Farm income 2007	.245**	2.58	.09	
Groundwater consumption 2010	←	Subsidies 2007	.177***	2.94	.11	
Groundwater consumption 2010	←	Groundwater consumption 2005	.393***	9.45	.45	.84
					Overall R^2	.76

Fit Statistics	
Chi-square (12)	21.90, $p = .04$
SRMR	.03
RMSEA	.06
CFI	.99
TLI	.98
$N = 177$	

†p <.10 *p <.05 **p <.01 ***p <.001 (two-tailed tests)

By itself, this coefficient could be interpreted as evidence that technological modernization reduces water consumption; that is, water-conserving irrigation technologies could have become more widespread and/or more efficient in terms of water productivity, resulting in declines in groundwater consumption. However, we test these propositions explicitly (see below), and the evidence does not support this interpretation. Rather than demonstrating water-conserving effects from technological modernization, this coefficient likely reflects declining well yields in the region. Groundwater consumption lowers the saturated thickness of the aquifer, which reduces well yield: the maximum pumping rate (usually measured in gallons per minute) supported by the saturated thickness of the aquifer below the well (Driscoll 1986). Past groundwater consumption constrains future withdrawals because declining groundwater levels cannot support continued, proportional increases in consumption. Well yield data are not collected systematically, but this result is

Table 3. Standardized Total Effects

	Groundwater Consumption 2005	*Irrigated Acres 2005*	*Market Production 2007*	*Water Productivity 2007*	*Subsidies 2007*	*Farm Income 2007*	*Irrigated Acres 2010*	*Precipitation 2010*
Irrigated acres 2005	.74							
Market value of production 2007	.58	.36						
Subsidies 2007	.48	.44						
Water productivity 2007	−.46	−.25	.16					
Farm income 2007	.35	.41	−.01	−.01	.17			
Irrigated acres 2010	.73	.98	.00	.00	−.02	−.02		
Groundwater consumption 2010	.85	.47	.02	−.07	.12	.08	.36	−.15

consistent with hydrological evidence of sustained declines in saturated thickness throughout the region (USGS 2012).

Three key mechanisms motivate groundwater consumption, and technological modernization plays a role in each of these dynamics. Contrary to ecological modernization theory, more extensive deployments of irrigation infrastructures increase groundwater consumption. To start, higher levels of groundwater consumption [GW 2005] allow more extensive deployments of irrigation technologies [IRRIG 2005] ($b = .07$). Once deployed, farms must pump groundwater for agricultural production to recover the costs of these fixed investments and generate profit. Irrigated acreage in 2005 explains nearly 96 percent of the variation in irrigated acreage five years later in 2010 [IRRIG 2010]. Moreover, this relationship is unit elastic ($b = 1.0$), meaning that a change in irrigation acreage in 2005 is associated with a proportionate increase in irrigation acreage in 2010. In turn, the extensiveness of irrigated acreage in 2010 [IRRIG 2010] is a very strong explanation of agricultural groundwater consumption in 2010 [GW 2010] ($b = 3.2$). The relationship between irrigation acreage and groundwater consumption is highly elastic: a 1-percent increase in acres under irrigation is associated with a disproportionate (3.2 percent) increase in groundwater consumption. In unit terms, if the average farm consumed 10,000,000 gallons of groundwater on 1,000 irrigated acres, an increase of only 10 irrigated acres (1-percent increase) raises groundwater consumption by 320,000 gallons (3.2 percent). The dynamic of this treadmill can be illustrated by tracing the model forward (or back in time): an additional 320,000 gallons consumed (10,320,000 total gallons now) is associated with a further, but smaller, expansion in irrigated acreage of .07 percent, which generates a subsequent round of water withdrawals.

A second treadmill dynamic occurs as an interaction of technological modernization and treadmill of production mechanisms. Consistent with ecological modernization theory, increases in water productivity [WP 2007]—efficiency—are associated with decreases in groundwater consumption [GW 2010] ($b = -.05$, $p < .10$). However, integrating technological modernization into a treadmill framework reveals a more complicated story about the role of technological modernization. The two forms of technological modernization—extensity of irrigation infrastructures and water efficiency—are related, and they have opposite effects of different magnitudes on groundwater consumption. Expansions in irrigation technology [IRRIG 2005] are associated with lower water efficiency [WP 2007] ($b = 4.16$) to the extent that a mere 1-percent increase in irrigated acreages is associated with 4 percent lower water efficiency. Lower water efficiency, in turn, increases groundwater consumption, as indicated by the negative path coefficient linking water productivity [WP 2007] to groundwater consumption [GW 2010] ($b = -.05$). Thus, although water efficiency is associated with lower groundwater consumption, the magnitude of the effect of irrigation extensity overwhelms the conserving effect of water efficiency. The overall effect of technological modernization on groundwater consumption exhibits Jevon's Paradox (Clark and Foster 2001; York 2006). Technological advances in irrigation increase production efficiency—more crop per drop—but groundwater consumption still increases because of a more extensive deployment of irrigation technologies across the landscape. These results are consistent with prior research showing irrigation technologies exacerbate groundwater depletion in the Ogallala Aquifer region (Pfeiffer and Lin 2014), and that water savings from efficiencies seem to be used to expand irrigated acreages (Golden and Peterson 2006).

A third mechanism appears as an income-subsidy dynamic, which puts more "spin" on the treadmill. Farm income [INC 2007] is positively associated with groundwater consumption [GW 2010] ($b = .25$) such that a 1-percent increase in the average farm income raises groundwater consumption by .25 percent. As expected in a "product-price" treadmill (Cochrane 2003), the level of agricultural production does not significantly drive groundwater consumption, net of the effects of irrigation technology, farm incomes, and subsidies. Consuming more groundwater [GW 2005] ($b = .25$) and expanding irrigated acreage [IRRIG 2005] ($b = 3.1$) both increase production [PROD 2007] in terms of the total market value of commodities farms can generate. Yet, as expected, higher production levels are not associated with farm incomes [INC 2007], as indicated by the nonsignificiant path coefficient. Moreover, water productivity [WP 2007] also has no effect on farm incomes, suggesting that farmers have very little incentive to use water more productively because doing does not influence incomes.

Farm incomes are affected not by increased production or using water more productively, but mainly by expansions of irrigation technologies, which supports incomes by generating subsidies. Increasing irrigation acreage [IRRIG 2005] by 1-percent raises farm incomes by 1.1 percent [INC 2007] ($b = 1.1$), and higher farm incomes are associated with increases in groundwater consumption [GW 2010] ($b = .25$). Subsidies support this irrigation-income dynamic. Subsidies are very responsive to irrigated acres ($b = 2.4$) such that expanding irrigation acreage by 1 percent [IRRIG 2005] results in 2.4 percent larger subsidy payments [SUB 2007], and larger subsidies are associated with higher farm incomes [INC 2007] ($b = .10$) and with groundwater consumption [GW 2010] ($b = .18$). Overall, the total effect (unstandardized) of irrigation extensities on farm incomes is highly elastic: expanding irrigated acres by 1 percent raises incomes by 3.6 percent ($b = 2.4 + b = .1 + b = 1.1$). Thus, consistent with treadmill of production theory, farms have a very strong economic incentive to consume groundwater by expanding irrigation acreage, and subsidies play a key role in this dynamic, augmenting the treadmill.

CONCLUSION

The Ogallala Aquifer supports one of the most productive agricultural regions in the world, but unsustainable groundwater consumption threatens the future of this region. Residents throughout the region, and policymakers at all levels—local to federal—have acknowledged the problem of depletion for nearly 40 years. However, widespread recognition and myriad resources, programs, and policies have failed to stem depletion. Why has it proven so difficult to cease unsustainable groundwater consumption, given such extensive support for water conservation?

Failure to conserve the resource despite manifest intentions suggests that the problem is structural; that is, the problem is "built-in" to everyday interactions between farmers and the ecosystem. Drawing on treadmill of production theory and ecological modernization theory, we constructed and tested a structural model of groundwater depletion in the Ogallala Aquifer region. The results reveal that groundwater consumption has a strong internal momentum driven by technological modernization and agricultural production treadmill dynamics. The findings have theoretical and policy implications.

Our results suggest that the treadmill of production theory remains quite salient for understanding socio-ecological change, nearly 40 years after it was first developed. Agriculture was central to the initial formulation of the treadmill of production theory (cf. Schnaiberg 1980) and the theory continues to inform studies of agricultural change.

Our model refines and extends treadmill theory. We elaborate key mechanisms—income, subsidies, and technological modernization—that link social structures to ecosystem withdrawals, the main goal of the theory. Further, our model extends the framework by integrating water into the agricultural production treadmill. In doing so, we demonstrate the conceptual utility of the theory for understanding water consumption. Because water is the material basis of agriculture, and indeed the basis of all life-supporting systems, our model lays groundwork for future research on water use in a variety of contexts, and especially in agricultural contexts. Certainly, agriculture connects humans to the ecosystem differently across space, in different socio-ecological systems, and over time, but our model provides a general framework that can be further tested, and elaborated, through future research in other socio-ecological contexts.

Ecological modernization theory has become a prominent theory of the human-environment nexus. Our approach to ecological modernization theory is motivated by Richard York and Eugene Rosa (2003), who argue that "The central issue is whether EMT's claims are theoretically coherent and empirically valid" (p. 274), and Dana Fisher and William Freudenberg (2001) who contend that "The task that now faces the scientific community is thus to work toward greater rigor in identifying conditions under which 'ecological modernization' outcomes are more or less likely" (p. 704). By embedding a key facet of modernization—technological modernization—into a production treadmill framework, we found that technological modernization makes groundwater conservation (an ecological modernization outcome) *less likely* in the Ogallala Aquifer region. Our model advances understanding of both *why* technological modernization continues and *how* technological modernization accelerates groundwater depletion.

Ultimately, however, the findings should encourage other efforts to integrate treadmill of production and ecological modernization theories. Despite often treated in opposition, our study lays theoretical and empirical groundwork for further synthesis. The "environmental flows" approach seems promising in this regard (Spaargaren, Mol, and Buttel 2006). Although not yet a theory, per se, an emphasis on the material dimensions of environmental change is consistent with the treadmill framework, and by placing technology at the center of change, the perspective resonates with a core tenet of ecological modernization theory. Perhaps more intriguing is the ability to use environmental flows as a unit of analysis to approach reemerging questions about power and inequality of access to resources across multiple scales of exchange. This makes the environmental flows perspective especially attractive for understanding water, a fugitive resource that does not respect political boundaries. An environmental flows perspective could provide new insights into cross-scale interactions and governance in socio-ecological systems that are increasingly less place bound as a result of globalization. Our analysis provides analytical leverage for further integration of treadmill and ecological modernization theories within an environmental flows perspective.

Along these lines, one logical extension of this study is to extend the scale and scope through macro-comparative analysis. There is a real paucity of work examining the drivers of water use (see Longo and York [2009] for a notable exception), which is surprising given the importance of water. Our results raise questions about the role of ecological unequal exchange (Bunker 1984; Hornborg 1998; Jorgenson 2003, 2006, 2009; Rice 2007) in groundwater consumption. Does unequal ecological exchange put more spin on the treadmill, to paraphrase Stephen Bunker (2005)? The finding that neither groundwater consumption nor agricultural production directly supports farmers' incomes opens up the possibility that value from water consumption is accumulated elsewhere in the (global) food system through international trade. We cannot address this important question at the scale employed in this study, but this line of inquiry merits attention on the basis of our results.

The results point to a key limitation of prior policies, and also suggest how policy might more effectively ameliorate depletion. Thus far, the solutions are aimed at individual farms, with the objective of empowering farmers, as individuals, to voluntarily manage groundwater more sustainably. If the goal is to ensure that the Aquifer will support future generations and the world food system, however, these policies have not succeeded. Our findings suggest that the scale of problem has not matched the scale of the solution. Farm-level policies have not been more successful because groundwater depletion is a part of a structural dynamic—a production treadmill. Structural problems require collective action because they exceed the capacity of any one individual to remedy them.

Past policies have at least implicitly acknowledged depletion as a social problem. In Kansas, for example, irrigators formed groundwater management districts in the 1970s. Still in existence today, groundwater management ostensibly recognize that farmers have a collective, shared responsibility to manage the Aquifer. Yet, groundwater management districts leave untouched the technological and political-economic dynamics of the treadmill that drive depletion, instead defaulting to voluntary, individual-level efforts to conserve groundwater that have proven ineffective. The individual farmers that comprise these districts have good reason to avoid directly addressing treadmill dynamics: as individuals, they do not directly control them. Indeed, our analysis suggests that the social problem of groundwater depletion extends beyond the farm, the GMD, or even the Ogallala-High Plains region to international markets, where prices for agricultural products are made, and the seats of government, where policies governing agriculture are made.

At these scales, there are several means of restructuring agriculture in semiarid regions like the High Plains of the United States to reduce the intensity of water consumption. We focus on one that seems reasonable as an initial, but potentially transformative step: reforming policies that subsidize agriculture. Our findings provide evidence suggesting that weakening the connection between groundwater withdrawals and farm income can slow the treadmill. Revising policies that subsidize agriculture can play a critical role in this regard. Government subsidies distort agricultural prices and promote overproduction, both of which result in unsustainable water consumption throughout the world (Pimentel et al. 2004). Subsidy policies that encourage farmers to maximize production above all other goals have had only limited benefits to rural communities (Arbuckle et al. 2012; Drabenstott 2005) while exacerbating groundwater depletion—the material resource supporting many of these communities. If the total market value production at the farm level is not associated with farm incomes, as the results indicate, then more production will not allow farmers to escape the treadmill and reduce groundwater consumption. Similarly, to the extent that subsidies support the further expansion of water-conserving irrigation technologies, our findings lend skepticism about the role of these efforts in stemming depletion. If water use efficiency is not associated with farm incomes, as the results indicate, then increases in efficiency will not slow the treadmill.

Instead, the results presented here support policies that encourage farmers to transition to less-water-intensive forms of production while maintaining their incomes and recognizing the legacy costs of irrigation infrastructures. Given that the United States has subsidized agriculture for over 80 years, it is not reasonable to expect the end of agricultural subsidies soon. Similarly, farmers have no incentive to idle the extensive irrigation infrastructures in place throughout the region, and every incentive to use them to maximum capacity. Thus, rather than promoting depletion, as the model suggests they do, subsidies could be re-directed over the intermediate time horizon toward idling the irrigation infrastructures and softening the return to lower-value, dryland commodities, which would otherwise further depress farm incomes. The current U.S. Farm Bill (Agricultural Act of 2014, PL 113-79) ended direct payments while expanding subsidies for crop insurance. It is too soon to assess the effects of this change on groundwater consumption, but this would be a worthwhile area for future research. Using subsidies to encourage a shift into less water intensive commodities could provide precious time for farmers in the High Plains region to transition over a longer-term horizon toward a more sustainable agriculture, one that does not require such significant government assistance or ecological depletion. Reforming subsidies would only be a first step. It would not directly address the legacy effects and sunk costs of irrigation infrastructures, nor would it address any of the dynamics in international commodity markets that motivate the treadmill. But, it might slow the rate of "spin" on the treadmill enough to initiate a transition away from water-intensive production in this region.

Regardless, time is of the essence. Concerns over the ecological and social effects of agriculture in this region are growing, as are tensions between farm and nonfarm populations over the water that remains (Gasteyer 2008). A transition must begin soon because the window of opportunity to slow the race to the bottom of the Ogallala Aquifer is closing (Steward et al. 2013).

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