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Review

Jevons' Paradox and Efficient Irrigation Technology

Louis Sears [1], Joseph Caparelli [2], Clouse Lee [1], Devon Pan [3], Gillian Strandberg [1], Linh Vuu [1] and C. -Y. Cynthia Lin Lawell [1,*]

1 Charles H. Dyson School of Applied Economics and Management, Cornell University, Ithaca, NY 14853, USA; lss34@cornell.edu (L.S.); cjl277@cornell.edu (C.L.); gls235@cornell.edu (G.S.); lav59@cornell.edu (L.V.)
2 Computing and Information Science, Cornell University, Ithaca, NY 14853, USA; jcc394@cornell.edu
3 College of Agriculture and Life Sciences, Cornell University, Ithaca, NY 14853, USA; dtp38@cornell.edu
* Correspondence: clinlawell@cornell.edu

Received: 30 April 2018; Accepted: 13 May 2018; Published: 16 May 2018

Abstract: Water is one of our world's most essential natural resources, but it is also a resource that is becoming increasingly scarce. The agricultural use of groundwater is particularly important to manage sustainably and well. However, popular and well-intentioned water conservation and management policies, including those that encourage the adoption of more efficient irrigation technology, may have unintended and possibly perverse consequences if policy-makers do not account for water users' behavioral responses to their policies. In particular, a Jevons' Paradox may arise, whereby a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource. In this paper, we discuss efficient irrigation technology, Jevons' Paradox, and the possible perverse consequences of incentive-based programs for agricultural groundwater conservation.

Keywords: efficient irrigation technology; Jevons' Paradox; incentive-based conservation programs; agricultural groundwater; perverse consequences; unintended consequences

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1. Introduction

Water is one of our world's most essential natural resources. Without water, a human being cannot survive for more than about a week, and no organic matter would exist. As Leonardo da Vinci once stated: "Water is the driving force of all nature".

Water is not only an essential natural resource, but it is also a resource that is becoming increasingly scarce. As Rachel Carson wrote in 1962 in her book *Silent Spring*: "Of all our natural resources water has become the most precious" [1].

The agricultural use of groundwater is particularly important to manage sustainably and well. Many of the world's most productive agricultural basins depend on groundwater resources for which water table levels are declining. The food we eat, the farmers who produce our food, and the local economies supporting agricultural production are all affected by the depletion of groundwater stocks [2,3]. In some countries, the share of groundwater withdrawn that is used for agriculture can be as high as 90 percent [4]. Moreover, climate change, urban water demand, and trends in agricultural production in developing countries are projected to increase pressure on renewable water resources, making the preservation of groundwater resources, which have an important role in mitigating the effects of dry years on surface water supplies, even more vital [5].

When designing polices and institutions for managing groundwater, it is important to consider any possible perverse consequences from these policies. Policies that encourage the adoption of more efficient irrigation technology may be appealing under the premise that they will decrease the amount of applied water required to maintain current crops and yields. However, this ignores the possibility that farmers may adjust their behavior in response to the change in irrigation efficiency, for example by switching to higher-revenue crops that are more water intensive, or by irrigating previously unirrigated land, resulting in an increase rather than a decrease in groundwater consumption. This unintended and possibly perverse consequence is an example of a Jevons' Paradox, whereby a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource [6]. In this paper, we discuss efficient irrigation technology, Jevons' Paradox, and the possible perverse consequences of incentive-based programs for agricultural groundwater conservation.

2. Efficient Irrigation Technology

Irrigation efficiency measures what proportion of consumed water is beneficially used by a crop. Formally, irrigation efficiency is defined as the fraction of the consumptive use of water (defined as applied water minus any return flow) that is effective water (defined as water that is beneficially used by a crop), and is given by the following equation [2,7]:

$$\text{irrigation efficiency} = \frac{\text{effective water}}{\text{consumptive use of water}}. \tag{1}$$

More efficient irrigation technologies increase this proportion, allowing less water to be applied for a given yield [2,7]. In addition, land-augmenting technologies such as more efficient irrigation increase the ability of lower quality soils to provide water and nutrients to crops [8].

An example of a more efficient irrigation technology are dropped nozzles, which attach to center-pivot irrigators and hover right above the canopy of crops, thereby reducing water lost to evaporation and drift [9].

Another example of more efficient irrigation technology is drip irrigation [10]. Under drip irrigation, water is conveyed to plants through a network of pipes and emitters. This technology allows the slow and controlled application of water, and allocates a smaller volume of water per unit of time with higher precision [11]. According to Netafim, which makes drip irrigation technology, drip irrigation saves an average of 25–75% pumped water compared to flood irrigation [12].

The adoption of drip irrigation technology has historically been driven in many cases by its yield-enhancing properties. In California, for example, early adoption was limited to high-value tree crops like avocados, whose yields could be increased through more efficient irrigation without raising costs [11]. While there was widespread adoption of drip irrigation during the extended drought of the late 1980s and early 1990s, this was accompanied by increased well drilling and reliance on groundwater, as surface water supplies became scarce [11]. Since then, the adoption of drip irrigation technology has been concentrated in lower-value crops, where other technological changes have made the yield effect of a switch to drip technology more advantageous [11].

Adoption of more efficient irrigation technology may also be driven in part by other agricultural input subsidies [13]. According to evidence from an agricultural input subsidy program in Malawi, subsidies to fertilizer and other productivity-enhancing inputs were found to be positively correlated with investment in some efficiency-enhancing technologies related to water conservation, likely due to a switch in crop allocation from staple crops to cash crops [14]. In addition, Caswell and Zilberman [15] show that land quality variation affects the extent of technology adoption as well.

3. Effects of Increasing Irrigation Efficiency

Although more efficient irrigation technologies allow less water to be applied for a given yield, these improvements in irrigation efficiency may lead a profit-maximizing farmer to increase rather than decrease the consumptive use of water [2].

Some papers in the previous literature on the effects of irrigation efficiency on water consumption have found that increases in irrigation efficiency tend to decrease consumptive use [2,7]. In their theoretical analysis, Caswell and Zilberman [15] show that the adoption of more efficient irrigation technology will always increase effective water and yields, but its effect on water consumption depends on the elasticity of demand for irrigation water. When demand is inelastic, an increase in irrigation efficiency results in a decrease in water consumption. On the other hand, when water demand is elastic, increases in irrigation efficiency will increase water consumption [15]. Huffaker and Whittlesey [16] develop a similar theoretical model that incorporates the possibility of return flows. Gómez and Perez-Blanco [17] use a theoretical model to decompose the effect of irrigation efficiency into its effects on productivity, technical efficiency of irrigation, and the cost of operating the irrigation system; they find that the first effect must dominate the other two in order for water consumption to increase. Using a data-calibrated simulation model, Peterson and Ding [18] find that conversion from flood irrigation to center pivots can reduce overall irrigation water use for corn in Western Kansas.

Other papers in the previous literature on the effects of irrigation efficiency on water consumption predict that increasing irrigation efficiency will increase water consumption [2,7]. In their simulation of the High Plains region of Texas, Ellis et al. [19] find that because dropped nozzles improve delivery efficiency and reduce the variable cost of irrigation, their adoption leads agricultural producers to plant more water-intensive crops, increase irrigated acreage, and apply more water per acre to increase yields. Using a data-calibrated simulation model, Huffaker and Whittlesey [20] find that investment in more efficient irrigation technology will be used to increase yields, leading to an increase in the consumptive use of water. Scheierling et al. [21] find using a data-calibrated simulation model that a subsidy for irrigation efficiency will cause consumptive use to never decrease, the number of irrigations to increase when acreage is fixed, and the number of irrigated acres of the most water-intensive crop to increase when acreage is not fixed. In their numerical analysis of the effect of subsidies for the adoption of drip irrigation, Ward and Pulido-Velázquez [22] find that subsidies for the adoption of drip irrigation lead to increases in not only yields and net farm income, but also in total water depletion. Contor and Taylor [23] show that because a rational producer behavior will equate the marginal cost of irrigation water with its marginal benefit, total consumptive use of water will generally increase when irrigation efficiency improves.

What explains the seemingly mixed results of the previous literature on the effects of irrigation efficiency on water consumption? First, the theoretical models of Caswell and Zilberman [15] and Huffaker and Whittlesey [16] model a single year only. However, this assumption is unreasonable for a modern crop production system. The relevant time horizon is longer than one season, and the long-run demand for irrigation water is likely to be more elastic than short-run demand. As Caswell and Zilberman [15] and Huffaker and Whittlesey [16] show, when demand is inelastic, an increase in irrigation efficiency results in a decrease in water consumption.

Second, the theoretical models of Caswell and Zilberman [15] and Huffaker and Whittlesey [16] and the data-calibrated simulation model of Peterson and Ding [18] model a single crop only. Such single-crop models do not consider the possibility that farmers may respond to increases in irrigation efficiency by changing their crops, crop rotation patterns, or fallow cycles, all of which may lead the farmers to increase rather than decrease their water use.

Third, Peterson and Ding [18] do not consider the possibility of expanding irrigated acreage and assume that the center pivots cannot irrigate as many acres as a flood system can. Peterson and Ding [18] therefore do not allow for the possibility that increases in irrigation efficiency may lead farmers to respond by expanding their irrigated acreage, which may result in an increase rather than a decrease in water use. Ward and Pulido-Velázquez [22] find in their simulation model that water depletion increases even more as a result of subsidies for the adoption of drip irrigation when total irrigated acreage is allowed to increase [22].

Fourth, while the theoretical models of Caswell and Zilberman [15] and Huffaker and Whittlesey [16] find that the demand for irrigation water must be elastic in order for an increase in irrigation efficiency to increase water consumption, it is possible that the demand for irrigation water may be more elastic than previously believed to be [13]. For example, evidence from a framed field experiment suggests that farmers respond elastically to price signals related to groundwater extraction, such as electricity prices [24]. Empirical evidence also shows that farms respond to energy prices [25]. Using panel data from a period of water rate reform, Schoengold et al. [26] estimate that the price elasticity of agricultural water demand is greater than that found in previous studies. Similarly, Smith et al. [27] use panel data to show that farmers' response to groundwater pumping fees is more elastic than it was previously believed to be, and also that in the short run this response operates through irrigation-intensive margin adjustments rather than through crop acreage adjustments or technological change. While surface water users may respond more to changes in the availability of water than its price, groundwater users may not face a formal cap on extraction, but instead are limited by the cost of extraction, making them more sensitive to price [28]. In addition, the demand for irrigation water is likely to be more elastic in the long run than in the short run [29].

Fifth, the theoretical models of Caswell and Zilberman [15] and Huffaker and Whittlesey [16] assume that the efficient irrigation technology does not affect either revenue or cost. However, it is possible that efficient irrigation technologies can affect a farmer's revenue and costs. For example, dropped nozzles have a higher efficiency and directed spray pattern, which aids with the inter-seasonal timing of irrigation, allowing farmers to better fulfill a crop's water requirements during peak water demand days and critical growth stages, thereby increasing a farmer's revenue [23,30]. Corn yields under dropped nozzles can be up to 13 percent higher than yields under conventional center pivots; this yield benefit is greatest under situations such as drought [30–33]. In addition, dropped nozzle systems require significantly less pressure to operate than do conventional center pivots, and thus have a lower energy cost of groundwater extraction and application, thereby decreasing a farmer's costs [34].

Pfeiffer and Lin [7] incorporate these above considerations, including the possibility that efficient irrigation technology may affect revenue and cost, as well as the possibility that efficient irrigation technology may lead farmers to respond by changing their crops and expanding irrigated acreage, both theoretically and empirically. They develop a theoretical model that allows irrigation efficiency to affect revenue indirectly through the transformation of applied water into effective water, as well as directly, by enabling farmers to better fulfill the crop's water requirements during critical growth stages. They show that, if demand is elastic enough, if the higher efficiency technology operates at a lower marginal cost, and if the higher efficiency technology increases revenue, then irrigation efficiency will increase applied water [7]. Using back-of-the-envelope calculations for the elasticity of demand, revenue, and cost effects in western Kansas, they show that it is indeed possible that increases irrigation efficiency may increase groundwater extraction [7].

4. Incentive-Based Water Conservation Programs

Incentive-based water conservation programs are popular policies for managing water since everyone seems to benefit: farmers receive a subsidy for adopting more efficient irrigation technology; less groundwater is "wasted" through runoff, evaporation, or drift; farmers can receive payments for retiring marginal lands; and farmers can choose whether to participate.

In many places, policy-makers have implemented incentive-based water conservation programs in an attempt to decrease groundwater extraction. For example, the state of Kansas spent nearly US$6 million between 1998 and 2005 on incentive programs such as the Environmental Quality Incentives Program (EQIP) and the Irrigation Water Conservation Fund to fund the adoption of more efficient irrigation technology. Such programs subsidized up to 75% of the cost of purchasing and installing more efficient irrigation technology, and much of the money was used for conversions to dropped nozzle systems [35]. These incentive-based water conservation programs were implemented in response to declining aquifer levels, in hopes of conserving groundwater [7].

California's State Water Efficiency and Enhancement Program (SWEEP) provides financial assistance to California agricultural operations to implement irrigation systems that save water, including evapotranspiration-based irrigation scheduling, micro-irrigation, and drip systems [36]. For example, the San Luis Canal Company in the San Joaquin Valley offered US$250 per acre to "encourage the transition to pressurized irrigation systems among other actions" [13,37,38]. Similarly, though its funding was not passed, the Water and Energy Saving Technologies Executive Order B-29-15 stipulated that the California Department of Water Resources, California Energy Commission, and State Water Resources Control board were to provide rebates if high-pressure drip irrigation systems were converted to low-pressure drip irrigation systems [13,38,39].

The U.S. Department of Agriculture (USDA) has a long history of supporting the adoption of conservation practices, mostly through conservation programs that provide both financial and technical assistance to farmers for addressing resource-related issues on farms. The USDA's suite of conservation programs includes the Environmental Quality Incentives Program (EQIP), Conservation Stewardship Program (CSP), Regional Conservation Partners Program (RCPP), Conservation Reserve Program (CRP), Agricultural Conservation Easement Program (ACEP), and Conservation Technical Assistance (CTA) [40]. For example, the Conservation Reserve Program (CRP) created by the federal government in 1985 include payments to landowners to retire, leave fallow, or plant non-irrigated crops on their land [41]. These programs are voluntary, relying on farmers to approach the USDA to enroll and to choose which resource issues to address. After substantial increases in conservation funding under the 2002 and 2008 Farm Acts, funding held steady under the 2014 Farm Act, and increases are not anticipated in the near future [40].

Participation in incentive-based water conservation programs is affected by the incentive. For example, landowner participation in the Colorado Republican River Conservation Reserve Enhancement Program is predicted to increase by 0.087 percentage points with a US$10 increase in the incentives offered [42]. Similarly, using actual enrollment and geographic information systems (GIS) data in six geographically diverse states, Suter et al. [43] demonstrate that enrollment rates in the Conservation Reserve Enhancement Program (CREP) are a function of the incentives offered. Likewise, in their analysis of program participation in the binary-choice setting of the Conservation Reserve Enhancement Program using data from six states, Suter et al. [44] find that landowners react positively to the incentives that are offered, and that increases in one-time incentives offered at the time of signup are a more cost-effective means to increase enrollment than increases in the incentives offered on an annual basis. In their analysis of New York State's Draft Conservation Reserve Enhancement Program proposal, Jaroszewski et al. [45] find that net social benefits are nearly 75% lower than for options that explicitly account for opportunity costs of production, environmental benefits, and participation response functions.

Incentive-based water conservation programs are popular policies for managing water not only in the United States, but also in other countries throughout the world. India is encouraging the adoption of drip irrigation through subsidies [12].

In the United Kingdom, the Enhanced Capital Allowance (ECA) scheme for water allows businesses that invest in water-efficient plant and machinery to write off 100 percent of the cost against taxable profits in the year of purchase [46–48].

The Chinese government has implemented several policies to promote the adoption of water-saving irrigation technologies such as border irrigation, furrow irrigation, drip irrigation, and underground pipe and canal lining [49]. For example, the North China Plain Water Conservation Project supports the implementation of improved conservation technologies including canal lining, wells, drains, sprinklers, and micro-irrigation systems [50].

5. Jevons' Paradox

Though popular, incentive-based water conservation programs can have perverse consequences [2,7,9,13,38,51–54]. In particular, a rebound effect, or "Jevons' Paradox", may arise, whereby a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource [6].

For example, policies that encourage the adoption of more efficient irrigation technology may not have the intended effect. In arid regions, irrigation enhances the productivity of rain-fed cropland, since it allows the production of higher value crops on previously marginal land. More efficient irrigation technology also lowers the effective cost of irrigation by limiting non-consumptive use of applied water, lowering the relative cost of more water-intensive crops. Thus, by making more efficient irrigation technology cheaper to adopt, an incentive-based policy can induce the planting of more water-intensive crops on already irrigated land, as well as a shift away from dry-land crops to irrigated crops, both of which may lead to an increase rather than a decrease in water consumption [2,7].

In addition, farmers may self-select into incentive programs, and some participants would have purchased the technology even without the subsidy [55]; as a consequence, public funds used to provide these farmers with the subsidy may have been unnecessary expended. Indeed, in direct response to concerns over a possible rebound effect, in 2012 the European Commission called for mandatory minimum reductions in water use as part of its policy to incentivize higher efficiency irrigation technology [56].

Similarly, land conservation and retirement programs may not be effective for inducing farmers to lower extraction. For programs such as the Conservation Reserve Program (CRP) that include payments to landowners to retire, leave fallow, or plant non-irrigated crops on their land, theory predicts that farmers may enroll their least productive, least intensively farmed lands in the programs. It is quite unlikely that parcels on which the farmer has made significant irrigation investments for the purpose of enhancing productivity will be among a farmer's least productive, least intensively farmed lands. Instead, farmers may opt to enroll their least productive plots in the CRP program. Since these plots are unlikely to be irrigated, enrolling them in the CRP program does not have any effect on the amount of irrigation water extracted [2,7].

Groundwater conservation is especially important in areas like California where high-value crops are grown, and where surface water supplies are highly stressed or unavailable. However, land retirement policies are particularly ineffective in areas of high-value agricultural production like California, where farmers will demand much higher payments to voluntarily abandon crop production. Since much of the land in California's most water-stressed regions is also used to produce high-value irrigated agriculture, land retirement programs in these areas may be limited in their effectiveness, or be very costly [13].

Pfeiffer and Lin [7] innovate upon the erstwhile theoretical and numerical previous literature on the effects of irrigation efficiency on groundwater extraction by conducting an empirical analysis of incentive-based groundwater conservation policies in Kansas. According to their results, which have been featured in such media outlets as the New York Times [57,58], the Washington Post [59], Bloomberg View [60], and AgMag Blog [61], incentive-based groundwater conservation policies in Kansas that subsidize a shift toward more efficient irrigation systems have not been effective in reducing groundwater extraction. Instead, farmers responded to the subsidized increase in irrigation efficiency by increasing their irrigated acreage and producing more water-intensive crops, causing water consumption to increase rather than decrease [7]. Similarly, Pfeiffer and Lin [7,51,52] find essentially no effect of land conservation programs on groundwater pumping, since farmers may opt to enroll non-irrigated plots instead [2,7,51,52]. Thus, the results of Pfeiffer and Lin [7] provide empirical evidence for a "Jevons' Paradox" whereby incentive-based groundwater conservation policies that encourage the adoption of more efficient irrigation technology may lead to an increase rather than a decrease in water use.

The eponymous intellectual who first described "Jevons' Paradox" was William Stanley Jevons, who observed in 1865 that the Watt steam engine, a form of technology which greatly improved the efficiency of coal-fired steam engines, led to an increase in the use of the steam engine in a wide range of industries, which in turn increased total coal consumption [6]. As he wrote in his 1865 book *The Coal Question* [6]: "It is a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth." Thus, Jevons observed, a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource [6].

The possibility of a "Jevons' Paradox" arises with the more efficient use of any natural resource. In the case of energy resources, for example, many economists have grappled with the possibility of an energy rebound effect whereby some of the gains from improving the efficiency of energy use is offset by increases in energy consumption [62,63]. When consumers obtain a more fuel-efficient car, it is possible that they may end up driving more and using more fuel than they would have with a less fuel-efficient car. Similarly, households that obtain a more energy-efficient appliance may end up using that appliance more, consuming more energy than they would have with a less energy-efficient appliance. Zhang and Lin Lawell [63] find that in some provinces in China, improvements in energy efficiency that have spurred economic growth have actually increased rather than decreased energy consumption. Similarly, Si et al. [64] find that policies in China that provide education and information for increasing energy efficiency have the perverse effect of leading to a significant increase in electricity consumption per capita, possibly due to a rebound effect.

In the case of agricultural groundwater, Pfeiffer and Lin [7] show both theoretically and empirically that technology that increases irrigation efficiency does not necessarily lead to less consumption of groundwater [2,9,13]. In particular, if demand for groundwater by farmers is elastic enough, if the higher efficiency technology operates at a lower marginal cost, and if the higher efficiency technology increases revenue, then irrigation efficiency will increase applied water [2,7].

Li and Zhao [65] similarly find that water extraction in the High Plains Aquifer region of Kansas moderately increases after adoption of Low Energy Precise Application (LEPA) irrigation technology, and show that this rebound effect is in general higher for farmers with larger water rights.

In their research on the Colorado Republican River Conservation Reserve Enhancement Program, Monger et al. [42] find that the probability of enrollment in this land retirement program is influenced by soil characteristics that impact land productivity. In particular, wells that irrigate less-productive land are more likely to be enrolled in the program [42].

According to an analysis of the contracts completed under the Environmental Quality Incentive Program (EQIP), which promotes irrigation methods that use less water, more than 20 percent of the program's funding between 2009 and 2016 went towards infrastructure practices that produced relatively little environmental benefit [66].

California's State Water Efficiency and Enhancement Program (SWEEP) grant funds allow farmers to adopt technology that lowers the marginal cost of irrigation, and therefore may encourage farmers to irrigate more marginal lands and grow high-revenue crops that are more water intensive, and may also discourage them from exiting irrigated cropping even as groundwater becomes scarcer. Farmers who are more sensitive to the price of irrigation have the most to gain from programs funded by SWEEP, and thus may select into them [13]. Unlike surface water, water use by farmers who are reliant on groundwater is driven by price signals and not quantity constraints; as a consequence, these farmers may be expected to be more sensitive to price [28], and thus likely to select into SWEEP-funded programs.

In a pilot program within SWEEP recently introduced by the California Department of Agriculture and the California Department of Water to reduce groundwater, farmers are given incentives to implement more efficient irrigation technology in return for an agreement to halt the agricultural use of groundwater [67]. However, a potential unintended consequence is that the incentives may be used most by farmers who rely relatively little on groundwater as their source of water, thus resulting in little or no effect on groundwater use. As a result, the costs of the program may unfortunately outweigh its benefits [13].

As part of any efficiency gains from new irrigation technology purchased with California's SWEEP grant funds, farmers may choose to convert more marginal land that is currently used for rangeland and dry land farming to more productive irrigated cropland, and this possible increase in irrigated acreage may lead to an increase in groundwater consumption. Indeed, in a survey of farmers in Yolo County, California, Niles and Wagner [68] found that some farmers believed that drip irrigation led to increases in water use by facilitating the expansion of almond orchards onto previously unirrigated land, and by limiting the re-use of "tail-water". Similarly, if farmers are credit-constrained, then the additional profits from subsidized irrigation technology might be used to expand production on other lands, which may also lead to an increase in groundwater consumption [11]. Furthermore, cultivation of marginal land often requires excessive use of chemicals, and can damage other nearby water sources [69,70].

In research on China, Song et al. [71] find that although the water productivity of China's agricultural sector has increased over the last 20 years via improvements in irrigation technology, the total agricultural water use did not decline as expected, mainly due to continuous increases in agricultural output partially derived from technological progress. The authors find that much of the expected water savings from more efficient irrigation technology are offset by increased water use for the resulting increase in agricultural production made possible by the more efficient irrigation technology [71].

Thus, though still sparse, the empirical literature on the effects of incentive-based groundwater conservation policies on groundwater extraction lends support for the possibility of a "Jevons' Paradox" and the unintended, or even perverse, consequence of possibly increasing rather than decreasing groundwater extraction. Table 1 summaries this empirical literature.

Table 1. Empirical evidence for a "Jevons' Paradox" in groundwater conservation policies.

Region	Policy	Source
Kansas	subsidies for more efficient irrigation technology	Pfeiffer and Lin [7]
Kansas	land conservation programs	Pfeiffer and Lin [7,51,52]
Kansas	water rights and more efficient irrigation technology	Li and Zhao [65]
Colorado	Conservation Reserve Enhancement Program	Monger et al. [42]
China	more efficient irrigation technology	Song et al. [71]

When designing policies for sustainably managing agricultural groundwater use, policy-makers therefore need to account for all the possible behavioral responses to their policy, including any potential unintended perverse consequences that may arise. To so do, it is important for policy-makers to continually gather detailed data on the groundwater extraction, groundwater levels, crop acreage, and irrigation technology decisions of individual groundwater users on an ongoing basis, so that researchers can then empirically analyze the effects of past and ongoing policies, and to better design future policies [13].

In order to mitigate any potential unintended or perverse consequences, policy-makers may wish consider one or more of the following alternative or complementary aspects of sustainable agricultural groundwater management when designing policy. First, policy-makers should consider incorporating insights from behavioral economics such as behavioral "nudges", or non-financial changes in the manner in which options are presented to decision-makers that may increase the likelihood of a certain behavior [72]. Second, policy-makers should consider reporting the groundwater extraction data they collect to enable groundwater users to make peer comparisons, which has been shown to promote conservation in domestic water use [55,73]. In addition, the reporting of decisions of non-neighbors may make groundwater users more likely to coordinate with their neighbors [74]. Thus, improved monitoring of groundwater extraction and transparent publication of basin-wide information regarding extraction may be important lower-cost alternatives or complements to policies that encourage the adoption of more efficient irrigation technology [13].

6. Conclusions

Although they are popular and well-intentioned policies for water management, policies that encourage the adoption of more efficient irrigation technology may not have the intended effect. Instead, a Jevons' Paradox may arise, whereby a technology that enhances the efficiency of using a natural resource does not necessarily lead to less consumption of that resource. In particular, incentive-based groundwater conservation programs may have the perverse consequence of actually increasing rather than decreasing groundwater extraction.

Irrigation efficiency incentives may lead to an increase in groundwater use by lowering the marginal cost of irrigation, and by making marginal land cheaper to irrigate. Thus, farmers may adjust their behavior in response to an increase in irrigation efficiency, for example by switching to higher-revenue crops that are more water intensive, or by irrigating previously unirrigated land, resulting in an increase rather than a decrease in groundwater consumption.

Similarly, land retirement programs may prove ineffective since they incentivize farmers to retire their least productive, and thus least likely to be irrigated, land. Since these plots are unlikely to be irrigated, retiring these plots does not have any effect on the amount of irrigation water extracted.

Thus, when designing policies for sustainably managing agricultural groundwater use, policy-makers need to account for all the possible behavioral responses to their policy, including any potential unintended perverse consequences that may arise.

Author Contributions: L.S., J.C., C.L., D.P., G.S., L.V., and C.-Y.C.L.L. wrote the paper.

Acknowledgments: We benefited from the excellent research of Lisa Pfeiffer. We thank Emmanuel Asinas, Randolph Barker, Chris Bowman, Mark Carlson, Colin Carter, Jon Conrad, Ariel Dinar, Jim Downing, Paul Ferraro, Roman Hernandez, Richard Howitt, Richard Kravitz, David Lee, Shanjun Li, Jay Lund, Julie McNamara, Ariel Ortiz-Bobea, Krishna Paudel, H. Michael Ross, Ivan Rudik, Jim Sanchirico, Kurt Schwabe, Rich Sexton, Bill Schulze, Cindy Simmons, Mike Springborn, Dan Sumner, Ed Taylor, Kristina Victor, Jim Wilen, and David Zilberman for invaluable comments, insight, and support. We also benefited from helpful comments from participants at the Water Pricing for a Dry Future workshop; at the Special Symposium in Memory of Gregory L. Poe; and at our Honorable Mention Bacon Public Lectureship. We received funding from a Cornell University Institute for the Social Sciences Small Grant; from the Giannini Foundation of Agricultural Economics; and from the 2015–2016 Bacon Public Lectureship and White Paper Competition. All errors are our own.

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

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