Groundwater Management in the Presence of Greenhouse Gas Mitigation Incentives for Agriculture

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ABSTRACT

This study explores the interactions of groundwater extraction, quality, and greenhouse-gas (GHG) emissions within a productive agricultural region. Two conceptual models are proposed. In the first, GHG emissions are managed at the local level, and an efficient level of abatement is solved for endogenously to the system. Here, regional management of GHG emissions offers an alternative policy tool for managing quantity/quality by internalizing the costs of a common externality associated with both groundwater extraction and nitrogen fertilizer application. A simple numerical simulation is used to illustrate the potential groundwater co-benefits of managing agricultural GHG emissions within the system. The second model reflects the reality that GHG mitigation efforts will occur at the national or international level; agricultural markets and production will respond according to the scope of the policy mechanism and the anticipated effect on agricultural markets and input costs. For this scenario, the impacts of GHG mitigation on regional groundwater supplies are ambiguous. A set of scenarios is derived in which groundwater co-benefits or co-costs can be expected within a region. Groundwater managers should be cognizant of the indirect market pressures created by agricultural GHG mitigation and bioenergy development, and should adapt conservation and quality protection measures accordingly.

I. Introduction

Growing populations and associated water demands, environmental matters, and the uncertainties of future climatic conditions are factors influencing water management decisions and increased competition for fresh water supplies. Contemporary concerns include current policy ambitions to displace fossil fuel consumption with biofuels that enhance water demand as stimulated by higher commodity prices and agricultural land values. Greenhouse gas (GHG) mitigation policy could have a similar impact by further increasing the demand for low carbon bioenergy and through indirect market effects as land is set aside for carbon sequestration purposes. GHG mitigation efforts could also benefit water quantity by making extraction more costly and improve quality by reducing chemical application rates and livestock management intensity (if non-CO2 emissions are targeted).

There is a clear signal of a societal need to conserve and manage scarce groundwater as efficiently as possible. Thus, the implications of environmental and energy policies on water resource systems should be carefully considered. This study evaluates the implications of GHG mitigation incentives, in particular those directed toward the agricultural sector, on the derived demand for groundwater and other agricultural inputs to assess the net implications of such policy efforts on regional groundwater systems. This is a unique situation in which the provision of a public good (atmospheric GHG concentration reduction) interacts with the management of a common property resource. If inefficient management of the common property resource leads to under (over) provision of the public good (bad), then one is confronted with an interdependent set of externalities. It is possible that a policy mechanism used to correct one market failure (i.e. GHG emissions, or over-exploitation of an aquifer) can benefit or exacerbate the other externality in the system.

This study incorporates the basic sources of GHG emissions that occur within a regional agricultural groundwater management system. Two management scenarios are considered for a regional groundwater system under agricultural GHG mitigation incentives. In the first model, emissions reductions are solved for endogenously to the model such that a social planner chooses a level of abatement consistent with the social cost of GHG emissions and the marginal abatement costs of altering farm management intensity. Through numerical simulation, I show that targeting GHG emissions directly within a groundwater management system can reduce depletion rates (slightly) and improve water quality. While managing groundwater quantity and quality conjunctively has proven to be difficult, managing GHG emissions provides an alternative for indirectly alleviating both depletion and degradation concerns.

In the second model, GHG mitigation incentives are set externally to the system, and groundwater managers respond accordingly to the exogenous stimuli. This reflects the reality that mitigation and offset schemes will be set at a national or international level, and agricultural managers will adapt production decisions depending on the scope of these policy mechanisms and the associated marginal effects on input costs and commodity markets. Conceptual diagrams and an augmented mathematical model are used to illustrate why the net effects of climate mitigation policies on regional groundwater systems are so difficult to evaluate, and ultimately depend on regional hydrologic and production characteristics, as well as the full scope of the policy implemented.

II. Background and Literature

To date, most studies within the climate/water paradigm have focused on the biophysical impacts of climate change on water resource systems, and implications for future water availability (Christensen, et al., 2004, Jackson, et al., 2001). The economics literature has examined water management institutions in a changing climate, or how agricultural production systems might respond to climate change (Chen, et al., 2001, Döll, 2002, Fischer, et al., 2007, Hatch, et al., 1999, Mendelsohn and Dinar, 2003, Mendelsohn, et al., 1994). These studies take an adaptation perspective, choosing to explain the economic consequences of changing temperatures and precipitation patterns, with most studies highlighting the potential benefits of increased agricultural yields brought on by warmer temperatures, higher atmospheric CO_2 concentrations, and increased regional water availability.

However, few studies have considered the impact of climate mitigation opportunities, or policies designed to reduce GHG emissions, on regional water resource systems. This is a growing area of concern, as highlighted by the most recent Assessment of the Intergovernmental Panel on Climate Change (Bates, et al., 2008). This paper argues that the interactions of water, energy, and climate policy are critical, especially when climate mitigation efforts are aimed at (or explicitly interact with) the agricultural sector.

Water-Energy-Climate Nexus

To start, consider the Water-Energy nexus, a term used to describe the interdependencies of water and energy. At the core of this concept is the notion that the provision of either water or energy is often highly dependent on the availability of the other. This is evident in the abundance of energy produced directly through hydropower or indirectly through water resource inputs. Further complicating the water-energy nexus is the interaction of energy production and water quality. Preparing for future energy demands signals a need to co-manage water and energy to maximize the returns to the entire water/energy portfolio.

Extending this concept to include climate, the connection is obvious. Fossil-fuel derived energy accounted for approximately 29,000 $MTCO_2$ in 2006, roughly 56.6% of global anthropogenic GHG emissions (IPCC, 2007). The consumption of energy and provision and/or delivery of water resources are GHG emitting activities. Globally, the delivery of water resources for human consumption is responsible for approximately 26 Quads of energy, accounting for roughly 7% of global energy consumption and 2,030 $MTCO_2$.

As renewable energy is expected to be a main component of climate and energy legislation, water consumed for the production of renewables will increase. Water is used directly to supply renewable energy through hydropower, cooling nuclear reactors, geothermal energy, and the cultivation of biofuels (Bates, et al., 2008). Biofuels in particular are highly consumptive of water resources, with the majority of water consumed via irrigation (Mubako and Lant, 2008). Reliable water resource supplies are vital to ensure a sustainable path forward for renewable energy.

As a corollary, the availability of water fit for human consumption is rapidly declining, and water scarce regions will have to rely on energy-intensive means of delivering adequate supplies in future generations. For example, wastewater treatment and re-use, and desalination have become popular backstop solutions to alleviate water scarcity; however both options are highly emitting activities (Cakir and Stenstrom, 2005, Préndez and Lara-González, 2008, Zhou and Tol, 2005). The use of groundwater has increased significantly over the last few decades as surface water has been over-allocated and supplies have diminished (Llamas and Martinez-Santos, 2005). Groundwater is particularly important within the water-energy-climate nexus due to the energy needed for extraction and delivery. Arid regions that have become increasingly dependent on groundwater now consume energy at higher rates to satisfy growing water demands. In the Northern Mexico states of Chihuahua and Sonora, groundwater pumping accounts for 16 and 10% of the states' energy budgets, respectively (Scott, 2007). In India, subsidized energy for agricultural producers has led to inefficient use of energy as well as over-exploitation and quality degradation of important groundwater resources (Kumar, 2005).

As climate mitigation schemes raise the cost of energy inputs, water managers in groundwater dependent regions will be forced into difficult decisions. In regions where scarcity is not a concern, increasing the marginal costs of water provision indirectly through GHG mitigation efforts raises equity concerns. Where scarcity and over-exploitation are prevalent, raising the unit cost of water extraction could help sustain the lifetime of the aquifer. In addition, higher energy costs could lead farmers to switch to more energy and water efficient irrigation systems, such as the Low Energy Precision Application system[1]. Regardless of region, or relative water availability, climate mitigation incentives will be pervasive in water management decisions. Policy makers should be careful in promoting carbon benefits at the expense of water resources; water quantity/quality trade-offs should be carefully weighed.

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[1] Recent studies refute the claim that such systems actually promote water conservation Peterson, J. M., and Y. Ding. "Economic Adjustments to Groundwater Depletion in the High Plains: Do Water-Saving Irrigation Systems Save Water?" *American Journal of Agricultural Economics* 87, no. 1(2005): 147-159..

Implications of Agricultural GHG Mitigation Incentives

In no way is the carbon/water trade-off more appropriate than with GHG mitigation incentives for agriculture and forestry. Although domestic agricultural production only accounts for approximately 6% of U.S. CO_2 emissions, it can play a significant role in U.S. GHG policy (Murray, et al., 2005). GHG mitigation potential in agriculture and forestry has been discussed in previous analyses (Schneider and Kumar, 2008, Smith, et al., 2008). Mitigation activities can be temporary, taking the form of terrestrial carbon sequestration in agricultural soils and plant biomass.

Alternatively, offsets can be permanent through crop mix alteration, reduced farm management intensity, and reduced non-CO_2 emissions. Conversion of crops and biomass into bioenergy can indirectly offset emissions by displacing combustion of fossil fuels. Economic feasibility of such activities will vary regionally due to the heterogeneous nature of terrestrial carbon sequestration and agricultural production potential.

The current policy landscape is making many of these mitigation and offset initiatives a reality. The Energy Independence and Security Act of 2007 established a Renewable Fuels Standard (RFS) that will continue to push the development of a viable biofuels industry over the long-term. An excess of 30 Billion Gallons/year of biofuels must be produced annually by 2022, pressuring commodity markets and raising concerns of increased water resource consumption/degradation. Additionally, existing and proposed climate mitigation legislation and voluntary carbon markets (i.e. Chicago Climate Exchange) have established offset protocols for afforestation/reforestation and soil carbon sequestration incentives. Again, as agricultural land is taken out of production, local water resources unequivocally benefit, but leakage is still a concern.

While previous research has suggested that climate mitigation in agriculture can directly benefit water resources (Greenhalgh and Sauer, 2003, Pattanayak, et al., 2005), this study argues that the net effects are largely ambiguous, and vary by region. Table 1 identifies terrestrial-based mitigation activities and potential impacts on water resources. Notice that each activity has the potential to reduce GHG emissions, though recent studies have questioned the net climate implications of significant biofuel expansion (Fargione, et al., 2008, Searchinger, et al., 2008). The net impacts of such policy options on water depend on multiple factors.

Table 1: Interactions of GHG Mitigation Activities on Water Resource Systems

	Water Implications		**GHG Potential**
Terrestrial GHG Mitigation Incentive	**Consumption**	**Quality**	**Net Emissions**
Biofuels	Increase	Degradation	Unknown
Bioelectricity	Unknown	Unknown	Reduction
Soil Sequestration	Unknown	Unknown	Reduction
Afforestation	Unknown	Unknown	Reduction
Non-CO_2 Emissions	Unknown	Improvement	Reduction

Biofuels present the most ostensible dilemma. There is valid concern that a global biofuel industry will increase use of irrigation water and degrade water quality through agricultural chemical application (National Research Council (U.S.). Committee on Water Implications of Biofuels Production in the United States., et al., 2008, Rajagopal and Zilberman, 2007). However, some argue that the net impacts of biofuel development will be negligible at a global scale, but could have acute impacts locally, especially where water is scarce to begin with (Berndes, 2002, de Fraiture, et al., 2008). In terms of quality, increased nitrogen runoff and leaching are likely; for surface water supplies this can lead to hypoxia in the Gulf Coast as well as other residual environmental impacts (Donner and Kucharik, 2008).

If allocation of land to energy production in one region extends production in another, indirect impacts on water resources could negate any benefits in the conservation region. Literature to this point has been primarily concerned with leakage, or the net GHG consequences of indirect land use change caused by climate mitigation incentives (Fargione, et al., 2008, Lee, et al., 2007, Murray, et al., 2004, Searchinger, et al., 2008). The water implications of leakage can also be quite severe if production is exported to regions with existing scarcity or quality concerns.

The cultivation of dedicated energy crops or use of agricultural residues for bioelectricity will likely have less pronounced effects on water. Perennial biomass crops such as switchgrass, hybrid poplar, and willow can reduce agricultural input use and irrigation requirements relative to alternative biofuel crops such as corn and soybean (Scharlemann and Laurance, 2008, Zah, et al., 2007). However, leakage is still a concern. If dedicated energy crops replace food production, this could stimulate agricultural development and farm management intensity in other regions, possibly at the expense of water quantity/quality.

Soil sequestration initiatives include setting aside (idling) agricultural lands or reducing tillage intensity on-farm. The former will ostensibly reduce irrigation withdrawals and improve water quality locally as land is taken out of production; though leakage remains a concern with set-aside agricultural land (Wu, 2000). Conservation tillage is another option to increase the sequestration potential of agricultural lands (Lal, 2004). The advantage of conservation tillage is that it helps nutrient and water retention in agricultural soils, leading to decreased input use and long-term production sustainability. Conservation tillage also reduces soil erosion, which decreases sedimentation runoff (Lal, 2004, Pimentel, et al., 1995). However, reduced tillage is often accompanied by additional herbicide application, which can degrade water quality (Schneider and Kumar, 2008).

Afforestation incentives can have indirect consequences on water via leakage, similar to the aforementioned options. Additionally, new forest stands could directly impact hydrologic systems by reducing stream flow and disrupting natural hydrologic processes (Jackson, et al., 2005, Jackson, et al., 2005, Le Maitre and Versfeld, 1997). The extent of reduced runoff and water system disruption depends on the geographic location of afforested lands, and the species of vegetation planted (Farley, et al., 2005). Depending on the geographic location of afforested land, impacts on the hydrologic cycle can be quite serious (Zomer, et al., 2006). However, an emerging policy effort not included in Table 1, avoided deforestation, can benefit ecosystems and water supplies by reducing run-off, preventing erosion and flooding, protecting fisheries, and lowering siltation of river systems (Chomitz and Kumari, 1996, Parrotta, 2002).

While agricultural and forestry-based GHG mitigation is promising, potential impacts on regional water resource systems should be carefully weighed, especially in groundwater predominant regions sensitive to external market shocks. The following section discusses groundwater management in general, both in terms of consumption and quality. Then, a theoretical model is introduced that extends previous modeling efforts to explore the possibility of managing GHG emissions within a regional agricultural production system that relies on groundwater as the primary source of irrigation. The model is then augmented to evaluate the potential policy driven impacts of external GHG mitigation incentives on regional water resource systems.

III. Managing Groundwater

Groundwater has garnered considerable attention in the economics literature. Given the importance of groundwater as an agricultural input and its increasing use in municipal and industrial settings, continued emphasis on effective management alternatives are needed. Groundwater is often mismanaged and overexploited, especially in agricultural settings where institutions do not effectively monitor extraction. In addition to inefficient consumption, groundwater quality is affected by economic activity. Like other common property resources subject to dynamic processes, impacts of management decisions can often have irreversible consequences on groundwater systems. Recent advances in water resource economics include integrating management of water extraction and activities that impact water quality.

Managing Consumption

The common property nature of groundwater can elicit a tragedy of the commons in which over-exploitation leads to rapid depletion. Such depletion can in turn lead to multiple market inefficiencies, including stock externalities, saltwater intrusion, land subsidence, increased production risk, and overall sustainability concerns (Provencher and Burt, 1993). This signals a clear need to manage the rate at which groundwater is consumed; though choosing an appropriate policy mechanism is difficult.

For instance, there is some debate regarding the actual welfare gains of a command and control approach in a groundwater setting (Gisser and Sanchez, 1980, Koundouri, 2004). This assertion has been tested and confirmed, which devalues the case for applying economic tools in a control setting to manage groundwater (Lee, et al., 1981, Nieswiadomy, 1985, Nieswiadomy, 1988). However, such analyses ignored a number of important aspects of groundwater management, including heterogeneity in land quality/aquifer characteristics, risk preferences, energy cost considerations, nonlinear demand specifications, and private property regimes (Worthington, et al., 1985). Furthermore contemporary studies have refuted the Gisser-Sanchez effect, giving credence to the notion that economic efficiency in groundwater use can extend the overall life of the aquifer.

While water conservation is an important societal goal, achieving it is often very difficult. Policy instruments available for groundwater managers include taxing groundwater extraction or overall groundwater levels, subsidizing improvements in irrigation efficiency, tradable pumping permits, or voluntary agreements among stakeholders (Koundouri, 2004). All instruments have high monitoring and enforcement costs, and can vary in terms of overall effectiveness. The preferred approach for encouraging conservation might be direct taxation of extraction and/or the energy inputs required to pump water.

Ultimately, managing the extraction of groundwater can be cumbersome and costly, often requiring institutional reform, and improved information regarding the availability and cost-effectiveness of existing supplies. Also, such management regimes only alter the rate at which water is pumped out of the ground, and do not account for the impacts of agricultural chemical use on the quality of that water.

Managing Quality

Another portion of the groundwater literature deals with water quality impacts of agricultural input use. As agricultural chemicals leach into groundwater, water can become unsuitable for human consumption, and decrease the value of water as an agricultural input (Vickner, et al., 1998, Yadav, 1997). Pollutants in groundwater, especially those derived from agricultural sources, are non-point, making management difficult (Griffin and Bromley, 1982). Groundwater quality is also difficult to monitor and costly to improve; benefits of managing quality are often outweighed by costs of protection and/or improvement (Abdalla, 1994). Policy instruments are limited to reducing nitrogen loading by imposing a tax or input quotas on chemical application at the farm level.

There is a lengthy literature that discusses optimal management of non-point source pollution from farming activities (Griffin and Bromley, 1982, Hellegers, et al., 2001, Nolan, et al., 1988 , Rauscher, 2007, Vickner, et al., 1998, Wu, et al., 1994, Yadav, 1997, Zeitouni and Dinar, 1997). In particular, nitrate leaching has been the subject of such studies. Nitrates are the most pervasive nonpoint source pollutant, and high concentrations can degrade the productive value of groundwater, and can be hazardous to human health, leading to methemoglobinemia (blue baby syndrome) among other adverse health effects (Vrba, 2003). Many regions throughout the U.S. are considered “high risk” for nitrate contamination (Nolan, et al., 1988), and contemporary pressures on agricultural markets suggests that this trend will persist. With In regions where depletion is also a concern, water quality degradation could be exacerbated by a lower water table, as nitrate concentrations are less diluted.

Endogenous Quantity and Quality Management

Recent advances in groundwater modeling have incorporated endogenous quality management directly into a controlled groundwater system to simultaneously model extraction and quality dynamics, and to evaluate the interactions of quantity and quality management options. Hellegers, Zilberman, and Ierland, describe the dynamics of groundwater extraction with implications for nitrate accumulation in the water supply. This model is later corrected by Rauscher (Hellegers, et al., 2001, Rauscher, 2007). While this approach explicitly models the interactions of water extraction with groundwater quality, it considers constant chemical application rates with water extraction serving as the only choice variable in the model.

Roseta-Palma augments this model by allowing nitrogen fertilizer to be an explicit choice variable in the model. If one knows the value of damages caused by degraded groundwater quality, this approach allows for an efficient solution that mitigates against these damages. Additionally, this framework illustrates the importance of incorporating water quantity and quality management considerations. Roseta-Palma argues that independent management of quantity and quality are in fact special cases of joint quality-quantity management models.

Including GHG emissions

This analysis extends the Roseta-Palma framework by incorporating damages due to GHG emissions directly into the model; which is an important extension for a number of reasons. First, groundwater extraction requires an increased level of effort (energy) as the water table drops. As energy inputs rely on fossil fuels, the GHG emissions from water extraction are positive, and increasing monotonically with the amount of water extracted, and inversely to the water table. This implies increased damages for higher levels of irrigation, as well as higher GHG emissions over time as the water table declines. While this may seem insignificant at the farm level, aggregating total pumping emissions to a regional scale can be quite significant. Controlling the emissions from energy consumption for irrigation can slow down extraction rates and reduce stock/risk externalities.

While nitrogen fertilizer application can lead to excessive nitrate concentrations in groundwater, it also emits nitrous oxide into the atmosphere through soil volatilization and denitrification; N_2O has roughly 310 times the global warming potential of carbon dioxide (CO_2), meaning it is a very potent, and socially important GHG. Emissions of N_2O from fertilizer use and agricultural management in the U.S. account for approximately 270 Million T CO_2 Equivalent year^{-1}, which is roughly 4% of all U.S. emissions (Murray, et al., 2005). Nitrogen fertilizer application thus has the unique distinction of generating both a local and global pollutant simultaneously (Schneider and Kumar, 2008).

Incorporating GHG emissions will capitalize on the external damages caused by both water consumptive and quality degrading activities. While managing extraction or water quality in isolation may not imply a reduction in the other, targeting on-farm emissions can improve efficiency on both fronts.

IV. Theoretical Model

While managing common property resources such as groundwater can be difficult, managing agricultural GHG emissions and offset sources is also challenging, and brings a unique set of complications (Murray, et al., 2004, Murray, et al., 2005, Schneider and Kumar, 2008, Smith, et al., 2008). However, given the interactions of water management and GHG emissions, conjunctive management of the two can lead to potential welfare gains within a productive system. The proposed theoretical outline below, along with subsequent numerical illustrations, shows that managing groundwater consumption, quality, and GHG emissions in conjunction is possible. In fact, emissions abatement at the regional level can provide additional co-benefits to water resources and an alternative for managing water extraction and quality simultaneously.

First, consider dynamics of the aquifer itself. The stock of groundwater, denoted by S_t, follows a dynamic process that depends on the amount of water extracted (W_t), the rate of natural recharge from precipitation or surface water percolation (R_t), and the proportion of water extracted that returns to the aquifer (α):

(1) $$\dot{S} = R_t - \alpha W_t.$$

The stock of groundwater is a flow resource in which management decisions ultimately impact the relative level of decline in the water table. To put this equation of motion into a more economically relevant format, consider the dynamics of pumping lift, or the distance between the saturated zone of an aquifer, and the ground. Pumping lift is the vertical distance water needs to be extracted and is the main catalyst for determining pumping costs. This relationship is inversely proportional to the stock (water table). Equation 2 represents the dynamics of lift, L_t.

(2) $$\dot{L} = ((1-\alpha)W_t + R_t) / Area * Sp.Yield$$

Where: *Area* is the area of the aquifer, and *Sp. Yield* is the area specific yield, or proportion of extractable water per unit area.

In addition to the stock, the quality of the groundwater is subject to dynamic considerations. Following past modeling efforts, groundwater quality is proxied by the nitrate concentration of the aquifer (N_t^S). The concentration of nitrates in the aquifer will evolve over time according to the existing concentration (N_t^S) and the concentration of nitrates in the recharge (N_t^R). Typically, the percolation of nitrates into groundwater can vary depending on crop, topography, soil type, and climate, making nitrates difficult to model[2]. Allowing nitrate leaching to be some function of water extracted for irrigation and nitrogen fertilizer application ($N_t^R = N_t^R(W_t, n_t)$) allows for groundwater quality to be an endogenous variable in the control system. Nitrate concentrations also evolve over time through denitrification, a microbial process that breaks down nitrates into nitrous oxide (N_2O) and ultimately nitrogen gas (N_2) as part of the nitrogen cycle. However, the decay of nitrates in soils and groundwater due to denitrification is likely not large enough to counter-balance the nitrates leaching from fertilizer use (Liang and MacKenzie, 1994). For simplicity, the following generic functional form is used to describe the dynamics of nitrates in the groudnwater:

$$\dot{N}^S = l(N_t^R(W_t, n_t), N_t^S, S_t) \tag{3}$$

In essence, Equation 3 says that nitrate concentrations will evolve according to a process involving the nitrate concentration of recharge, the existing nitrate stock (subject to denitrification), and the supply of water itself. An excellent conceptual discussion of nitrate dynamics is provided by Hellegers et al (Hellegers, et al., 2001, Rauscher, 2007)[3]. Empirically, such dynamics have been evaluated in a number of studies using experimental data (Hanley, 1990, Martínez and Albiac, 2006, Nolan, et al., 1988 ,

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[3] The original formulation of Equation 2 in Hellegers, et al. was later corrected by Rauscher. The corrected version of this relationship is used here, as it has important implications for optimality conditions (Rauscher, M. "Dynamics of agricultural groundwater extraction: Comment and correction." *Ecological Economics* 61, no. 1(2007): 11-14.)

Vickner, et al., 1998, Yadav, 1997). Typically in these studies, econometric or simulation based procedures were used to estimate nitrate leaching functions, with parameters and functional forms varying across studies[4].

Equations 1 and 3 capture the basic structure of this dynamic system, and illustrate the point that groundwater depletion and quality interact such that the amount of water extracted will not only effect the level of water in the aquifer, but also the concentration of nitrates.

A third equation of motion in this model represents the change in the atmospheric GHG concentration due to production activities within this system. The contribution of emissions from regional activities increases monotonically with the amount of water and various agricultural inputs consumed. Let $G = g(W_t, n_t)$ be the total emissions caused by the choice of W_t and n_t. The function *g(.)* is increasing and convex in W_t and n_t such that $g'(W_t) > 0,\ g''(W_t) \geq 0$ and $g'(n_t) > 0,\ g''(n_t) \geq 0$.

(4) $$G\dot{H}G = g(W_t, n_t)$$

For simplicity, I assume a linear relationship between emissions, water extraction and nitrogen application:

(5) $$g(W_t, n_t) = \theta N_t + \phi(L_t * W_t)$$

Here, θ represents an emissions factor relating the amount nitrous oxide emitted per volumetric unit nitrogen fertilizer applied. A popular metric to represent θ is the IPCC default emissions factor. The emissions from water extraction take into consideration the current lift in the aquifer as well as the amount of water extracted, given

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[4] Estimated functional forms from these studies provide a convenient tool numerical simulation procedures, such as this analysis

the higher level of energy needed to extract water at greater depths. The parameter ϕ relates the amount of energy needed to pump water at a given rate and pump efficiency level, multiplied by the emissions factor per-unit energy consumed[5]. This parameter will vary by region or farm, given different pumping technologies, pumping efficiency, and choice of energy input.

Next, consider the regional production of some composite commodity y, which is dependent on the amount of irrigation water and fertilizer applied. The production of y takes the following form:

$$y = f(\alpha W_t, n_t) \tag{6}$$

Consistent with most agronomic relationships, the production of y is concave in W_t and n_t. Given this concavity, it is expected that there is an optimal water/fertilizer combination that maximizes production of y, and that a producer can trade between input levels of W_t and n_t depending on the relative marginal productivity, costs, and complimentarity of each. The price of the composite good (p_y) will define the relative marginal value product of each input.

Costs of extraction increase as the stock of the aquifer is depleted (or analogously, as lift increases). This relationship is decreasing and convex, such that $c'(L_t) < 0,\ c''(L_t) > 0$. Known as the stock effect, the cost implications of aquifer depletion are quite serious in areas with relatively low recharge potential (Provencher and Burt, 1993). In some cases, extraction costs are the most constraining element in the production system, often leading farmers to adopt more advanced technologies (Shah, et

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[5] Typically, groundwater pumping systems are fueled by grid electricity or natural gas. The choice of energy input will play an important role in the full GHG accounting of water extraction here, as natural gas is a far lower emitter of CO_2 than fossil-fuel derived electricity (CITE).

al., 1995). Pumping costs (Equation 7) are a function of water extracted, and the lift of the aquifer. The cost of energy input is denoted by P^e. The parameter ε represents the relationship between energy per unit water consumed, per foot of lift; this parametric representation of pumping costs is consistent across groundwater modeling studies.

$$PumpCost_t = \varepsilon P^e (W_t * Lift_t) \tag{7}$$

Damages from agricultural chemical application have been well documented. Nitrate accumulation in a groundwater setting is a local environmental damage, unlikely to significantly impact agents outside of the region considered. If the value of damages caused by nitrate concentrations is known, then an explicit damage function can be incorporated into the formal model.

Since GHGs are a global pollutant, the marginal damage function of GHG emissions is independent from damages caused by localized groundwater quality degradation and quantity depletion ($g(W_t, n_t)$). The value of GHG damages is p_c, which would be the per-Tonne social value of CO_2 (or equivalently, the unit value of CO_2/Carbon within a tax or cap-and-trade scheme). Thus, a social planner will maximize returns to production given marginal cost considerations for groundwater extraction, fertilizer application, and GHG emissions. Combining all variables and equations of motion, the Social Planner's welfare maximization problem (ignoring local environmental damages) is given by:

$$\max_{W_t, n_t} \int_o^\infty (p_y f(\alpha W_t, n_t) - p_c g(W_t, n_t) - c(S_t) W_t - c_n n_t) e^{-\delta t} dt \tag{8}$$

This maximization problem is subject to the equations of motion for the two state variables[6]. The implication is that a social planner will choose an optimal extraction rate of groundwater *and* fertilizer application that maximizes net returns to irrigated agricultural production while accounting for social costs of GHG emissions. This is relative to a common property extraction case where individuals will choose management intensity with little or no regard to environmental damages or the future in general. Expressing this problem in the current value Hamiltonian gives:

$$\begin{aligned} H &= p_y f(\alpha W_t, n_t) - p_c g(W_t, n_t) - c(S_t)W_t - c_n n_t \\ &+ \lambda_t (R - \alpha W_t) + \mu_t (l(N_t^R (W_t, n_t), N_t^S, S_t)) \end{aligned} \tag{9}$$

The variables λ_t and δ_t represent the current value shadow prices (co-state variables) associated with the quantity and quality of the resource over time. The following conditions guide optimal dynamic consumption and pollution of the groundwater stock:

$$\frac{\partial H}{\partial W_t} \Rightarrow p_y f'(\alpha W_t) = \frac{c(S_t) + p_c g'(W_t)}{\alpha} - \lambda_t + \mu_t \left(\frac{\partial l(\cdot)}{\partial N_t^R} \frac{\partial N_t^R}{\partial W_t} \right) \tag{10}$$

$$\frac{\partial H}{\partial n_t} \Rightarrow p_y f'(n_t) = c_n + p_c g'(n_t) + \mu_t \left(\frac{\partial l(\cdot)}{\partial N_t^R} \frac{\partial N_t^R}{\partial n_t} \right) \tag{11}$$

$$\dot{\lambda} = \delta \lambda_t + c'(S_t) W_t + \mu_t \left(\frac{\partial l(\cdot)}{\partial S_t} \right) \tag{12}$$

$$\dot{\mu} = \delta \mu_t + \mu_t \left(\frac{\partial l(\cdot)}{\partial N_t^S} \right) \tag{13}$$

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[6] While the GHG flux from farming activity was denoted by an equation of motion, it is not a constraining element in the system, and therefore does not enter the objective functional.

Equation 10 represents the standard equilibrium of marginal benefits accrued from extraction, the marginal costs of extraction and the marginal user cost of groundwater (λ_t), with three additional terms reflecting the costs per-unit extraction over time, and the marginal cost of nitrate concentration in the aquifer. The term $p_c g'(W_t)$ represents the marginal GHG implications of additional water use. Similarly, Equation 11 equates the marginal value of nitrogen productivity with the private and social costs of additional application. Equations 12 and 12 represent the rate of change in the marginal value of the groundwater stock and nitrate concentration over time, respectively.

Notice that for each state variable the steady state conditions will depend on the chosen value of the other. This suggests that policy efforts to manage water quality or quantity independently will not imply the socially optimal solution for the other. Indeed, this result has been illustrated numerically in previous studies (Roseta-Palma, 2002, Roseta-Palma, 2003). Additionally, this model has the added benefit of capturing the social costs of GHG emissions within this system. When GHG emissions are incorporated as a source of damages, the socially optimal choice of W_t and n_t will depend on the GHG intensity of each activity on the margin.

Numerical Example:

To illustrate the dynamics of this system and the water resource implications of regional GHG management, numerical analysis is applied using existing functional parameters taken from the literature. Here, simulation is used to illustrate the dynamics of GHG emissions resulting from unregulated agricultural production within the system.

Production (*f()*) and nitrate leaching (*n()*) functions are borrowed from Larson et al 1996, as displayed in Table 2 (Larson, et al., 1996)[7]. Both functions take a quadratic form. Water and nitrogen are strategic compliments in this system, so efforts to manage one will reduce use of the other. The rate of nitrate decay within the aquifer is set to 0.2, consistent with other past modeling efforts (Yadav, 1997). GHG emissions for nitrogen fertilizer application and energy use for groundwater pumping are adopted from IPCC default values for electricity and nitrogen fertilizer, respectively.

Table 2: Production and Nitrate Leaching Functions (Larson, et al., 1996)

Variable	**Parameter Values**	
	Production Function	**Nitrate Leaching Function**
Constant	2.52	-26.06
N_t	5.35*10^-5	-0.152
W_t	1.51*10^-4	0.158
N_t* N_t	5.38*10^-7	3.63*10^-4
N_t* W_t	-2.0*10^-7	0
W_t* W_t	-8.85*10^-8	0

Other parameters representing exogenous economic variables and hydrologic characteristics come from various sources, or are arbitrarily assigned (within the bounds of realistic expectations). We begin with the aquifer in pristine condition, at an initial lift of one meter, and a nitrate concentration of zero. This of course can be varied for purposes of sensitivity analysis; initial aquifer conditions and historic trends in agricultural management intensity will dictate the level of emissions within the system. Values for this setting are assigned purely for illustrative purposes. Future work will focus on incorporating this methodology into a larger system with heterogeneous hydro-economic characteristics.

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[7] There are few papers that have estimated production and nitrate leaching parameters within the same groundwater system. The same parameters are used in the Roseta-Palma, 2006 study.

Table 3: Other Model Parameters

Variable	Value
P_y ($/Ton)	500
Pump Cost ($/mm-ha/m)	0.003
Initial Lift	1
P_n ($/kg)	0.4
Land (Ha)	1,000
Alpha (irrigation return proportion)	0.1
Natural Recharge (m^3)	55,000
θ (kg N_2O- IPCC Emissions Default Factor for Nitrogen Fertilizer)	0.000125
Aquifer Area	10,000,000
Specific Yield	0.10
Delta (decay rate of nitrates)	0.2
Discount Rate	0.04
ϕ CO_2 emission factor (T/KwH)	0.001225

The system is simulated over a period of 50 years, holding prices and productivity constant. Similar simulation techniques have been applied across numerous groundwater management studies.

Results

The following figures represent groundwater extraction, nitrogen use, and GHG emissions, respectively for the groundwater system. Beginning with the optimal control solution in the absence of GHG pricing, the optimal values of water and nitrate leaching are solved for endogenously; both decrease over time due to decreased returns to production, higher extraction costs, and lower levels of nitrate leaching[8]. However, due to higher levels of lift, the net emissions from production also increase over time. For policy comparison, both CO_2 and non-CO_2 emissions are priced. As emitting activities are priced in the model at higher rates, there is a monotonic decrease in input use and nitrate accumulation, consistent with expectations. This trend is expected given the linear

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[8] The common property extraction case is not solved for in this analysis.

relationship between the GHG damage function and input use. Since water and nitrogen are strategic compliments for this specification, there is little trade-off among input use.

Figure 1: Water Extraction across Scenarios

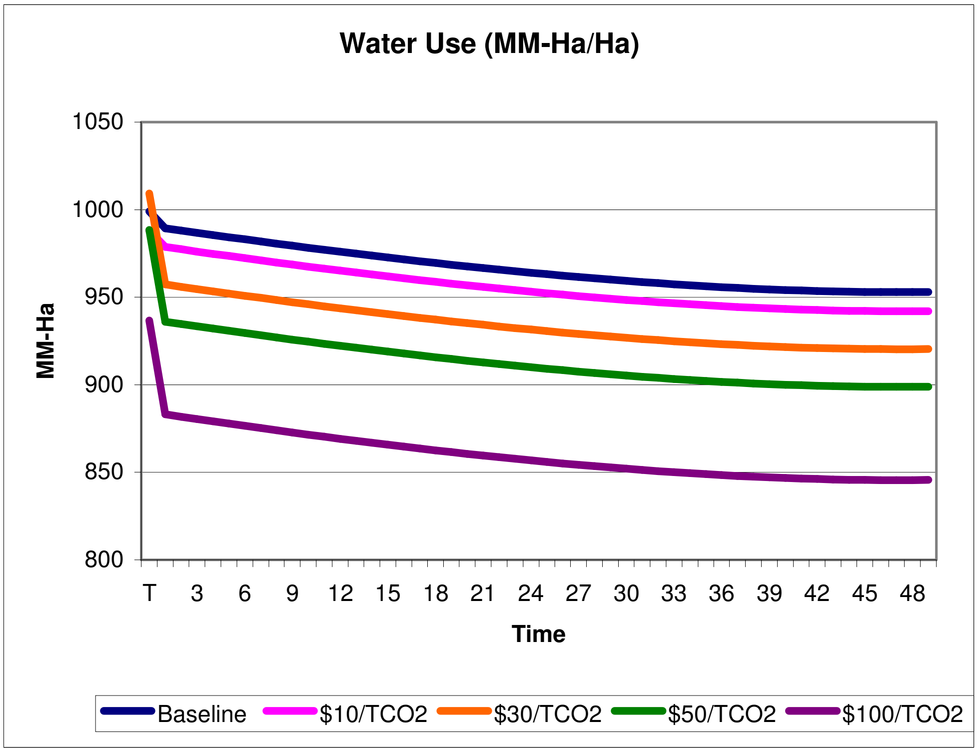


Figure 2: Nitrate Leaching across Scenarios

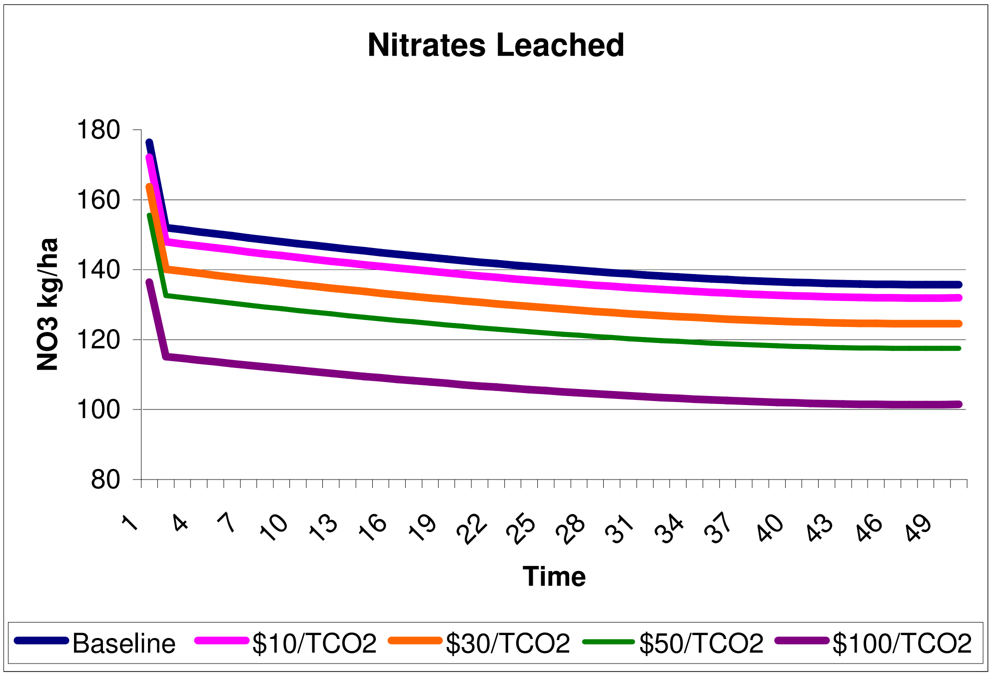
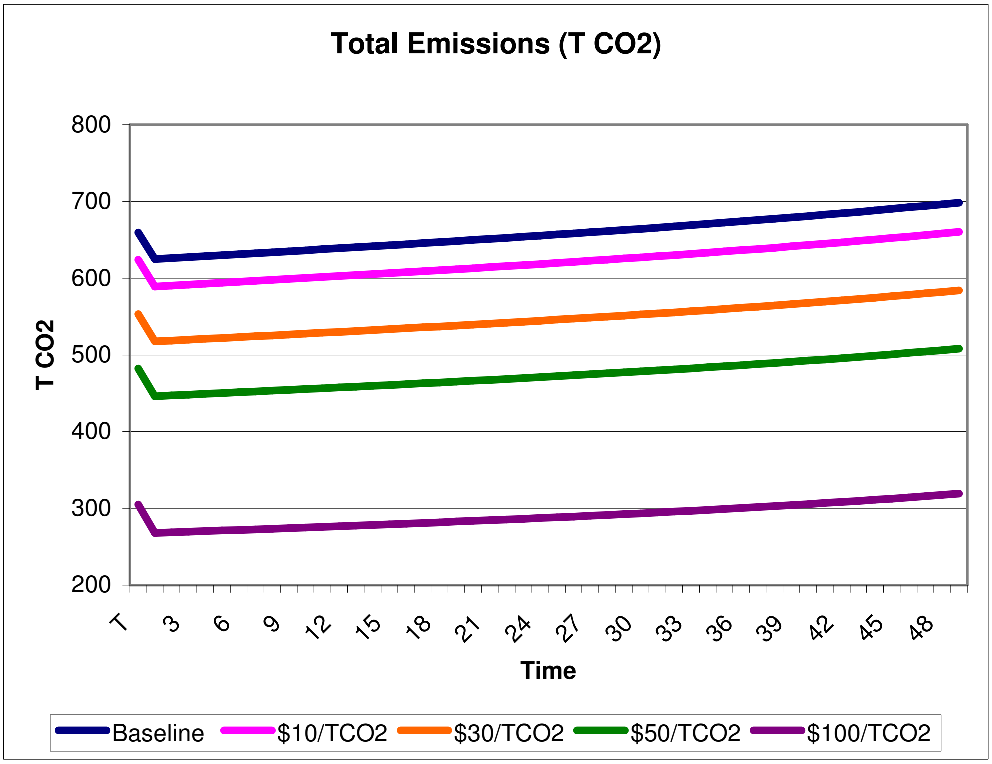


Figure 3: Total Emissions across Scenarios



Total GHG emissions from the system, displayed in Figure 3 continue to rise over time as the water table drops and increased energy is consumed to pump water, consistent with expectations. As emissions are priced at higher rates, there is a monotonic drop in aggregate emissions across sources, similar to the change in water and nitrogen use. Table 4 summarizes these results. Net changes in water use, emissions, and nitrates are summed over the entire 50 year horizon and 1,000 Ha plot. These changes appear small for the first two carbon pricing scenarios, but increase greatly in significance. At $100/T CO_2, the total water savings average 106 Ha-Meter/year, with an annual reduction in nitrate leaching of approximately 34 Tonne/year. Also, at $100/T CO_2 annual water use and nitrate leaching fall 11% and 24%, respectively.

Perhaps more significant is the net change in emissions. For the $10/T CO_2 scenario, total emissions fall 6% relative to the baseline case, and rises to approximately 39% at $100/T CO_2. To compare the mutual water and GHG gains within this system, the bottom rows present a "benefit ratio" of GHG to water quantity/quality benefits. This is a useful metric in measuring the co-benefits of GHG policy on water resources.

Table 4: Simulation Results

	$10/T$CO_2$	**$30/T$CO_2$**	**$50/T$CO_2$**	**$100/T$CO_2$**
Change in Total Water Use (Ha-Meter)	541.90	1578.18	2,650.90	5,308.45
Change in Total Nitrates Leached (Tonnes)	195.83	574.49	936.08	1,767.25
Change in GHG Emissions (T CO_2 Eq.)	1,848.07	5,538.61	9,221.71	18,397.52
T CO_2 Eq./Ha-Meter Water	3.41	3.51	3.48	3.47
TCO2 Eq./Tonne NO3	9.44	9.64	9.85	10.41

This simulation helps to illustrate GHG emissions due to irrigated agricultural production within an isolated system, and the various interactions of extraction, water quality, and GHG emissions. Pricing GHG emissions within the system offers a policy alternative to independent or conjunctive quantity and quality management by internalizing the contribution of each activity to aggregate emissions. Since groundwater extraction and nitrogen application are both highly emitting activities, targeting emissions reduction will benefit management of long-term water consumption and quality.

Groundwater Management under Exogenous Climate Mitigation Incentives

In reality, however, managing GHG emissions from local production systems is not a likely scenario. As discussed in previous sections, national GHG mitigation incentives can stimulate agricultural markets and drive up the cost of energy inputs. Such effects can have residual impacts on regional water resource systems. Understanding these indirect impacts is difficult, as the connections of climate policy, agricultural commodity markets, and energy resources are not well understood at this time. Since no precedent exists for scenario analysis, the previous modeling framework is augmented to illustrate a set of conditions for which groundwater will benefit under exogenous policy drivers, or alternatively conditions when co-costs are expected.

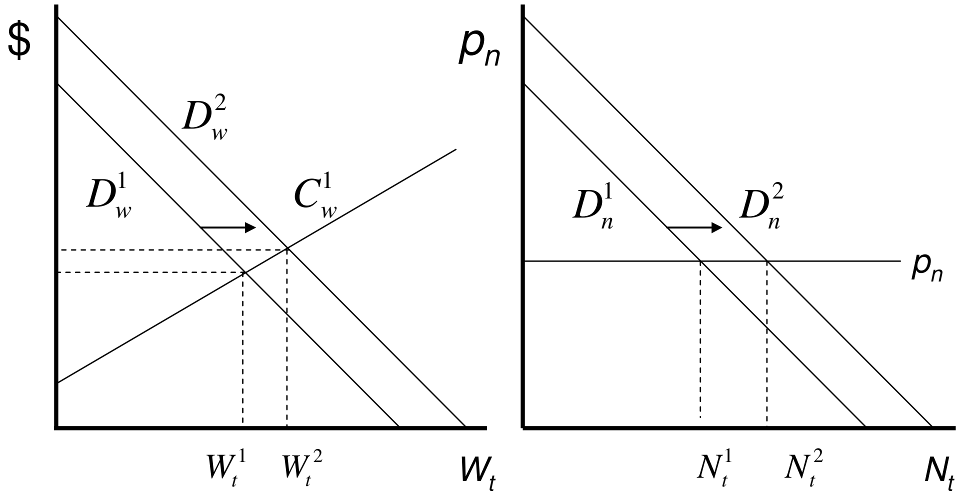
The previous control model is extended to include the implicit marginal impacts of exogenous climate policy mechanisms on the benefit and cost arguments of the system, and the alternative to produce conventional crops, bioenergy, or idle land for sequestration purposes. Simply put, policy mechanisms can shock the agricultural sector as a whole through commodity markets, where prices increase, and through input markets, where the costs of energy and fertilizer increase. The following framework attempts to address these relationships explicitly.

Policy Option 1: Bioenergy Mandates

Following the announcement of the Energy Independence and Security Act of 2007 which imposed stringent mandatory increases in biofuel production over time, commodity prices soared, giving rise to the concerns that bioenergy mandates stimulate agricultural commodity prices (World Bank, 2009). While prices have stabilized somewhat, the implication is that federal policies can have resounding impacts on markets as a whole, which ultimately changes the land management decision. The concern now is that long-term upward trends on prices, and short-lived volatility increases in water use and chemical application can damage groundwater supplies irreparably.

To visualize the implications that biofuel mandates will have on water resources, consider Figure 4. Here, the graph on the left-hand side of the figure represents derived demand and marginal extraction costs of groundwater. The right-hand side shows the derived demand for nitrogen fertilizer, available at some constant cost p_n. Shifts in derived demand are a function of higher commodity prices present under the new policy regimes (Just, et al., 2004). Consistent with expectations and concerns echoed in recent literature, mandatory bioenergy production exogenously shifts the derived demand for irrigation water and nitrogen fertilizer by indirectly raising commodity prices. This leads to unequivocal increases in groundwater extraction and fertilizer application rates. The implication is that bioenergy production does not have to exist within the groundwater production system to exacerbate consumption and quality degradation. This is an important result, because regional groundwater managers do not have the option of choosing a level of mitigation that balances the carbon benefits of bioenergy production with the co-costs imposed on regional water resources.

Figure 4: Effects of Bioenergy Incentives on Groundwater



Ignoring momentarily the scenario that only food/fiber crop production can occur within the system, consider a region that has the capacity to grow feedstock for biofuel production. Assume that production of y can be dedicated to food or bioenergy. When dedicated to food, there is a positive contribution to the atmospheric GHG stock, as with the previous framework, only now a unit of bioenergy production represents an emissions reduction, as the energy can be used to offset highly emitting fossil fuel equivalents. A new parameter θ is introduced which captures the per unit GHG emission reduction from a unit of bioenergy.

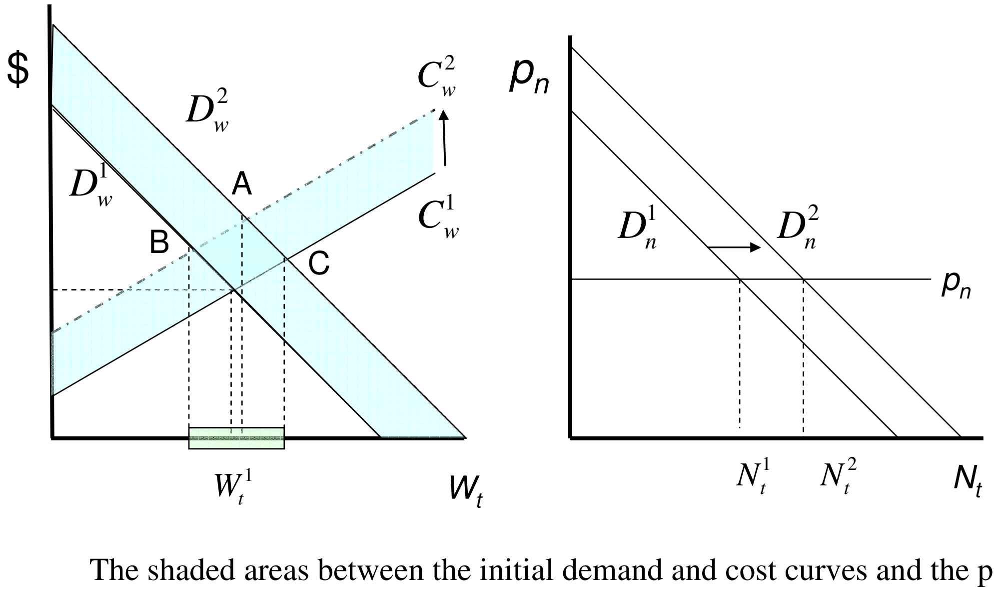
Additionally, the parameter γ_t represents the proportion of output allocated to bioenergy production in the region (assuming the necessary infrastructure exists within the region). Given the substantial increases in biomass needed to satisfy the Renewable

Fuels Standard by 2022, it is safe to assume that a significant portion of land in most productive regions will be allocated to cultivation of biomass for energy.

Policy Option 2: Bioenergy and CO_2 Emissions (All Sources)

Now consider a situation similar to the current policy climate in which an existing bioenergy mandate is in place, and climate policy measures that directly target CO_2 emissions are a distinct possibility. If comprehensive climate policy is passed, the production system could be affected in a number of ways, including increased extraction costs. Previously, extraction costs were not affected by the exogenous policy shock, but here it is assumed that any comprehensive climate policy will have residual impacts on fossil-fuel derived inputs, shifting the marginal extraction costs of groundwater. Additionally, inclusion of agricultural-based offset schemes and pressure on bioenergy markets raises commodity prices, therefore shifting the derived demand for water much like the previous case. Figure 5 displays this scenario:

Figure 5: Effects of Bioenergy and CO_2 Mitigation Incentives on Groundwater

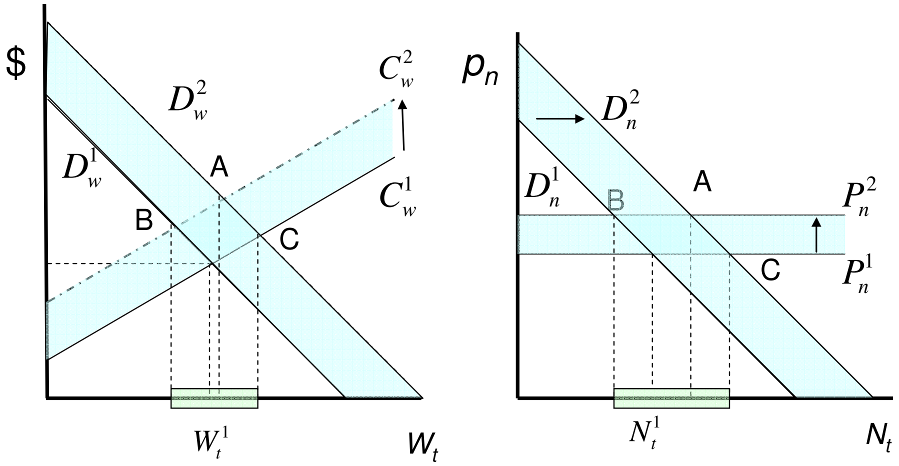


The shaded areas between the initial demand and cost curves and the potential shifts located at D_W^2 and C_W^2 denote a region of uncertainty, in which the total effect of the exogenous policy shifter is unknown. While we can be confident in the direction of these exogenous shifts, the relative magnitudes remain unclear. Consider the case outlined above. If this scenario holds, and D_W^2 and C_W^2 are the new arguments in the system, then an overall increase in groundwater extraction is expected from W_t^1 to A. However, if the exogenous shift in the derived demand is smaller in magnitude, then the cost effect would dominate, and overall extraction will decrease. The theoretical bounds of uncertainty for this system exist at B and C, where the price and cost effects, respectively, fully dominate the other. While not conceptually modeled here, a production system in which water and nitrogen are strategic substitutes might experience higher nitrate leaching in this scenario as landowners adapt production decisions accordingly for the higher extraction cost regime.

Policy Option 3: Bioenergy and all GHG Emissions

Extending the previous policy instrument to target all sources of GHG emissions, (CO_2 and non-CO_2) Figure 6 outlines potential water resource implications. Following the previous section, there is a region of policy uncertainty surrounding the sign and magnitude of water extraction implications. However, since non-CO_2 emissions are directly targeted by the policy, the unit-cost of nitrogen fertilizer increases to some new hypothetical level P_N^2. This creates a region of policy uncertainty for water quality, in addition to the uncertainty surrounding the net change in extraction. The implication is that water quality and quantity co-effects remain uncertain. Depending on the full price and cost argument effects of the exogenous policy shock, groundwater supplies could benefit or not. The following section attempts to include these exogenous impacts into a unified conceptual framework.

Figure 5: Effects of Bioenergy, CO$_2$, and non-CO$_2$ Mitigation Incentives on Groundwater



Augmented Theoretical Model

The previous section diagrammatically illustrated the potential benefits/costs of climate mitigation on groundwater systems. Using the fully integrated policy option (bioenergy plus all sources of emissions), the initial theoretical framework developed is expanded to illustrate the conditions under which exogenous mitigation efforts indirectly benefit/cost the regional groundwater system. If hydrologic and economic relationships are known for a productive groundwater system, numerical sensitivity analysis can be performed to assess long term water implications across a range of potential outcomes.

In addition to the new parameters for bioenergy production, soil sequestration incentives could play a role here. A new variable (*cs*) is added that refers to the soil sequestration potential of land within the regional system. Soil carbon offsets have been discussed in a number of past studies, and continue to play an important role in climate policy discussions. While soil carbon accumulation will naturally follow a logistical growth pattern before reaching a saturation point we assume constant accumulation (*cs*).

An additional parameter τ_t represents the proportion of land in production ((1-τ_t)*L is set-aside for carbon sequestration purposes). Letting L represent the amount of land available for production or sequestration in the system, the augmented Social Planner’s Problem becomes:

$$(14)\qquad \max_{W_t,n_t,\tau_t} \int_o^{\infty} \left[\begin{array}{l} \tau_t \cdot L \cdot \left[\begin{array}{l} (p_y(\gamma_t, p_c) f(\alpha W_t, n_t) + \\ \gamma_t \cdot \theta \cdot p_c \cdot f(\alpha W_t, n_t) \\ -c(S_t, p_c) W_t) - c_n(p_c) n_t \end{array} \right] \\ + \left[(1-\tau_t) L \cdot cs \cdot p_c \right] - p_c g(W_t, n_t) \end{array} \right] e^{-\delta t} dt$$

Expressed as the current value Hamiltonian:

$$(15)\qquad \begin{array}{l} H = \tau_t \cdot L \cdot \left[\begin{array}{l} (p_y(p_c) f(\alpha W_t, n_t) + \gamma_t \theta p_c f(\alpha W_t, n_t) \\ -c(S_t, p_c) W_t) - c_n(p_c) n_t - p_c g(W_t, n_t) \end{array} \right] \\ \\ \quad + \left[(1-\tau_t) L \cdot cs \cdot p_c \right] + \lambda_t (R - \alpha W_t) - \\ \quad \mu_t l(N_t^R(W_t, n_t), N_t^S, S_t) \end{array}$$

While the model appears to have increased in complexity a great deal, the implications are straight forward. As previously mentioned, the parameter γ_t can be taken as a given exogenous value. In simulation, this proportion can be varied over time for sensitivity analyses.

Before discussing the first order conditions of the system, notice that the benefit and cost arguments are now functions of the carbon price and bioenergy mandate, reflecting the reality that pricing GHG emissions has the potential to impact agricultural commodity markets and for reasons previously discussed. In addition, input costs as energy and fertilizer application become more expensive. Thus, the following expression holds:

(15.a)
$$\frac{\partial p_y(\cdot)}{\partial p_c} > 0$$

Consistent with the diagrams above, the presence of agricultural GHG mitigation will boost commodity prices and producer's surplus. This price effect will be the impetus shifting derived demand as illustrated above. All energy intensive forms of production are expected to incur higher costs as well.

(15.b)
$$\frac{\partial c_w(\cdot)}{\partial p_c} > 0$$

(15.c)
$$\frac{\partial c_n(\cdot)}{\partial p_c} > 0$$

Processing nitrogen fertilizer will become more expensive, and incentives to mitigate non-CO_2 emissions will likely increase this marginal effect. The net implications of conditions 15.a-15.c are ostensible. If the system is operating at optimality prior to any exogenous GHG policy, then the net impact on water resources will be contingent on the following conditions:

(15.d)
$$\frac{\partial p_y(\cdot)}{\partial p_c} > \frac{\partial c_w(\cdot)}{\partial p_c} + \frac{\partial c_n(\cdot)}{\partial p_c}$$

If 15.d holds, then instantaneous benefits to the exogenous policy stimulus will outweigh the marginal cost increases. Here, producers would increase W_t and n_t. Thus, the implied impact on the aquifer is more rapid depletion and degraded quality. The extent of these damages will depend on the production function relationships between W_t and n_t and the relative cost increases for the exogenous stimulus. If W_t and n_t are technical substitutes and the cost increase is relatively larger for one input, then use of the alternative will increase at a higher proportion. As an example, consider a case where non-CO$_2$ emissions are targeted such that $\frac{\partial c_w(\cdot)}{\partial p_c} < \frac{\partial c_n(\cdot)}{\partial p_c}$. If substitution possibilities exist among inputs, then extraction would actually increase, even as extraction costs rise.

If the inequality in 15.d were reversed, then the groundwater stock could benefit while quality takes a hit. This net benefit is again contingent on the production function relationship and marginal cost implications for groundwater extraction and fertilizer application, respectively.

Returning to the previous model (Equation 15), if an exogenous policy is implemented that supports conservation programs for soil sequestration purposes, then τ_t is solved for in the following manner: A groundwater manager can choose to idle a proportion of land in production (*L*) for sequestration purposes, and receive compensation equal to the marginal value of carbon accumulation for the land parcel ($cs \cdot p_c$). Beginning with the choice of τ_t, the initial first order condition of the system is:

(16) $$\frac{\partial H}{\partial \tau_t} \Rightarrow \begin{bmatrix} (p_y(\gamma_t, p_c) f(\alpha W_t, n_t) + \gamma_t \theta p_c f(\alpha W_t, n_t) \\ -c(S_t, p_c)W_t) - c_n(p_c)n_t - p_c g(W_t, n_t) \end{bmatrix} = cs \cdot p_c$$

Equation (16) implies that the choice of τ_t will equate the net marginal benefits of production in the system to the marginal benefit of soil sequestration. In this system, production qualities are homogeneous, which implies that τ_t will take a value of 0 or 1 at optimality. It is easy to extend this analysis to incorporate a distribution of land qualities and sequestration potential. Additionally, partial equilibrium modeling efforts have included reduced or no-till management options. The implications remain the same; within a regional groundwater system with heterogeneous land quality, lands with marginal production potential could benefit from accepting a payment for carbon sequestration. The residual benefit is that as τ_t increases, regional water quality improves and extraction rates are lowered. In terms of water conservation efforts, this is an important result. If local water conservation efforts fail, perhaps coupling water conservation programs with carbon sequestration payments can promote benefits to both.

The standard equilibrium of benefits and costs in the system now becomes:

$$\frac{\partial H}{\partial W_t} \Rightarrow p_y(\cdot)f'(\alpha W_t) = \frac{c(S_t) + \gamma_t \theta p_c f'(W_t)}{\alpha} - \lambda_t + \mu_t \left(\frac{\partial l(\cdot)}{\partial N_t^R} \frac{\partial N_t^R}{\partial W_t} \right) - p_c g'(W_t) \tag{16}$$

This condition has strong policy implications. First, all benefits and costs in the system are evaluated, including the carbon cost of production activities. In terms of mandatory bioenergy production, the marginal implications of increasing the proportion of land allocated to bioenergy production are found by differentiating (17) with respect to γ_t:

$$\frac{\partial^2 H}{\partial W_t \partial \gamma_t} = p'(\gamma_t) = \theta p_c f'(W_t) \tag{17}$$

The left hand side represents the instantaneous price increase (or marginal benefit) for allocating additional land to bioenergy on the margin. For the model to achieve a steady-state, this increase should equate to the value of replacing GHG intensive production from food crops with GHG offsetting biofuels. If not, then increased use of W_t and n_t. The equi-marginal specification for chemical application now becomes:

$$\frac{\partial H}{\partial n_t} \Rightarrow p_y(\gamma_t)f'(n_t) = \theta \gamma_t p_c f'(n_t) + \mu_t \left(\frac{\partial l(\cdot)}{\partial N_t^R} \frac{\partial N_t^R}{\partial W_t} \right) \tag{18}$$

Here, the marginal implications of γ_t on nitrogen application are the same as in (17). The marginal values of the state variables are subject to the same dynamic relationships as in the prior model, given by equations 8 and 9.

Summary

The framework presented above presents an initial attempt to model the net effects of national GHG policy stimuli on regional groundwater resources; both extraction and quality can be impacted through such efforts as commodity and energy input prices are driven by the policy mechanism. Two sources of uncertainty arise in this scenario that will ultimately dictate the direction and magnitude of the regional water consumption/quality implication. The first source is policy uncertainty. As mentioned previously, the overall scope of the GHG mitigation policy considered will dictate the amount of additional pressure placed on the agricultural sector to provide a source of mitigation. The second source of uncertainty lies in the magnitude of the exogenous policy stimuli. While theory gives us a good indication of the direction of policy effects, the magnitude remains uncertain; depending on the full price and cost effects, co-benefits or co-costs on groundwater systems are possible. Table 5 summarizes the potential impact, contingent on the magnitude of marginal cost or price effects of the policy.

Table 5: Environmental Responses to Exogenous Climate Policy

Climate Policy Scope	**Groundwater Extraction**		**Nitrate Leaching**	
	Decrease	**Increase**	**Decrease**	**Increase**
Bioenergy Only	No	Yes	No	Yes
Bioenergy and CO2 only	If Cost Effect Dominates	If Price Effect Dominates	No	Yes
Bioenergy and non-CO2 only	No	Yes	Yes	No
Bioenergy and all GHGs	If Cost Effect Dominates	If Price Effect Dominates	If Cost Effect Dominates	If Price Effect Dominates

It's easy to see that bioenergy expansion, although able to reduce damages from GHG emissions, can have adverse implications on water quantity and quality. Higher revenues from crop production and no marginal cost impacts indicate that landowners will increase both irrigation rates and fertilizer application rates in the immediate term under common property. The remaining scenarios can either benefit or cost groundwater, depending on the marginal price and cost effects of the exogenous policy stimuli. Taken as a whole, this modeling framework shows that exogenous climate policy mechanisms can generate co-benefits or costs to a regional groundwater production system. Due to the interdependencies of water, energy, and commodity markets, policy makers should be cognizant of these policy driven impacts. Further analysis is needed to determine the full-extent of climate policy scenarios on agricultural commodity prices and input costs.

V. Conclusions

This paper makes an initial attempt to conceptually model the interactions of climate policy and groundwater management. Several observations are made. First, given the GHG intensity of water extraction and nitrogen fertilizer application, a regional optimal control approach that endogenously solves for regional GHG abatement will have the added benefit of reducing extraction rates and improving water quality. While water savings and GHG benefits are not large at the farm level, when aggregated to a much larger region they can be quite significant. An important implication of this result is that any policy effort at the local level to reduce groundwater extraction, or improve water quality through decreased management intensity will directly reduce on-farm GHG emissions. This implies that any policy effort to improve water management or reduce GHG emissions independently will directly benefit the other initiative, ultimately bringing the system closer to true social efficiency. Likewise, managing GHG emissions from CO_2 and non-CO_2 emissions at the regional level offers an alternative to independent quantity/quality management. Managing extraction or quality independently may not imply an efficiency improvement in the other, but managing GHG emissions offers a convenient tool that effects both extraction and fertilizer costs.

However, given the broad nature of GHG mitigation policy, any mechanism designed to reduce GHG emissions through agricultural activities will most likely be set exogenously to the regional groundwater/productive system. The prior model is extended to show that 1) depending on the policy mechanism chosen, exogenous GHG mitigation incentives can benefit or cost regional groundwater systems, and 2) when management intensity, carbon sequestration, non-CO_2 emissions, and bioenergy are all included in the exogenous mitigation portfolio, climate mitigation can have ambiguous, unintended effects on water resources.

Understanding these consequences is important for effective GHG mitigation policy and regional water management. Future work is needed to identify policy combinations to help regional groundwater managers adapt conservation and quality protection measures in the face of indirect market pressures. Policies that improve overall efficiency in groundwater and agricultural input use and improve GHG abatement at the production level are needed. Water management and GHG mitigation are two important societal goals that are inextricably linked. This paper addresses one of those linkages that will become increasingly important in the coming years- groundwater management under agricultural GHG mitigation incentives.

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