Tradeoffs among multiple ecosystem services and economic returns from groundwater depletion on a farm landscape

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Selected Paper prepared for presentation at the 2016 Agricultural & Applied Economics Association Annual Meeting, Boston, Massachusetts, July 31-August 2

Abstract

Groundwater overdraft has long-run consequences for the crops grown, the economic viability of the agricultural community, and the ecosystem services from the landscape. We investigate how groundwater scarcity affects the tradeoff of economic returns and ecosystem services (namely, groundwater supply, surface water quality, and greenhouse gas (GHG) reductions) in the Mississippi Delta farm production region of Arkansas, USA. As groundwater is more depleted, farmers are turning to conjunctive water management with on-farm reservoirs and tail water recovery. Distinct objectives either for economic returns and for ecosystem service guide whether on-farm reservoirs are built amidst a backdrop of cropping and irrigation decisions. Reservoirs enable the landscape to sustain a higher level of economic returns and ecosystem services. This is done through a synergy of economic returns, groundwater conservation, and GHG reductions that lowers irrigation costs and reduces the fuel combustion and associated GHGs from groundwater pumping.

Keywords: Ecosystem services, Conjunctive water management, Spatial-dynamic optimization
JEL classification: Q15, Q24, Q25, Q28

Introduction

Overdraft of groundwater in farming regions increases the cost of groundwater pumping, and this may change irrigation from sole reliance on groundwater toward the use of surface water, known as conjunctive water management. Although the economic and institutional aspects of conjunctive water management are well studied (Blomquist et al. 2001; Kovacs et al. 2015; Noel et al. 1980), the effect of this irrigation management on multiple ecosystem services (in particular, groundwater supply, surface water purification, and greenhouse gas (GHG) reduction) has received less attention. Conjunctive water management affects the aquifer volume, which in turn affects the crops grown, and the cropping decisions influence nutrient and sediment runoff and GHG emissions. This paper investigates whether economic returns and ecosystem services both rise with the use of conjunctive water management and tradeoff between economic and ecosystem service objectives.

One approach for conjunctive water management is through on-farm reservoirs that store surface water abundant in the off-season and a tail-water recovery system that returns runoff leaving the field to the reservoir. Tail-water recovery can enhance surface water quality by reducing the sediment and nutrient rich tail-water leaving the farm (Popp et al., 2003). However, the influence of the reservoirs and tail-water recovery on a suite of ecosystem services is uncertain. Groundwater use and agricultural runoff may decline with reservoirs, but the release of methane from more rice production may destabilize the climate. Greater economic returns from reservoirs and tail-water recovery are not guaranteed because, although surface water is less expensive to pump than groundwater, the reservoirs and tail-water recovery systems occupy productive land and have construction and maintenance costs.

The farming region of the Lower Mississippi River Basin in Arkansas (referred to as the Arkansas Delta) has long relied on groundwater from the Mississippi River Valley Alluvial Aquifer. Projections by the Arkansas Water Plan indicate that by 2050, agricultural demand for groundwater will outpace available supplies by 7 million acre-feet per year (ANRC, 2015). We model spatially explicit farm returns across a dynamic landscape by varying the extensive crop margin (i.e. shift from irrigation intensive crops such as rice to non-irrigated crops like wheat) and the irrigation water source (i.e. reservoir or well). The use of deficit irrigation (i.e. reducing the irrigation water applied to the crop) in response to groundwater scarcity, although plausible, does not appear to be common in practice (Wang and Segarra 2011). As groundwater pumping costs rise, reservoirs with tail-water recovery systems are built to supplement the groundwater.

We model groundwater supply, surface water purification, and GHG emissions in response to landscape level farm production decisions. Groundwater flows in response to the aquifer's saturated thickness, hydro-conductivity, and distance to surrounding wells. The surface water purification depends principally on the land gradient and the tillage and irrigation practices that affect soil and phosphorous runoff to waterbodies. The GHG emissions depend on the soil type, fuel combustion from irrigation pumping, and other farm practices. Social prices for the ecosystem services give the change in the ecosystem services a monetary value for comparison with economic returns.

We combine the economic and ecosystem service models to search for efficient crop and irrigation method allocations. An efficient allocation is one that generates the maximum economic returns for a given value of the ecosystem service(s) provided. By maximizing the economic returns over the entire range of possible ecosystem service values we trace out the efficiency frontier for the landscape, which demonstrates the degree of inefficiency of other crop and irrigation method allocations not on the frontier. The slope of the frontier indicates the opportunity cost in terms of ecosystem value necessary to achieve greater economic returns. Frontiers are made without and with conjunctive water management to examine whether the reservoirs increase efficiency.

Kovacs et al. (2014) find reservoirs increase economic returns, groundwater supply, and water purification, but there is no examination of whether these gains come at the expense of climatic stability. Most prior work looking at the spatial pattern of ecosystem services describes the spatial correlation given the current pattern of land use (e.g., Chan et al. 2006; Egoh et al. 2009; Raudsepp-Hearn et al. 2010). For example, intensive agricultural production is associated with high production of agricultural products but low water quality and carbon storage; while, on the other end of the spectrum, conserved forested areas often have high carbon storage, habitat, and recreation value, but low commercial returns. The closest prior papers looking at ecosystem service tradeoffs with agricultural economic returns are Nelson et al. (2009) and Polasky et al. (2011), but neither of the papers uses efficiency frontiers or optimization. Nelson et al. (2008) use efficiency frontiers to examine the tradeoff between carbon sequestration and species conservation, but not economic returns, while Polasky et al. (2008) examine the tradeoff between economic returns and species conservation, but not ecosystem services. White et al. (2012) more recently use efficiency frontiers to inform marine spatial planning with multiple ecosystem services. None of these papers addresses groundwater supply as an ecosystem service or evaluate how conjunctive water management influences crop and irrigation method patterns.

The model of the dynamics of land and irrigation faced by the profit maximizing producers are described first. Second, the models of groundwater supply, water quality, and GHG emissions for the ecosystem service maximizing social planner are presented. The data for the models are described next followed by the results and a discussion of their implications.

Methods

The agricultural land covers are the primary input to the economic and ecosystem service models. Crops generate economic returns when sold in markets. Also, the crops affect ecosystem services because irrigation can deplete groundwater, agricultural runoff pollutes surface water, and farm production activities release GHGs. Our area of study has multiple types of agricultural land cover due to spatial differences in water resources, soil types, and historical investment in particular farm practices. A grid of m cells (sites) is chosen to represent these spatial differences, and a time horizon T is chosen to allow for observable depletion of the aquifer while remaining within the planning horizon for one generation of farmers.

We track the cumulative amount of land in n possible cover types j that include major crops in the region (rice, irrigated soybean, irrigated corn, irrigated cotton, non-irrigated soybean, double cropped irrigated soybean with winter wheat, and non-irrigated sorghum), woody and herbaceous cover as part of the US Department of Agriculture's Conservation Reserve Program (CRP), and on-farm reservoirs with tail-water recovery at the end of period t as denoted by L_{ij_t} for site i with land cover type j. We assume land (in acres) can become on-farm reservoirs and tail-water recovery, L_{iR_t}, from any other land cover j during period t, and the reservoir store surface water to reduce reliance on groundwater and capture agricultural runoff.

Farmers can switch their land cover at each period t according to the objective they have for the landscape. For instance, farmers with declining groundwater availability may switch land out of irrigated crops into non-irrigated crops. No matter what land cover the farmer decides, the sum of the chosen land covers at site i at any time t must equal the initial land availability (Eq. 1).

$$(1) \qquad \sum_j^n L_{ij\_t} = \sum_j^n L_{ij\_0} \text{, for } j = \text{crops, CRP, on-farm reservoirs}$$

The economic model

The economic model calculates the net present value of the agricultural land covers (namely crops and CRP) for the landscape. A significant component of the economic model is the irrigation model which tracks groundwater pumping, volume of the aquifer, and surface water availability from on-farm reservoirs.

Irrigation

Irrigation demand varies by crop and is given by wd_j, representing average annual irrigation that crop j (acre-feet) receives to supplement precipitation. The variable AQ_{i_t} is the amount of groundwater stored in the aquifer beneath site i at the end of the period t. The amount of water pumped from the wells is GW_{i_t} during period t, and the amount of water pumped from the on-farm reservoirs is RW_{i_t}. The natural recharge of groundwater at a site i from precipitation, streams, and underlying aquifers in a period is nr_i .

Kovacs et al. (2014) define the following function (Eq. 2) for the acre-feet of water stored in an acre reservoir as

$$(2) \qquad (\omega_{\max} + \omega_{\min}) - \frac{\omega_{\max}}{\sum_j^n L_{ij\_0}} L_{iR\_t} ,$$

which depends on the number of acres of the reservoir L_{iR_t} and the total acreage at site *i*, $\sum_{j}^{n} L_{ij\_0}$. The low-end acre-feet of water in each acre of the reservoir is $\omega_{\min}$ when the reservoir occupies the entire site *i* and only the rainfall fills the reservoir. The high-end is approximately $\left(\omega_{\max} + \omega_{\min}\right)$ when the reservoir is less than the size of the site with runoff and rainfall filling the reservoir to capacity. The values for $\omega_{\max}$ and $\omega_{\min}$ are estimates because evaporation, leakage, rainfall, and the timing of rainfall during the growing season change by year. There is also no accounting within a given year of additions and uses of water stored in the reservoir.

We suppose aquifer depletion varies over space in response to the intensity of well pumping at any particular site. We define p_{ik} as the expected proportion of the groundwater in the aquifer that flows underground out of site *i* into the aquifer of site *k* when an acre-foot of groundwater is pumped out of site *k*, where p_{ik} is a negative quadratic function of the distance and the lateral speed of underground water movement given average soil texture and profiles observed in the region between sites *i* and *k*. The amount of water leaving site *i* is then $\sum_{k}^{m} p_{ik} GW_{k\_t}$.

To represent the cost of pumping to the surface an acre-foot of groundwater at site *i* in period *t* is GC_{i_t}. Pumping costs depend on several parameters including the cost to lift one acre-foot of water by one foot using a pump, c^p, and the initial depth to the groundwater, dp_i. These are the costs associated with the energy necessary to lift water to the surface. The capital cost per acre-foot of constructing and maintaining the well, c^c, accounts for the possibility of new well drilling if the aquifer drops below the initial drilled depth. We suppose groundwater pumps are uniformly efficient with identical power units that deliver a fixed number of gallons per minute, and the producer drills a well deeper than the depth to the aquifer to allow for decline in the water table.

The dynamics of irrigation and pumping cost at each site is then represented by:

$$\sum_{j=1}^{n} wd_j L_{ij\_t} \le GW_{i\_t} + RW_{i\_t} \tag{3}$$

$$RW_{i\_t} \le \left(\left(\omega_{\max} + \omega_{\min}\right) - \frac{\omega_{\max}}{\sum_{j}^{n} L_{ij\_0}} L_{iR\_t} \right) L_{iR\_t} \tag{4}$$

$$AQ_{i\_t} = AQ_{i\_(t-1)} - \sum_{k}^{m} p_{ik} GW_{k\_t} + nr_i \tag{5}$$

$$GC_{i\_t} = c^c + c^p \left(dp_i + \frac{\left(AQ_{i\_0} - AQ_{i\_t}\right)}{\sum_{j}^{n} L_{ij\_0}} \right) \tag{6}$$

Each period, the sum of water used for irrigation on all the crops at a site must be less than the water pumped from wells or reservoirs (Eq. 3), and the amount of water pumped from reservoirs must be less than the maximum amount of water that can be stored by the reservoirs (Eq. 4). The aquifer volume by the end of period *t* is the volume in the previous period plus natural recharge less the amount of water pumped from the wells of surrounding sites weighted by the proximity to site *i* (Eq. 5). Pumping an acre-foot of groundwater has a full cost that includes the capital costs per acre-foot, c^c, plus c^p times the depth to the groundwater which depends on how depleted the aquifer is under the site *i* (Eq. 6).

Economic returns objective

Several economic parameters are needed to complete the formulation of the economic returns objective. The price per conventional unit of the crop is pr_j and the cost to produce an acre of the crop excluding the irrigations costs is ca_j, which depend on the crop *j* and are constant in real terms. The yield of crop *j* per acre is y_{ij} at site *i* and is constant meaning no productivity growth trend. The net value per acre for crop *j* is then $pr_j y_{ij}$ - ca_j excluding pumping costs of well and reservoir water, and the maintenance and construction costs of the wells and reservoirs. The net value per acre of CRP ($pr_{crp}y_{icrp} - ca_{crp}$) is the government payment per acre to the landowner ($pr_{crp}y_{icrp}$ such that the yield is normalized to one and the price is the payment per acre) less the cost to establish and maintain an acre of CRP (ca_{crp}). The real discount factor to make values comparable over time is δ_t.

The well capacity and pumping equipment require ongoing maintenance and capital payments represented by the capital cost per acre-foot, c^c. Other costs constant in real terms include the annual per acre cost of constructing and maintaining a reservoir, c^r, and the cost of pumping an acre-foot of water from the tail water recovery system into the reservoir and from the reservoir to the field plus the capital cost per acre-foot of the re-lift pump, c^{rw}.

The economic objective is to maximize the economic returns from farm production:

$$\max_{L_{ij\_t}, RW_{i\_t}, GW_{i\_t}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \left(pr_j y_{ij} - ca_j \right) L_{ij\_t} - c^r L_{iR\_t} - c^{rw} RW_{i\_t} - GC_{i\_t} GW_{i\_t} \right) \tag{7}$$

subject to:

$$L_{ij\_0} = L_0^{ij}, L_{iR\_0} = 0, AQ_{i\_0} = AQ_0^i, \tag{8}$$

$$L_{ij\_t} \geq 0, RW_{i\_t} \geq 0, GW_{i\_t} \geq 0, AQ_{i\_t} \geq 0 \tag{9}$$

and the spatial dynamics of land and irrigation (Eqs. 1-6). The objective (Eq. 7) is to determine L_{ij_t},, RW_{i_t}, and GW_{i_t} (i.e. the amount of land in each crop or CRP, the reservoir water uses, and groundwater use) to maximize the present value of farm profits over the fixed time horizon *T*. Revenue accrues from crop production constrained by the water availability and other inputs for the crops. Costs include the irrigation costs and all other production costs. Equation 8 represents the initial conditions of the state variables, and Equation 9 has the non-negativity constraints on land types, water use, and the aquifer. Optimization of Eq. 7 and the resulting crop and irrigation method patterns have repercussion on ecosystem services related to GHGs, water purification, and groundwater availability; however these are not directly considered by producers in their objective in Eq. 7.

The ecosystem service model

The ecosystem service model calculates the social net present value of GHG reductions, water purification, and groundwater supply from the landscape. The physical quantities of the ecosystem services are tracked over time, and the value of each ecosystem service is monetized using their social price.

Greenhouse gas reductions

The cultivation of crops is the primary source of GHG emissions in agriculture (EPA, 2014). GHG emissions per acre associated with the production of crops and CRP for the major production practices of the Arkansas Delta are based on life cycle assessment (LCA) up to the farm gate (Nalley et al. 2011). Multiple GHGs, principally generated from methane emissions from rice production, nitrous oxide emissions from the application of nitrogen fertilizer to the soil, fuel use and emissions generated during the manufacture of chemicals and fertilizer, are converted to carbon equivalents (CE) based on their global warming potential and tracked in kg per acre of land cover j (E_j) as shown in Figure B.1. Emissions from fuel combustion associated with pumping groundwater and reservoir water are considered in the model optimization separate from the E_j, although a range of irrigation emissions is shown in Figure B.1. The LCA excludes emissions associated with the upstream production of farm equipment and inputs that contributed to less than 2% of total emissions.

The GHG emissions from fuel combustion for irrigation depend on the amount of water pumped from the ground and reservoirs and the depth to the groundwater for the well pumping. The emissions from groundwater pumping at site i, EG_{i_t}, equal the depth of the well multiplied by a conversion factor σ_g that identifies the carbon emitted from fuel combustion to lift an acre-foot of water one foot and multiplied by the acre-feet of groundwater pumped. The emissions from pumping reservoir water at site i, ER_{i_t}, equal the acre-feet of reservoir water pumped multiplied by a conversion factor σ_r that indicate the carbon emitted from fuel combustion to pump an acre-foot of water into a reservoir and back out to the field.

Equation 10 indicates total carbon emissions for time *t* at site *i* (E_{i_t}) as

$$E_{i\_t} = \sum_j^n E_j L_{ij\_t} + EG_{i\_t} + ER_{i\_t} . \qquad (10)$$

Following Popp et al. (2011), we estimate the carbon sequestrated from aboveground biomass (AGB_{ij}) and belowground biomass (BGB_{ij}) that depend on the soil texture and tillage practices among other factors. The mathematical formulation of the equations and factors determining the above- and belowground biomass carbon sequestration for the model is described in Appendix B.

A final adjustment to the above- and belowground biomass carbon sequestration is by a soil factor, ξ_i, determined as the fraction of carbon lost to respiration due to soil related microbial activity weighted by the proportion of the soil texture areas in each site *i*. Finer textured soils (i.e. clayey) have less intense wetting and drying cycles which discourages microbial activity and respiration compared to more porous soil (i.e. sandy). The dynamics of total carbon sequestration (Eq. 11) for time *t* at site *i* (S_{i_t}) is estimated by

$$S_{i\_t} = \sum\nolimits_{j}^{n} \left[\left(AGB_{ij} + BGB_{ij} \right) \xi_i \right] L_{ij\_t} . \tag{11}$$

We suppose carbon sequestration on CRP land occurs evenly over time although the sequestration is likely to be greater initially and slower later (Barker et al. 1995). Since greenhouse gases do not affect the economic returns objective, Equations (10) and (11) do not influence optimal decisions when using that objective. However, the ecosystem services objective includes the value of GHGs, and Equations (10) and (11) are constraints in that optimization.

The monetary value of GHG reductions from the agricultural landscape is based on the social cost of carbon (Tol 2009). The social cost of carbon, p_c, is the cost to society incurred by the predicted damages to the climate from each additional ton of carbon emitted to the atmosphere. Ecosystem service value of avoided climate change damages, V_c, is positive if sequestration exceeds emissions while the value is negative if the emissions outweigh sequestration (Eq. 12).

$$V_c = \sum_{t=1}^{T} \delta_t \left(\sum\nolimits_{i}^{m} p_c \left(S_{i\_t} - E_{i\_t} \right) \right). \tag{12}$$

Water purification

Surface water purification in the Mississippi Delta occurs by purifying agricultural runoff containing sediment, phosphorus, and nitrogen pollution (Intarapapong et al., 2002). The InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs; Tallis et al., 2011) water purification model estimates how these agricultural pollutants respond to land cover transitions. The first step estimates the expected annual water yield at each site based on precipitation, slope, soil characteristics, and evapotranspiration. Second, the water yield is combined with expected pollutant loading and the filtering capacities for each land cover to calculate the pollutants from each site that eventually reach a stream. The water purification model includes natural land, public land, lakes, and urban areas (although not part of the optimization model) because they affect the agricultural pollution from each site that reaches streams.

A run of the water purification model with the initial land cover calculates pollutant export per acre from land cover *j* for farm site *i* reaching a stream, P_{ij_0}. The optimization model cannot route pollutants downstream, and this requires us to assume that changes in pollutant exports from site *i* are associated only with the land cover changes at site *i* but not the land cover changes at surrounding sites. The slope of site *i* affects the tail-water recovery's ability to capture runoff. Steep land captures less runoff than flat land, and $0 \le \theta_i \le 1$ represents the tail-water recovery effectiveness such that θ_i is larger if site *i* is flatter (A. Sharpley, University of Arkansas, personal communication).

The dynamics of pollutant exports to the mouth of a watershed EX_i (i.e. phosphorous, nitrogen, sediment) from each site at time *t* shown as Eq. 13 is:

$$EX_{i\_t} = \sum_j^n P_{ij\_0} L_{ij\_t} \left(1 - \theta_i \frac{L_{iR\_t}}{\left(L_{iR\_t} + 1 \right)} \right), \tag{13}$$

where $P_{ij\_0} L_{ij\_t}$ is the total export of pollutant to a stream from site *i* without reservoirs. The term $\left(1 - \theta_i \frac{L_{iR\_t}}{\left(L_{iR\_t} + 1 \right)} \right)$ indicates even a small reservoir with tail-water recovery captures most of the runoff and unwanted pollutants.

Phosphorus is the limiting nutrient contributing to eutrophication in Arkansas Delta water bodies, and sediment increases turbidity which lowers recreational value. Each watershed basin k has a subset of the sites in the total study area. The willingness to pay (WTP) per household for a water purification improvement depends on the baseline water purity and median household income of the basin ($wtpq_k$) and assumes the improvement in water purity is permanent. The WTP values per household are prorated to the percent change in pollutant loadings from the optimization model; for example, a WTP value of \$50 per household for a 50% reduction means a 1% reduction in pollutant loading is prorated to \$1.[1] Multiplying the prorated WTP per household by the number of households in the basin (hh_k) gives the total value of the water purity for that basin.

The present value of the surface water purity (V_w) shown as Eq. 14 is:

(14)

$$V_w = \sum_{t=1}^{T} \delta_t \left(\sum_k hh_k wtpq_k \left(\frac{\sum_{i \in k} \left(EX_{i\_t} - EX_{i\_t+1} \right)}{\sum_{i \in k} EX_{i\_t}} \right) \right)$$

Groundwater value

Following Kovacs et al. (2014), the social value of groundwater (p_{bv}) includes the ability of groundwater to buffer against periodic shortages in surface water supplies, prevent subsidence of the land, dilute groundwater contaminants, and provide discharge to supplement in-stream flows. We consider only the value to agricultural producers to buffer against periodic shortages in surface water supplies because there is inadequate data to estimate the other values. Groundwater

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[1] Diminishing marginal WTP for an improvement in water quality is a better assumption, but the literature offers no guidance as to what functional form this diminishing marginal WTP would take.

buffer value, V_g , is positive if the aquifer grows over time because the natural recharge of the aquifer exceeds the groundwater withdrawal for irrigation. The present value of the groundwater buffer value (Eq. 15) is:

$$(15) \qquad V_g = \sum_{t=1}^{T} \delta_t \left(\sum_i^m p_{bv} \left(AQ_{i\_t+1} - AQ_{i\_t} \right) \right)$$

Ecosystem service objective

The ecosystem services objective (Eq. 16) is the sum of the present value of GHG reduction, surface water purity improvements, and groundwater buffer value. The objective is to determine L_{ij_t},, RW_{i_t} , and GW_{i_t} to maximize the present value of ecosystem services over the fixed time horizon T.

$$(16) \qquad \max_{L_{ij\_t}, RW_{i\_t}, GW_{i\_t}} : \; V_c + V_w + V_g \, ,$$

subject to the spatial dynamics of land cover, irrigation, GHG emissions, surface water purification, and groundwater (Eqs. 1-6 and 8-15). Optimization of Eq. 16 and the resulting land cover and irrigation method choices have repercussion on farm profits, but these are not directly considered by planners using the ecosystem services objective.

Efficiency frontier

By finding the maximum economic returns for a fixed value of all or one of the ecosystem services, and then varying the fixed value of the ecosystem service over its entire potential range, we trace out an efficiency frontier. This is done without and with reservoirs to compare how the reservoirs change the position of the efficiency frontier. The efficiency frontier illustrates the economic return and ecosystem service values feasible from the landscape, and the necessary tradeoffs between the objectives on the landscape. The efficiency frontier also illustrates the degree of inefficiency of landscapes not on the frontier, which shows how much either objective could be increased simply with a better arrangement of land cover and irrigation methods.

The first step for generating points on an efficiency frontier is finding the full range of possible ecosystem service values. The maximum value of ecosystem services is found by optimizing the ecosystem services objective without restriction on economic returns. Conversely, the minimum value of ecosystem services is found by optimizing economic returns with no restriction on the ecosystem service value. The second step is to choose ecosystem service values that extend across the range of minimum and the maximum ecosystem service values for tracing out the shape of the frontier. The final step is to maximize the economic returns for the given levels of ecosystem service values from the second step. The maximum economic returns matched to the given ecosystem service value is a combination that rests on the efficiency frontier.

The range of possible ecosystem service values are not the same for the frontier with reservoirs versus the frontier without reservoirs. Some ecosystem service values for the efficiency frontier with reservoirs are chosen only because they match the ecosystem service values chosen for the efficiency frontier without reservoirs. Using the same ecosystem service values across frontier allows a determination of the gains from moving to an outer frontier. The remaining ecosystem service values for the efficiency frontier with reservoirs are chosen to completely trace out the frontier. We perform the optimization with the Generalized Algebraic Modeling System

(GAMS) 23.5.1 using the non-linear programming solver CONOPT from AKRI Consulting and Development.[2]

Conservation policies

Ecosystem service values are not typically internalized in farm production because these values go to society as a whole rather than the producers that generate these services. Conservation policies help to align producers' profit making decisions with the provision of ecosystem services. We run the model using the economic returns objective with reservoirs but with no conservation policy and compare this to runs of the model with conservation policies that include cost-share on reservoir construction costs, tax on groundwater use, a total maximum daily load of phosphorous and sediment, and carbon credits. The transfers that result from policies like the cost-share on reservoir costs and groundwater taxes occur between the government and producers, while the cap and trade scheme that generates carbon credits represents transfers among producers. The use of any policy lowers economic returns excluding transfers because the landscape pattern moves away from economic return maximization. However the total value to society, which is the economic returns excluding transfers plus the ecosystem service values, may increase, which the policy makers should evaluate.

Data

Three watersheds at the eight-digit hydrologic unit code level that represent critical groundwater areas and non-point source pollution priority watersheds of Arkansas Delta region are chosen for

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[2] The problem is not linear because the groundwater pumping cost and the groundwater pumped are both solved as part of the problem and are multiplied together. The CONOPT solver available in GAMS is particularly effective at solving complex non-linear programs.

the outer boudary of the study area (Fig. 1) . There are eleven Arkansas counties that overlap these watersheds, and the average county crop yields for the past 5 years is a proxy for the yield of the crops, which is not adjusted over time (Division of Agriculture, 2012). The study area is divided into 2,724 sites to evaluate how economic return or ecosystem service objectives influence crop mix and irrigation methods on a spatially differentiated landscape. According to the 2013 Cropland Data Layer (CDL), all sites having entirely non-cropland land uses (e.g. urban areas, water, and public lands) are removed (Johnson and Mueller, 2010). The 2013 CDL determines for each site the initial acreage of rice, corn, cotton, soybeans, and sorghum, with the soybean acreage split into irrigated soybean, non-irrigated soybean, and double crop soybeans on the basis of harvested acreage for 2010-2011 (Table B.1) (USDA NASS, 2012) . A real discount rate of 5% is based on the average yield of the 30yr Treasury Bond over the last decade, a nearly risk free investment (US Department of the Treasury, 2012).

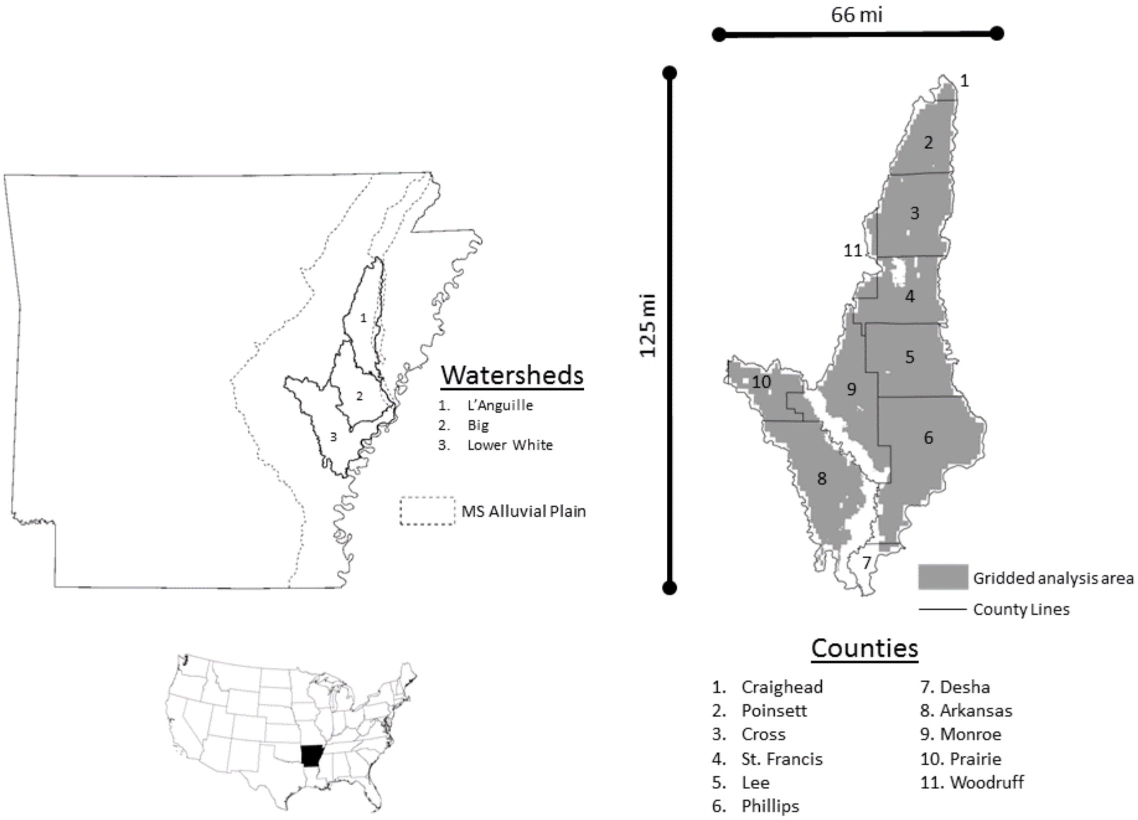

Figure 1. Three eight-digit hydrologic unit code (HUC) watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. County lines overlay the study area. Public land and urban areas are excluded. The location of the study area within the State of Arkansas is shown.

Farm production

Table B.2 indicates the costs of production by crop, excluding irrigation, from the 2014 Crop Cost of Production estimates (Flanders et al., 2015). Variable irrigation costs are described in more detail in Appendix B before Table B.2. The average annual irrigation water use by crop come from the Division of Agriculture (2012). Crop prices are the five year average of December futures prices for harvest time contracts for all crops (GPTC, 2012). The CRP payment per acre is based on all sign-ups in Arkansas as of March 2015 (USDA FSA 2015).

We assume that other than variable irrigation costs that the costs of production, as well as crop prices, annual irrigation water use, and yields do not vary over time.

On-farm reservoir and tail-water recovery system

Young et al. (2004) find that a tail-water recovery system collecting rainfall runoff alone can fill a reservoir by 16.5 acre-inches of water, and this is the minimum volume of water (ω_{min}) annually an acre reservoir will hold. The additional collection of irrigation runoff allows a reservoir to fill to a maximum annual capacity accounting for evaporation of 11 acre-feet per acre (Smartt et al., 2002). The average share of nutrients and sediment captured by reservoirs (θ_i) is 0.87 (Popp et al., 2003), but this varies according to the slope of each site *i* (A. Sharpley, University of Arkansas, personal communication; AR Land Information Board, 2006). On-farm reservoir/tail-water recovery construction and maintenance costs are described in more detail in Appendix B before Table B.2.

Aquifer

The initial depth to the water table and saturated thickness of the Alluvial aquifer shown in Table B.1 come from the Arkansas Natural Resources Commission (ANRC, 2012). The volume of the aquifer at site *i* is the acreage of the site times the saturated thickness of the aquifer. The natural recharge (nr_i) associated with precipitation, and the flow to and from streams and the underlying Sparta aquifer is based on recharge for the period 1994 to 1998 (Reed, 2003). Producers are assumed not to pump from the Sparta because the aquifer is used by urban areas for drinking water (McKee and Hays, 2002). Following Kovacs et al. (2015), we use the volume of underground flow to determine the spatial weight (p_{ik}) that decides how much an acre-foot of water pumped from a well reduces the aquifer beneath the surrounding cells. More detail about the aquifer model is found in Appendix B before Table B.1.

We use a baseline estimate of $5.19 per acre-foot groundwater that is constant in real terms and based on the net profit of soybeans, the variability of seasonal rainfall, and curvature of the soybean yield response to water at the average seasonal rainfall (Kovacs et al. 2015). Since the buffer value of groundwater is derived from soybean production rather than the more profitable and irrigation dependent rice production, the baseline estimate of buffer value is conservative.

Water Purification

One InVEST model finds the water yield and nutrient export to streams and a separate InVEST model finds the sediment export to streams as described in Kovacs et al. (2014). Using a geographic information system (GIS), surface water travels downhill according to a digital elevation model. Each downstream site either retains or augments the quantity of the nutrient (Table B.3) and sediment (Table B.4) flowing to the mouth of the watershed depending on the land cover. The total nutrient and sediments loadings at the mouth of the watershed is the aggregation of the nutrient and sediment export from each site to the streams. Appendix B has details on the water purification models.

Hite et al. (2002) report an average willingness to pay (WTP) value of $139.63 per household per year in 2013 dollars for a 50% reduction in pollutant loadings. The WTP per basin is the multiplication of the household WTP and the projection of the number of households in the basin in each period (Cole, 2003).

Greenhouse gases

Greenhouse gas emissions from fuel, chemical and fertilizer applications were tracked using input parameters as reported in cost of production estimates developed for crop enterprises for 2014 (Flanders et al., 2015). Soil carbon sequestration for the same enterprises are derived from county level yields by tracking above and below ground biomass production, with plant residue in soil contact leading to carbon fractions remaining in the soil after microbial decomposition and gas fluxes (Table B.5) as described in Popp et al. (2011). The analysis accounts for tillage and soil texture effects on the carbon sequestration side of the equation and modifies irrigation fuel use emissions on the basis of spatially varying depth to the water.

Increases in soil carbon sequestration from potential changes in land use or reductions in GHG emissions from less intensive irrigation may reduce the landscape's net GHG emissions over time. The reduction of GHGs present in the atmosphere has positive social value because of reduced damages from projected climate change. We use a baseline estimate of \$129 per ton carbon (\$35.14 per ton CO_2) that is constant in real terms, based on the median fitted distribution assuming a 1% pure rate of time preference after adjusting from 1995 to 2013 dollars (Tol 2009).

Results

We find four sets of efficiency frontiers for ecosystem service and economic returns (shown in Figures 2-4) for the groundwater constrained part of the Arkansas Delta. There are two frontiers for each set of efficiency frontiers, one that represents a landscape without on-farm reservoirs and a second one that represents a landscape with on-farm reservoirs. The four sets of frontiers examine the agricultural land cover and tradeoffs when economic returns are optimized while maintaining a minimum level of one or all of the ecosystem service values. The landscape looks different depending whether a minimum level is maintained of all the ecosystem services (Points

A to J), groundwater supply value only (Points K to T), water purification value only (Points U to DD), or GHG reduction value only (Points EE to NN).

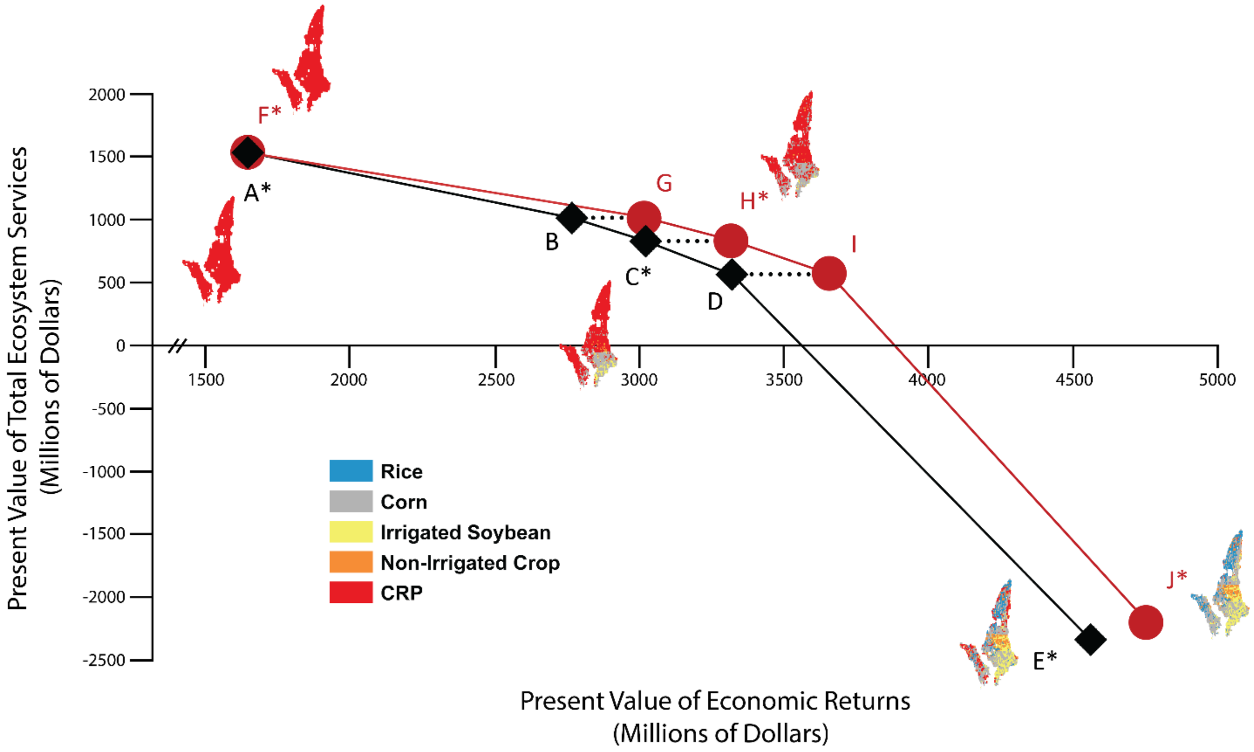

Figure 2. Crop mix patterns associated with specific points along the efficiency frontiers without reservoirs (Points A to E) and with reservoirs (Points F to J). Each crop mix pattern shown beside the efficiency frontiers correspond to a lettered point with an asterisk on the frontiers. Points on the efficiency frontier without reservoirs available have more CRP land and fewer irrigated intensive crops, and points on the efficiency frontier with reservoirs available have less CRP land and more corn and rice. As the ecosystem services objective is emphasized more relative to the economic objective, there is a shift from predominantly irrigated crops toward CRP land which occurs for the efficiency frontier without reservoirs before the efficiency frontier with reservoirs.

Starting with the landscape without reservoirs that generates the maximum of all ecosystem services (labeled as point A in Figure 2 where all the land is put into CRP), moving around the efficiency frontier increases economic returns while having little impact on ecosystem services. Moving from point A to point C increases the economic returns from $1649 to $3021 million, which is 47% of the maximum increase in economic returns, while reducing the value of all ecosystem services by only 18% (see Table 1 for ecosystem services and economic returns for selected points on the efficiency frontiers). Economic returns increase because land in CRP switches to irrigated corn and non-irrigated crops (see Table 2 and Table A.1). Although the greenhouse gas value decline is the greatest at $668 million (or 18%), the declines in groundwater supply value and water purification value are larger relative to their possible decreases, 26% and 33% respectively. When optimizing all ecosystem services, the landscape favors GHGs reduction because the social price of GHG reduction outweighs the social prices of groundwater supply or water purification.

Continuing around the efficiency frontier from point C to point E requires shifting nearly all CRP into irrigated production. The shift to irrigated crops increases the economic returns from $3021 to $4559 million, but this comes at a steep loss to ecosystem services. Rice acreage increases the most with the move to point E because there is no constraint on GHG reduction. The significant acreage in corn and irrigated soybean also contribute to the dramatic fall in ecosystem services to -253% of the maximum possible. The combined value of economic returns and all ecosystem services is higher at Point C than at Point E where ecosystem service value is 53% of the maximum possible and economic return value is 66% of the maximum possible.

With reservoirs the land use pattern labeled by point F in Figure 2 achieves the same maximum ecosystem services and associated economic returns as point A because all the land is put into the CRP. The availability of reservoirs has no effect on the maximum ecosystem services achieved because the CRP land provides the greatest ecosystem services and CRP land is not irrigated. By moving from point F to point H, economic returns increase from $1649 to $3322 million, which is 69% of the maximum increase in economic returns. The presence of reservoirs allow economic returns to rise more for a given level of ecosystem service values because crops like corn can be grown at a lower irrigation cost and less well pumping increases groundwater supply and lowers GHGs (see Table 2). Comparing points C and H in Figure 2, reservoirs increase corn on the landscape, and this is concentrated in the southern and eastern sites of the study area.

Table 1: Ecosystem service and economic return values for points along efficiency frontiers

Without reservoirs				**With reservoirs**			
Efficiency frontiers	**Present value of economic returns**	**Present value of optimized ecosystem service(s)**	**Present value of ecosystem services**	**Efficiency frontiers**	**Present value of economic returns**	**Present value of optimized ecosystem service(s)**	**Present value of ecosystem services**
All ecosystem service values							
A	1649	1532	1532	F	1649	1532	1532
B	2768	1000	1000	G	3021	1000	1000
C	3021	819	819	H	3322	819	819
D	3322	567	567	I	3656	567	567
E	4559	-2345	-2345	J	4757	-2206	-2206
Groundwater supply values only							
K	1649	60	1532	P	1650	60	1529
L	2539	50	885	Q	4169	50	-620
M	3463	20	331	R	4449	20	-796
N	4118	-10	-450	S	4638	-10	-1178
O	4559	-68	-2345	T	4757	-56	-2206
Water purification values only							
U	1649	32	1532	Z	1649	32	1531
V	3957	25	-1526	AA	4102	25	-1348
W	4102	23	-1699	BB	4260	23	-1524
X	4260	19	-1895	CC	4429	19	-1720
Y	4559	-1	-2345	DD	4757	-2	-2206
Greenhouse gas reduction values only							
EE	1649	1439	1532	JJ	1649	1439	1532
FF	2319	1200	1269	KK	2456	1200	1276
GG	2456	969	1033	LL	2961	969	1033
HH	2961	478	516	MM	3708	478	518
II	4559	-2276	-2345	NN	4757	-2147	-2206

Note: The values of economic returns and ecosystem service values are reported in millions of 2013 constant dollars.

As the movement along the efficiency frontier with reservoir continues, from point H to point J, more CRP land shifts into rice and irrigated soybeans. This shift happens predominantly in the western and northern sites where groundwater is relatively scarce. The move to point J raises the economic returns from $3322 to $4757 million, but ecosystem service value fall to -$2206 million. The value of ecosystem services at point J is slightly larger than at point E because reservoirs conserve more groundwater and allow more GHG sequestering corn to be grown. When looking at economic returns and ecosystem service values together, the Point H is greater than a Point J suggesting that a landscape managed for both objectives achieves a higher value for society.

Table 2: Present value of economic returns and ecosystem services for select points on the efficiency frontier using all ecosystem service value (in millions of 2013 constant dollars)

Ecosystem service or land cover	**Without reservoirs**			**With reservoirs**		
	A	**C**	**E**	**F**	**H**	**J**
Greenhouse gases	1439	771	-2276	1439	760	-2147
Groundwater supply	60	27	-68	60	41	-56
Water purification	32	21	-1	32	19	-2
Total ecosystem services	1532	819	-2345	1532	819	-2206
Rice	0	0	769	0	0	932
Irrigated soybeans	0	121	674	0	21	698
Non-irrigated crop	0	543	625	0	477	587
Corn	0	1300	1940	0	1953	2081
Cotton	0	54	430	0	21	439
CRP	1649	1003	121	1649	851	20
Total economic return	1649	3021	4559	1649	3322	4757
Total of economic return and ecosystem service value	3181	3840	2214	3181	4141	2551

Turning to the tradeoff of groundwater supply and economic returns, moving from point K to point M increases the economic returns from $1649 to $3463 million (Table 3). An extra dollar of economic return from Point K to M means 66 cents less in total ecosystem service value compared with a move from Point A to C where an extra dollar of economic return means only

52 cents less in the value of all ecosystem services. Targeting only groundwater supply value preserves less ecosystem service value than targeting all ecosystem services. There is a greater shift away from CRP into non-irrigated crops at Point M than to Point C because CRP and non-irrigated crop are equally valuable only groundwater supply matters (Table A.2). The consequence is that GHG value is much lower at point M than at Point C since non-irrigated crops absorb less GHG than CRP. Moving further along the frontier without reservoirs from point M to N generates an extra dollar of economic returns by sacrificing $1.19 of ecosystem service value. Assuming ecosystem services have the social prices used in this study, greater emphasis of economic returns beyond point M is socially harmful.

Table 3: Present value of economic returns and ecosystem services for select points on the efficiency frontier optimizing groundwater buffer value (in millions of 2013 constant dollars)

Ecosystem service or land cover	**Without reservoirs**			**With reservoirs**		
	L	**M**	**N**	**Q**	**R**	**S**
Greenhouse gases	813	300	-442	-672	-816	-1167
Groundwater supply	50	20	-10	50	20	-10
Water purification	22	11	2	2	0	0
Total ecosystem services	885	331	-450	-620	-796	-1178
Rice	0	0	125	702	757	816
Irrigated soybeans	0	0	315	290	377	634
Non-irrigated crop	945	942	937	817	823	646
Corn	521	1703	1959	1952	2056	2079
Cotton	16	132	423	386	412	437
CRP	1058	685	360	23	24	25
Total economic return	2539	3462	4118	4169	4449	4638
Total of economic return and ecosystem service value	3424	3793	3668	3549	3653	3460

Figure 3 shows that the use of reservoirs boosts economic returns and shrinks ecosystem service value for points with the same groundwater supply value across the frontiers (L and Q, M and R, and N and S). The reason for higher economic returns is that reservoirs allow valuable irrigated crops to be grown over most of the landscape with only minimal losses to groundwater supply. Unfortunately, these irrigation crops release GHGs (rice in particular) and surface water pollutants (corn in particular) rather than absorb them as CRP does, and this means that except for groundwater supply that total ecosystem service value falls when moving across frontiers. Along the frontier with reservoirs after Point P, greater economic returns do not cause large losses to total ecosystem service value because the land cover is similar for the points along the frontier (Table 3). The total of economic return and ecosystem service values is lower at Point R for the landscape with reservoirs than at Point M for the landscape without reservoirs because the reservoirs allow GHG releasing rice to be grown.

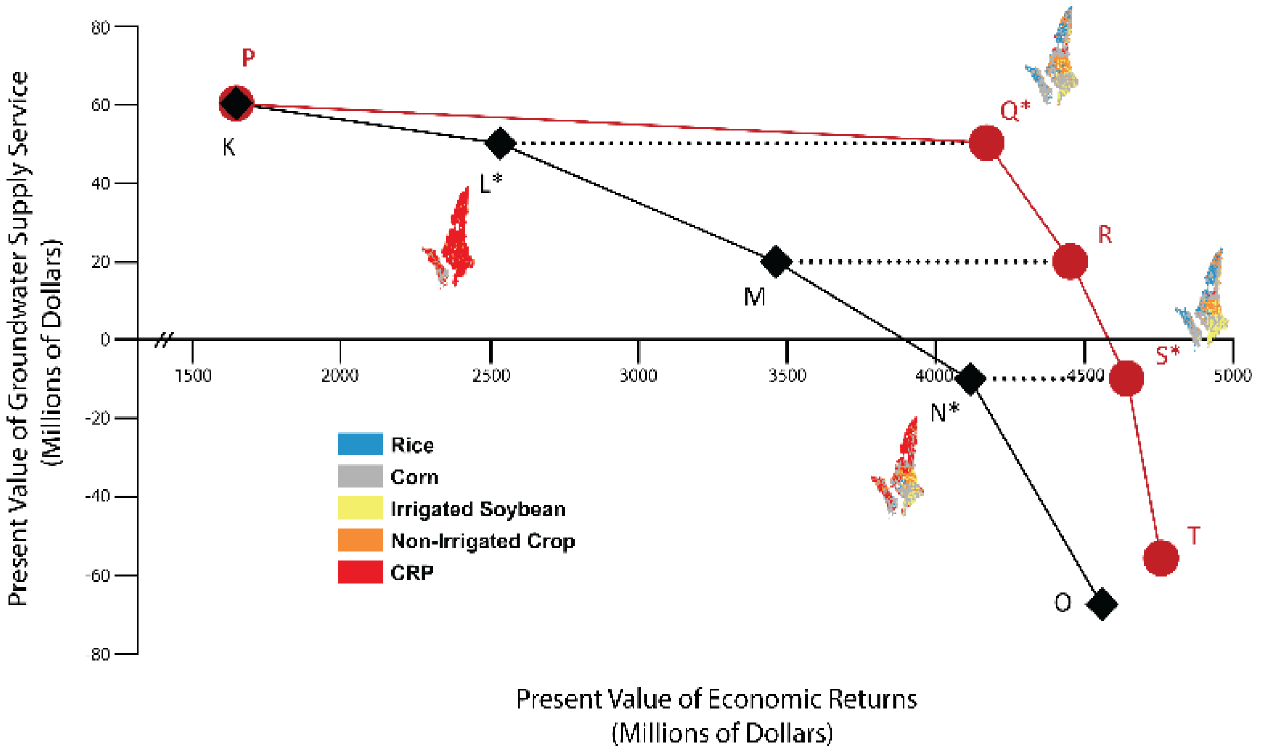

Figure 3. Crop mix patterns associated with specific points along the efficiency frontiers without reservoirs and with reservoirs that show the tradeoff of economic returns and groundwater supply. Each crop mix pattern shown beside the efficiency frontiers correspond to a lettered point with an asterisk on the frontiers. Efficiency frontiers are farther apart than in Figure 2 indicating reservoirs do a lot to increase groundwater and economic efficiency, and points on the frontier without reservoirs exhibit much more CRP land than points on the frontier with reservoirs.

The efficiency frontier for water purification value and economic returns shows the landscape has more rice and CRP than do the landscapes on the frontiers for groundwater supply or all ecosystem services (Figure 4). There is more rice and soybeans and less CRP for the efficiency frontier without reservoirs because rice can purify the water nearly as well as CRP and generates more economic returns. However rice is irrigation intensive and a significant GHG emitter causing the total ecosystem service value to be low (Table 4). For the landscape with reservoirs, there is less movement from CRP to corn because corn pollutes surface water (Table A.3).

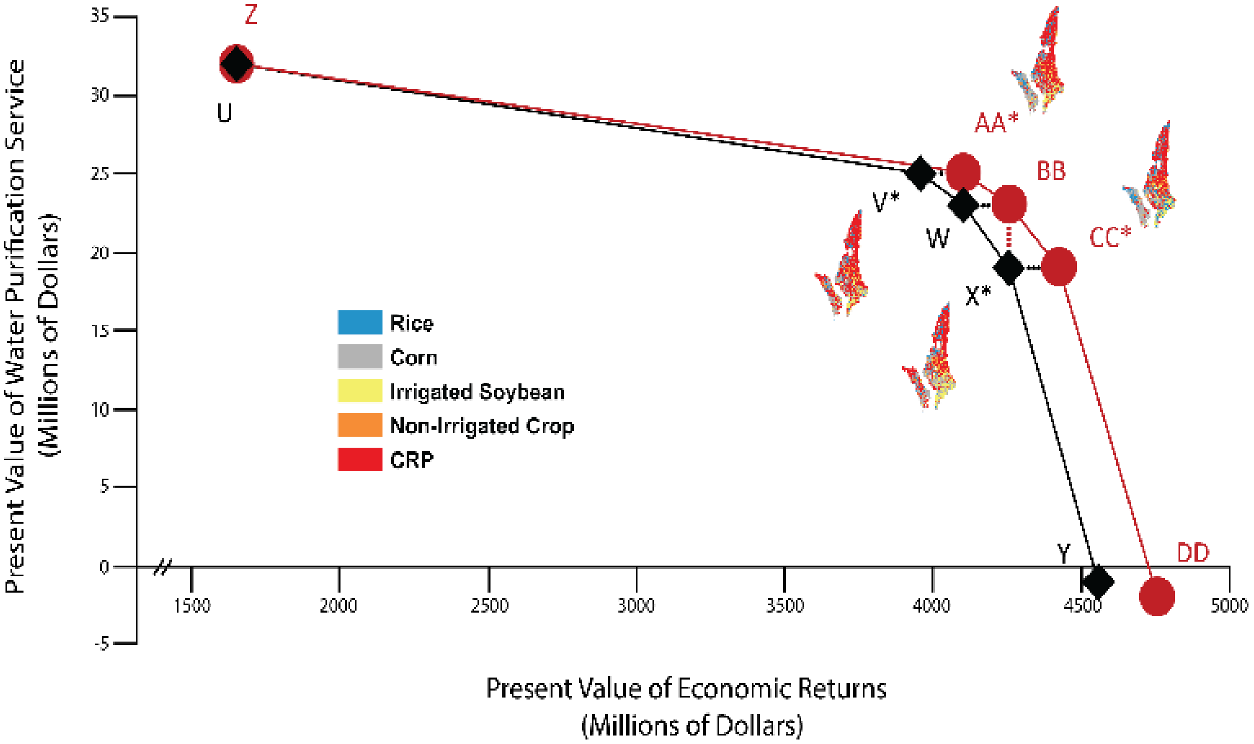

Figure 4. Crop mix patterns associated with specific points along the efficiency frontiers without reservoirs and with reservoirs that show the tradeoff of economic returns and water purification value. Each crop mix pattern shown beside the efficiency frontiers correspond to a lettered point with an asterisk on the frontiers. Efficiency frontiers are closer together than in Figure 2 indicating reservoirs do little to enhance water purification and economic efficiency, and points on the frontier without reservoirs have land cover similar to the points on the frontier with reservoirs.

Economic returns are greater with reservoirs because rice and other crops are grown at lower irrigation costs. Also, the GHG reduction value rises because the reservoirs reduce fuel combustion from groundwater pumping. A movement across frontiers while maintaining the same water purification value (V and AA, W and BB, X and CC) increases economic returns only slightly. This is because both frontiers have similar landscapes with abundant rice. Points V and AA correspond to the greatest total economic return and ecosystem service value for the two frontiers, respectively, because the GHG releasing rice is the least prevalent on the landscape for those points.

Table 4: Present value of economic returns and ecosystem services for select points on the efficiency frontier optimizing water purification value (in millions of 2013 constant dollars)

Ecosystem service or land cover	Without reservoirs			With reservoirs		
	V	W	X	AA	BB	CC
Greenhouse gases	-1506	-1671	-1858	-1340	-1509	-1697
Groundwater supply	-45	-51	-57	-32	-37	-43
Water purification	25	23	19	25	23	19
Total ecosystem services	-1526	-1699	-1895	-1348	-1524	-1720
Rice	739	746	758	887	904	924
Irrigated soybeans	547	587	625	556	601	635
Non-irrigated crop	347	377	440	319	362	419
Corn	1574	1685	1778	1675	1788	1898
Cotton	233	265	311	228	260	307
CRP	518	443	348	438	346	246
Total economic return	3957	4102	4260	4102	4260	4429
Total of economic return and ecosystem service value	2431	2403	2365	2754	2736	2709

The tradeoff between GHG reduction value and economic returns in Figure 5 indicates the presence of CRP, irrigated soybeans, and non-irrigated sorghum on the landscape without reservoirs and the presence of CRP and irrigated corn on the landscape with reservoirs. Points FF and KK have similar economic returns because both have predominantly corn and CRP on the landscape to maintain at least $1.2 billion in GHG value (Table 5). However, moving around the efficiency frontier to increase economic returns, the landscape without reservoirs switches corn into irrigated soybean and non-irrigated sorghum to reduce irrigation costs while the landscape with reservoirs maintains the corn (Table A.4). The gap between the frontiers widens as economic returns increase because growing irrigated soybeans and non-irrigated sorghum is the only way without reservoirs to maintain GHG reduction value and increase economic returns though these crops do not have as high an economic value as corn.

Table 5: Present value of economic returns and ecosystem services for select points on the efficiency frontier optimizing greenhouse gases value (in millions of 2013 constant dollars)

Ecosystem service or land cover	**Without reservoirs**			**With reservoirs**		
	FF	**GG**	**HH**	**KK**	**LL**	**MM**
Greenhouse gases	1200	969	478	1200	969	478
Groundwater supply	41	41	25	49	42	28
Water purification	28	23	13	28	22	11
Total ecosystem services	1269	1033	516	1276	1033	518
Rice	0	1	28	0	0	0
Irrigated soybeans	2	650	856	0	4	266
Non-irrigated crop	63	570	907	0	80	604
Corn	853	0	0	1087	1756	2076
Cotton	15	73	374	15	16	134
CRP	1386	1162	796	1354	1104	628
Total economic return	2319	2456	2961	2456	2961	3708
Total of economic return and ecosystem service value	3588	3489	3477	3732	3994	4226

For points on the frontiers without and with reservoirs with the same GHG value (FF and KK, GG and LL, HH and MM), the total ecosystem service value is similar since most of that value is GHG value. The frontier without reservoirs has slightly higher water purification value because less corn is grown and the frontier with reservoirs has higher water supply value because of the reservoirs. Point GG on the frontier without reservoirs is where total economic return and ecosystem service value is the greatest because economic returns are the largest before rice is heavily present on the landscape. Further along on the frontier with reservoirs Point MM has the greatest total economic return and ecosystem service value because rice has not yet appeared on the landscape.

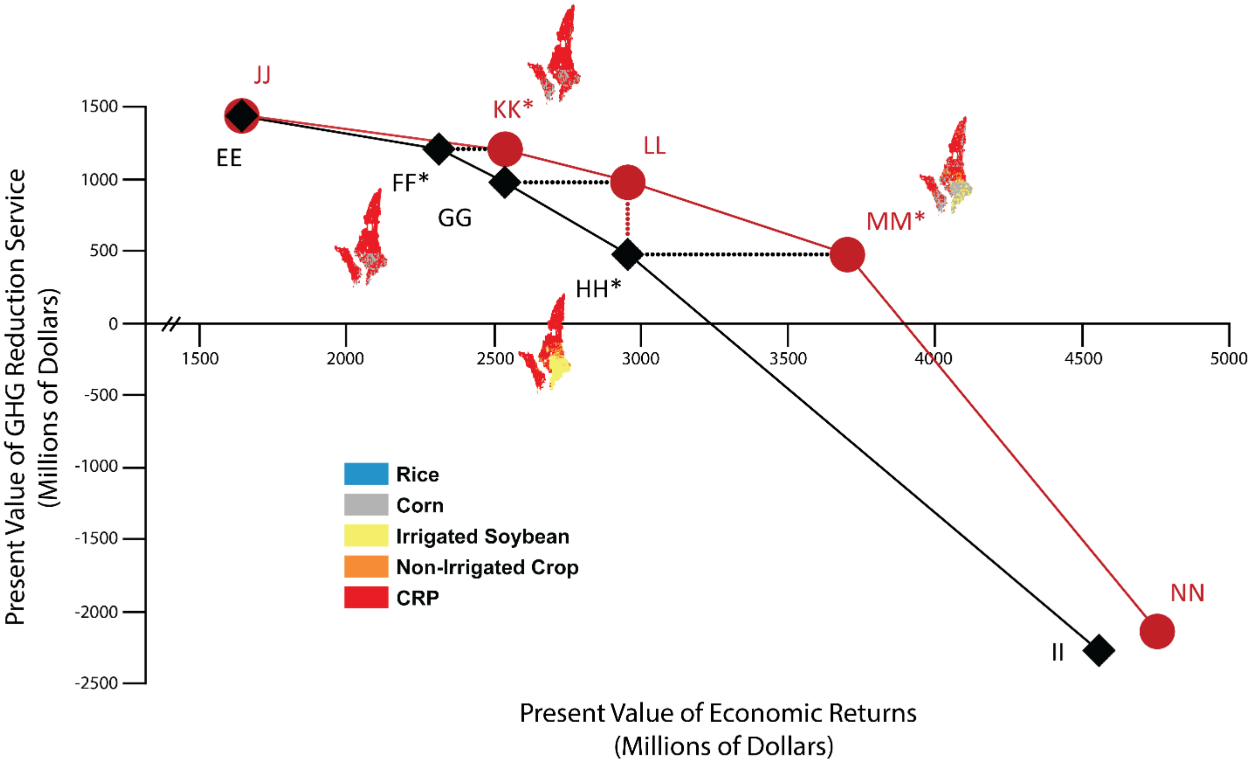

Figure 5. Crop mix patterns associated with specific points along the efficiency frontiers without reservoirs and with reservoirs that show the tradeoff of economic returns and greenhouse gas reduction. Each crop mix pattern shown beside the efficiency frontiers correspond to a lettered point with an asterisk on the frontiers. Efficiency frontiers are closer together than in Figure 2 at higher ecosystem service values and farther apart than in Figure 2 at lower ecosystem service values. This suggests reservoirs enhance the efficiency of greenhouse gases and economic returns when efficiency depends on the availability of cheap irrigation water for corn. Point MM on the frontier with reservoirs exhibits more corn and less soybeans and less CRP land than point HH on the frontier without reservoirs.

Table 6 indicates the cost-share on reservoir construction cost increases the total of economic returns before transfers plus ecosystem service value from 2551 million to 2877 million (or 13%) because the water supply and GHG value rise. The water supply value is larger because irrigated crops use more reservoir water and GHG reductions are greater since reservoir water pumping requires less fuel combustion. The tax on groundwater pumping increases the value of water supply and GHGs reduction more than the cost-share on reservoirs. The tax encourages a switch away from groundwater to reservoir water (rather just an increase in reservoir water), and while the reservoir water mostly sustains rice the acreage in the crop still falls (Table A.5). The decline in rice acreage, increase in CRP, and the decline in fuel combustion for irrigation all lower the GHG emissions. These policies also on groundwater conservation have the lowest economic cost per ecosystem dollar gained.

A total maximum daily load to improve surface water quality causes land to move into rice, CRP, and reservoirs (Table A.5). The increase in CRP and reservoirs allow the water supply and GHG reduction value to increase. However the increase in CRP land at the expense of corn makes the economic returns fall. The economic returns before transfers plus ecosystem service value rises from 2551 million to 2663 million (or 4%). Water purification has a lower social price than GHGs reduction and groundwater supply, and there is little alignment between water purification and the other ecosystem services. The ability to sell carbon offset credits causes rice and irrigated soybean acreage to decline while the land in reservoirs and sorghum goes up. Less rice makes GHG emissions fall, and the increase in reservoirs and non-irrigated sorghum reduces the GHG emissions from fuel combustion. The large transfers suggest that the market-clearing price for the carbon credits may fall in response to the producers' decision to generate these credits, and the lower price would lower the incentive to generate additional credits.

Table 6: Present value of economic returns and ecosystem services that result when conservation policies influence the economic returns objective for the landscape with reservoirs (in millions of 2013 constant dollars)

Ecosystem service or land cover	**Baseline (Point J)**	**Conservation policies**			
		Cost-share reservoir construction costs [a]	**Tax on ground-water** [b]	**Total maximum daily load** [c]	**Carbon credits** [d]
Greenhouse gases	-2147	-1815	-1715	-1948	-1203
Groundwater supply	-56	-40	-39	-49	-20
Water purification	-2	-2	-2	7	-1
Total ecosystem services	-2206	-1857	-1755	-1991	-1224
Rice	932	962	902	963	754
Irrigated soybeans	698	716	687	670	690
Non-irrigated crop	587	523	597	482	644
Corn	2081	2083	2086	2056	2087
Cotton	439	437	442	373	445
CRP	20	12	25	111	50
Total economic return before government transfer	4757	4734	4738	4654	4669
Government transfer	0	98	-125	0	2521
Total of economic return before government transfer and ecosystem service value	2551	2877	2983	2663	3445
Economic cost per dollar of ecosystem service value gained (dollars) [e]	--	0.07	0.04	0.48	0.09

[a] The cost share for irrigation reservoir construction is 65% based on the rate from Natural Resource Conservation Service's (USDA-NRCS) Agricultural Water Enhancement Program (USDA-NRCS 2014). [b] A tax on groundwater pumping cost of 15% is chosen to achieve groundwater conservation similar to the cost share on reservoir construction. [c] The total maximum annual load is chosen as the phosphorus and sediment exports from point CC on the efficiency frontier optimizing water purification value in the final period. [d] The value of a carbon credit is $28.51 per metric ton of carbon according to the clearing price of the March 2015 auction by the European Union Emission Trading Scheme and an exchange rate of $0.87 per euro (European Commission 2015). [e] The economic cost per dollar of ecosystem service value gained is calculated as the difference in economic returns without and with the policy and dividing this by the difference in total ecosystem service value with and without the policy.

Conclusion

Reservoirs effectively increase economic returns at any given value of all the ecosystem services. However, within the given value of all ecosystem services, not every one of the ecosystem services may increase. Reservoirs allow irrigated crop production to expand and use less groundwater, but the climate regulation and water purification services diminish. This is especially evident when only groundwater supply value is considered and the other ecosystem services ignored. Rice and corn production expand since the reservoirs preserve groundwater, but this causes GHG emissions and surface water pollution to increase. Likewise, if only the GHG reduction service is considered, the reservoirs increase groundwater supply and economic returns, but as the carbon sequestering corn expands then water purification value declines. Only when water purification alone matters do reservoirs increase all the ecosystem services since GHG emissions diminish because irrigation with reservoirs requires less fuel combustion. The general finding is that reservoirs supports a landscape with a higher value of ecosystem services and economic returns, but not all ecosystem services flourish even if valued at their true social prices.

A compromise among objectives typically generates more social value than directing the landscape exclusively to one objective. The efficiency frontiers at the economic maximum show that a small decrease in economic returns provides large gains to the value of the ecosystem service(s). At the other end of the frontiers where the landscape is at an ecosystem service maximum, small decreases in the value of the ecosystem service(s) provide large gains for economic returns. This compromise is possible in part because corn generates strong economic returns and effectively sequesters GHG while using less irrigation water than rice. Also many crops on the landscape, such as non-irrigated sorghum or irrigated soybeans, can provide moderate economic returns without significantly harming ecosystem services. The compromise would be much more difficult if corn prices fell or rice prices rose. Also, a higher social price of water purification would make corn, as a surface water-polluting crop, less effective at bridging economic and ecosystem objectives. For example, moving along the efficiency frontier from point W at the midpoint along the frontier to point U (equivalent to Point A) at the water purification maximum, the social value rises from 2403 million to 3181 million. This indicates a landscape like Point W that compromises objectives does not maximize social value in this case. Arguably, the agricultural landscape is managed currently for economic returns (Point J). Conservation policies targeting one or more of the ecosystem services can adjust the landscape to improve the equity of economic returns and ecosystem services. All policies increase social value but some do so at greater economic cost. The total maximum daily load has low administrative costs without any government transfers, but the economic cost per dollar of ecosystem service gained is large. Agricultural producers selling carbon credits achieve ecosystem services at a lower economic cost, but the transfers may be administratively cumbersome. Policies targeting groundwater conservation, either with a cost-share on reservoir construction costs or a tax on groundwater, achieve a dollar gain in ecosystem services at the least economic cost. With the cost of $120 million to taxpayers and the economy for the cost-share on reservoir construction costs, this suggests a feasible and worthwhile conservation investment of $7.8 million annually at a 5% discount rate.

Our results have similarities with studies that use efficiency frontiers to assess tradeoffs among ecosystem services, species conservation, and economic returns (Nalle et al. 2004; Nelson et al. 2008; Polasky et al. 2008; White et al. 2012). There are large conservation benefits that can be achieved at a relatively low economic cost when the economic returns are at the maximum, but achieving the maximum conservation benefits is expensive for the economy. Polasky et al. (2008) find that lowering economic returns to just 97.1% of a maximum economic score can increase the biological score to 94.7% of the maximum biological score. Nelson et al. (2008) find some policies increase carbon sequestration but lower species conservation, and we find policies that increase carbon sequestration and groundwater supply but decrease the water purification. The recognition of these conflicts and the ability to find alternative crop and irrigation patterns that benefit multiple objectives is the great utility of the efficiency frontier tool.

In confronting declining groundwater, the model can only heuristically suggest crop and farm practices to manage economic returns and ecosystem services in the Arkansas Delta. Relevant details remain that could change the results but go unaccounted in the model since data are unavailable. Some sites may have tenure arrangements between the tenant and landlord that make certain crop and irrigation practices impossible. Crop types and farm practices outside the study area can affect groundwater depletion and surface water pollution inside the study area. The intentional transition from the crops currently grown to the desired crops takes time because the experience and knowledge required in growing a new crop can take years to acquire. In addition, droughts, floods, insect invasions, or other natural events could delay or accelerate transitions among the crops. Also, the population decline in the Arkansas Delta or a major shift in relative crop prices could affect the optimal crop and irrigation patterns. The analysis of these important features of the agricultural landscape should be included in future work.

Acknowledgements

The authors thank the participants of the 2015 Southern Agricultural Economics Association for helpful suggestions. This project was supported by the University of Arkansas Division of Agriculture and the US Geologic Survey of the 104b research grant program, US Department of the Interior.

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