Cost Effectiveness of Greenhouse Gas Reductions through Afforestation of Agricultural Land in the Arkansas Delta

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Afforestation of Agricultural Land in the Arkansas Delta

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Abstract

Sequestration of atmospheric carbon in forested lands offsets carbon emissions from other industries. Conversion of private lands, particularly agricultural tracts in marginal areas, to forests can bolster carbon abatement. The United States government agencies administer some voluntary, incentive-based programs to encourage landowners to adopt production practices with positive environmental outcomes. This policy stream can be used to increase transition of marginal agricultural land to forests, thereby creating new carbon sinks. We analyze an eleven-county study area in the Arkansas Delta to determine feasibility for a subsidy focused on carbon abatement through afforestation. This study area is significant for two reasons: the long growing season and humid climate is ideal for fast growing trees such as loblolly pine, and groundwater depletion dynamics factor heavily into future optimal land use patterns. A spatially-explicit optimization programming model will determine the pattern of land use that maximizes discounted economic returns to landowners and explore responsiveness of optimal land use to government subsidies on forest activities. The result of this effort will assist policymakers in allocating limited resources to programs for greenhouse gas mitigation.

Acknowledgements

As I reflect on my journey, I am overcome with the notion that all I am and aspire to be is owed to Creator and the people who have invested in me. To my parents, my siblings, my family and friends, I give my endless love. To my teachers, advisors and mentors, I give my heartfelt gratitude. To all my relations, I give my faithful service. To my Creator, I give my all and all.

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Introduction

Increasing accumulation of anthropogenic carbon in the atmosphere is the primary driver of climate change (Pachauri and Meyer). Mitigating increasing levels of carbon in the atmosphere requires a reduction in emissions and/or escalation in sequestration. Emissions reduction is achieved through increased energy efficiency: a combination of lower energy demand via behavior change and cleaner energy supply by improved technology or renewable sources. While the most effective way to mitigate climate change may be to reduce emissions, that strategy does little to account for the pollution stock already present. Carbon sequestration, either engineered or natural, can offset damages from the existing state. In this paper, we will focus on afforestation as a cost-effective approach to policy-driven carbon sequestration.

Previous literature on forest carbon abatement is divided into two methodological strands: econometric models and programming models. In econometric models of land use decisions, researchers make future projections based on historical activities. Considerations in this revealed-preference model include accounting for non-pecuniary returns of land use to landowners and “decision-making inertia” that affects how quickly landowners make changes based on economic analysis (Stavins). Stavins (1999) followed by (Newell and Stavins) estimated costs of carbon sequestration associated with converting marginal agricultural land to loblolly pine plantations in the Delta states (Arkansas, Louisiana and Mississippi) by an econometric approach. (Lubowski, Plantinga and Stavins) also conducted an econometric estimation of carbon sinks with national coverage.

In programming models of land use decisions, researchers make future projections based on time-matched data related to exogenous parameters such as production costs, expected revenues, spatial yield potential and market prices. By lessening the tie to the past, this method allows a fuller representation of what may happen if landowners are strict maximizers of net returns. (Moulton and Richards) and (Sohngen and Brown) have previously used optimization programming models for the estimation of afforestation cost-effectiveness.

In this tradition, we employ a spatially-explicit optimization programming model that leans on engineering cost methods of alternative land uses. We seek to contribute to the literature by modifying the programming model's representation of the hydrologic state and broadening options for forest management by the landowner. The hydrologic state can be depicted in two ways, bathtub or spatial. In the bathtub portrayal, groundwater is depleted uniformly across the entire aquifer as if no barriers existed between sites. In the spatial portrayal, the aquifer is envisioned to be divided into site-specific wells that are non-uniformly depleted based on site-specific withdrawals. For forest management, we allow the programming model to determine the optimal rotation length for harvestable forests endogenously. This model and these features were selected in part due to the unique circumstances in the Arkansas Delta.

The Arkansas Delta is a good afforestation candidate for two reasons: it boasts an ideal environment for tree growth and has an increasingly tenuous groundwater situation affecting agricultural production profitability. The long growing season and humid climate in the Arkansas Delta is compatible with fast growing tree species such as loblolly pine, creating a favorable scenario for rapid carbon sequestration. While much of the land in the study area is highly valued for traditional agricultural production, the continuing depletion of groundwater in the area is shifting more land into a "marginal" category. As irrigation costs increase, it may be more profitable for landowners to adopt less water-intensive land cover, making afforestation attractive.

Methods

Land cover

There are n possible land covers include annual land uses, harvested forest types, and permanent forest types. The area of annual land uses s, harvested forest types f, and permanent forest types p for site i and period t are denoted by,,, respectively. The k possible annual land uses include furrow-irrigated corn and soybeans, dryland soybeans, flood irrigated rice, and fallow land. The l possible harvestable forest types are loblolly pine and mixed hardwood plantations, and the m possible permanent forest types are loblolly pine and mixed hardwood forest. The area of land chosen for annual uses, harvestable forest, and permanent forest in period t equals the area of all land covers j in period t, which must equal the initial land available at each site (Eq. 1),

$$\sum_s^k L_{ist} + \sum_f^l L_{ift} + \sum_p^m L_{ipt} = \sum_j^n L_{ijt} = \sum_j^n L_{ij0}\,. \tag{1}$$

Any annual land use can become another land cover in the subsequent period within the boundaries of the minimum and maximum amount of land for that land cover based on historical patterns. A permanent forest type remains in that forest type for perpetuity. The area of land planted to permanent forest type p at site i in period t is FP_{ipt}. The area in permanent forest type p in period t at site i is then (Eq. 2),

$$L_{ipt} = L_{ip(t-1)} + FP_{ipt}\,. \tag{2}$$

A harvestable forest type f must follow certain rules about forest rotation through time. The area of harvestable forest type f planted at site i at period t and harvested at any period $\tilde{t}$ after period t, is $F_{ift\tilde{t}}$. Likewise, the area of harvestable forest type f harvested at site i in period t

and planted at any period $\bar{t}$ before period *t*, is $F_{if\bar{t}t}$. The area in harvestable forest type *f* in period *t* at site *i* is as follows (Eq. 3):

$$L_{ift} = L_{if(t-1)} + \sum_{\tilde{t}}^{T} F_{ift\tilde{t}} - \sum_{\bar{t}}^{T} F_{if\bar{t}t} \,. \tag{3}$$

The area in harvestable forest type *f* at the end of period *t* is the area in forest type *f* in the previous period plus the net change of harvestable forest cover *f* during the period *t*. The net change in the harvestable forest type *f* is the land planted in harvestable forest in period *t* and harvested at a later period $\tilde{t}$, $\sum_{\tilde{t}}^{T} F_{ift\tilde{t}}$, that includes any period to end of the study horizon, *T*, less the land harvested from harvestable forest in period *t* and planted at an earlier period $\bar{t}$, $\sum_{\bar{t}}^{T} F_{if\bar{t}t}$.

A constraint on the harvest of forest type *f* after planting in period *t* ensures forest products can only be harvested at a period after planting in the case when the rotation length is chosen within the model, known as flexible rotation length (Eq. 4), or at a fixed time after planting in the case when the rotation length is fixed for forest type *f* (Eq. 5):

$$F_{ift\tilde{t}} \le m_{t\tilde{t}} \sum_{j}^{n} L_{ij0} \,, \tag{4}$$

$$F_{ift\tilde{t}} \le m_{t\tilde{t}f} \sum_{j}^{n} L_{ij0} \,. \tag{5}$$

where $m_{t\tilde{t}}$ in Eq. 4 takes a value of zero if $\tilde{t} < t$, meaning harvest occurs in a period before planting, and a value of one if $\tilde{t} > t$ which indicates that harvest occurs in a period after planting. Eq. 4 says that the planting of harvestable forest type *f* in period *t* is only possible if the harvest of the planted trees occur in a later period. The $m_{t\tilde{t}f}$ in Eq. 5 takes a value of one if $\tilde{t} - t = k_f$, where k_f is an integer that indicates the length of the fixed rotation for forest type *f*, and a value of zero otherwise. Eq. 5 says that the planting of harvestable forest type *f* in period *t* is only possible if the harvest occurs k_f periods later.

Irrigation and the model of the aquifer

The average annual irrigation that land cover *j* receives to supplement precipitation is wd_j. Irrigation water comes from groundwater pumping from wells, GW_{it}. The irrigation water applied to the crops at each site equals the water extracted from the wells at each site (Eq. 6),

$$\sum_j^n wd_j L_{ijt} = GW_{it} . \tag{6}$$

Farmers apply a constant wd_j to land cover *j* every period rather than deficit irrigate since, even in the long run, there is empirical evidence of a perfectly inelastic demand for irrigation water (Wang and Segarra).

If groundwater flows laterally without resistance across all sites, known as a bathtub aquifer, then the change in the depth to the aquifer, AQ_t, is the same at all sites in response to the collective groundwater extraction of all producers, $\sum_i^w GW_{it}$, across the *w* sites on the landscape, and the sum of the site level natural recharge, $\sum_i^w nr_i$, that occurs from precipitation, streams, and underlying aquifers (Eq. 7),

$$AQ_t = AQ_{t-1} - \sum_i^w GW_{it} + \sum_i^w nr_i . \tag{7}$$

The cost of pumping groundwater at a site, GC_{it}, depends on the cost to lift a unit of water by a unit of length, c^p, and the initial depth of the well, dp_i. The depletion of the bathtub aquifer volume, $AQ_0 - AQ_t$, divided by the area of the landscape, $\sum_i^w \sum_j^n L_{ij0}$, indicates how much the depth to the aquifer increases at all sites each period. Capital costs per unit of water to account for new well drilling and pumps in response to the aquifer decline is c^c (Eq. 8).

$$GC_{it} = c^c + c^p \left(dp_i + \frac{\left(AQ_0 - AQ_t\right)}{\sum_i^m \sum_j^n L_{ij0}} \right). \tag{8}$$

A spatial aquifer, where there is no lateral groundwater flow, has uneven aquifer depletion and regions of groundwater depression due to the variable intensity of well pumping across the landscape. The volume of a flat-bottomed aquifer beneath site *i* at the end of the period *t* is AQ_{it}. The change each period in the aquifer volume at site *i* is difference of the natural recharge and the groundwater pumping (Eq. 9). The depletion of the aquifer volume, $AQ_{i0} - AQ_{it}$, divided by the area of the site, $\sum_j^n L_{ij0}$, indicates how much the depth to the aquifer changes for each site (Eq. 10).

$$AQ_{it} = AQ_{i(t-1)} - GW_{it} + nr_i . \tag{9}$$

$$GC_{it} = c^c + c^p \left(dp_i + \frac{\left(AQ_{i0} - AQ_{it}\right)}{\sum_j^n L_{ij0}} \right). \tag{10}$$

The initial well depth for any given site in the bathtub and the spatial aquifer models is the same to examine how spatial differences in groundwater availability and depletion influence the model runs. Due to limited groundwater availability, a profit maximizing farmer might switch land out of irrigated crops into non-irrigated crops, fallow or forest land covers at a particular period.

Greenhouse gas (GHG) net sequestration

The GHG emissions in carbon equivalents come from the following sources: 1) a life cycle assessment (LCA) up to the farm gate of the *j* land covers, 2) fuel combustion associated with irrigation as groundwater levels decline, 3) carbon losses due to wood processing, and 4) the release of GHGs from the decay of wood products after the harvest of forest type *f*.

The GHG emissions E_s per unit of annual land cover *s* from the LCA are associated with fuel, the manufacture of chemicals and fertilizer, methane releases from rice production, and nitrous oxide emissions from nitrogen fertilizer application to the soil. The GHG emissions E_f per unit of harvestable forest land are calculated for chemicals used in site preparation, chemicals used for herbaceous weed control, fertilizer for growth promotion, and fuel for those applications plus thinning and harvest activities. The GHG emissions E_p per unit of permanent forest land are associated with site preparation and weed control. The emissions up to the farm gate for the annual and forested land covers, EL_{it}, for each site *i* depend on how much land is in each cover and the emissions per unit of land cover (Eq. 11).

$$EL_{it} = \sum_{s}^{k} E_s L_{ist} + \sum_{f}^{l} \sum_{\tilde{t}}^{T} E_f F_{if t\tilde{t}} + \sum_{p}^{m} E_p FP_{ipt} \tag{11}$$

Fuel combustion emissions from well pumping, EG_{it}, at site *i* depend on changing depth to the aquifer and the volume of water pumped from the well in period *t* (Eq. 12),

$$EG_{it} = GW_{it} \left(dp_i + \frac{\left(AQ_{i0} - AQ_{it} \right)}{\sum_{j}^{n} L_{ij0}} \right) \sigma_g \, , \tag{12}$$

where σ_g is a scalar that converts the diesel fuel combustion required to lift a unit of water up a unit of distance into carbon emissions.

The GHG emissions from forest product processing has two components. At harvest time *t*, a proportion, v_f, of the woody material with carbon planted at time for each unit of land in harvestable forest type *f* is taken off site for processing. At the processing facility, a proportion, u_f, of the carbon in the wood material releases during the transformation of industrial roundwood to primary wood products. Eq. 13 indicates the carbon emission, EP_{it}, from the processing of harvestable forest types at time *t* and site *i*.

$$EP_{it} = \sum_f^I \sum_{\bar{t}}^T u_f v_f TC_{f\bar{t}t} F_{if\bar{t}t} \ . \tag{13}$$

Primary wood products eventually take the form of end-use products such as houses, furniture or paper. At the end of these products' lifespan, a proportion of the carbon stored in them is emitted back into the atmosphere. The proportions x_f and z_f represent the present value of the proportion of carbon emitted to the atmosphere from the decay of pulp and sawtimber products of industrial roundwood in the South Central region, respectively, over the one hundred years since harvest (see Table 6 in Smith et al. 2005). The proportion of the harvested wood that becomes pulp products is π_f and saw timber products is λ_f. Eq. 14 indicates the value of carbon emission in time t, ED_{it}, from decay of end-use wood products for harvestable forest types planted at time and site *i*.

$$ED_{it} = \sum_f^I \sum_{\bar{t}}^T (x_f \pi_f + z_f \lambda_f)\left(1 - u_f\right) v_f TC_{f\bar{t}t} F_{if\bar{t}t} \ . \tag{14}$$

Eq. 15 indicates the present value of emissions, ET_{it}, from all land covers at time *t* and site *i*.

$$ET_{it} = \delta_t \left(EL_{it} + EG_{it} + EP_{it} + ED_{it} \right), \tag{15}$$

where the discount factor, , to obtain the present value of GHG emissions is the same as the discount factor for finding the present value of monetary flows (Lubowski et al. 2006).

For the sequestration of carbon, this occurs with annual land covers due to aboveground biomass and belowground biomass according to the plant residue, soil texture, and tillage practices (Popp et al. 2011). The carbon sequestered by aboveground biomass per acre for crop *j* in site, AGB_{ij}, is

$$AGB_{ij} = Y_{ij}\lambda_j(1-\alpha_j)\left(\frac{1}{H_j}-1\right)\kappa_j\eta_j\beta_j, \tag{16}$$

where Y_{ij} is the grain or fiber yields in conventional units per acre for crop j in site i, and yield is converted to tons per acre using λ_j, and then to dry mass using the moisture content for the (wet) yield of the crop *j* with α_j (Eq. 16). The harvest index, H_j, uses the crop yield to determine the aboveground biomass such as stems and leaves that remain on the field after harvest. The harvested grain or fiber once beyond the farm gate does not affect GHG reduction although products such as clothing from cotton can store carbon as effectively as soil. To convert the aboveground biomass into tons of carbon sequestrated, the proportion of plant residue incorporated in the soil depends on tillage methods for crop *j*, κ_j, and tillage affects the fraction, η_j, of carbon from incorporated plant residue remaining in the soil after microbial decomposition. The estimated carbon concentration of aboveground biomass is β_j.

The carbon sequestrated from the belowground biomass per acre for crop j in site i, BGB_{ij}, is estimated by

$$BGB_{ij} = Y_{ij}\lambda_j(1-\alpha_j)\left(\frac{\phi_j}{H_j}\right)\eta_j\chi_j\,, \tag{17}$$

where, like in equation (8), the dry mass of the yield in tons per acre is determined with Y_{ij}, λ_j, and α_j (Eq. 17). The shoot/root ratio ϕ_j divided by the harvest index H_j converts the yield to belowground biomass of which only a fraction, η_j, with tillage affecting microbial decomposition of incorporated plant residue with an estimated carbon concentration of χ_j.

The soil factor, ξ_i, which is the fraction of carbon lost to respiration due to soil related microbial activity is a weighting of soil textures at each site *i*. Porous soil (i.e. sandy) encourages microbial activity and respiration due to more intense wetting and drying cycles compared to finer textured soils (i.e. clay). Eq. 18 indicates the carbon sequestration for annual land covers, in period *t* carbon values, in period *t* and site *i* (SA_{it}).

$$SA_{it} = \sum\nolimits_s^k \left[\left(AGB_{is} + BGB_{is}\right)\xi_i\right]L_{ist} \tag{18}$$

The rise in carbon sequestration from woody material in time *t* since the previous period associated with trees planted in time $\bar{t}$ is $TC_{f\bar{t}t} - TC_{f\bar{t}(t-1)}$ for a unit of land in harvestable forest type *f*. We track this annual sequestration in time *t* for any harvestable forest land with trees planted at an earlier time $\bar{t}$ and harvested at the current or later period, $\tilde{t}$, and the land that meets this criteria is $m_{t\tilde{t}}F_{if\bar{t}\tilde{t}}$. Eq. 19 indicates the carbon sequestration, in planting period $\bar{t}$ values, from harvestable forest types in period *t* and site *i* (SF_{it}).

$$SF_{it} = \sum\nolimits_f^I \sum\nolimits_{\tilde{t}}^T \sum\nolimits_{\bar{t}}^T \left(TC_{f\bar{t}t} - TC_{f\bar{t}(t-1)}\right) m_{t\tilde{t}} F_{if\bar{t}\tilde{t}}\,. \tag{19}$$

The carbon sequestration increase from additional woody material for a unit of land in permanent forest type p in time t since the previous period associated with forest planted in time $\bar{t}$ is $TC_{p\bar{t}t} - TC_{p\bar{t}(t-1)}$. Eq. 20 indicates the carbon sequestration, in planting period $\bar{t}$ values, from permanent forest in period t and site i (SP_{it}).

$$SP_{it} = \sum_{p}^{m} \sum_{\bar{t}}^{T} \left(TC_{p\bar{t}t} - TC_{p\bar{t}(t-1)} \right) FP_{ip\bar{t}} \tag{20}$$

Eq. 21 indicates carbon sequestration for all land covers in present values in period t and site i (S_{it}),

$$S_{it} = \delta_t SA_{it} + \delta_{\bar{t}} \left(SF_{it} + SP_{it} \right). \tag{21}$$

The discount factor, $\delta_{\bar{t}}$, to obtain the present value of GHG emissions discounts from the planting period $\bar{t}$ rather than period t because the carbon sequestration from harvestable and permanent forest types is in planting period $\bar{t}$ carbon values.

Forest in permanent type p can continue to grow and sequester carbon after the end of the study horizon, T, and this gain in sequestration counts toward the sequestration that occurs due to forest planting during the study period. A permanent forest type p eventually reaches a maximum steady state amount of carbon sequestered, where the emissions from the decay of trees in the old growth forest are exactly offset by the sequestration from the growth of new trees in the forest, TCM_p. The carbon sequestered in permanent forest type p between the planting period $\bar{t}$ and the end of study horizon is $TC_{p\bar{t}T}$. Eq. 22 indicates the carbon sequestration, in planting period $\bar{t}$ values, from permanent forest that occurs after the end of the study horizon at site i (SPM_i).

$$SPM_i = \sum_p^m \sum_{\bar{t}}^T \left(TCM_p - TC_{p\bar{t}T} \right) FP_{ip\bar{t}} \; . \tag{22}$$

Farm returns objectives

We suppose no change over time in the yield of an annual crop s at site i, y_{is}. The cost to produce an annual crop per unit of land excluding the irrigation cost is C_s, and the price per unit of an annual crop s is p_s, which are both constant in real terms. The net return for annual crop s before irrigation cost is $p_s y_{is} - C_s$. Fallow land has an annual maintenance cost and no revenue.

The yield for harvestable forest planted in period $\bar{t}$ and harvested in period t is $y_{f\bar{t}t}$. The price per unit of harvested wood from forest type f is the weighted stumpage price of pulpwood, pp_f, and saw timber, pt_f, based on the proportions of wood that go to pulp and saw timber shown in Eq. 12, respectively, $pp_f \pi_f + pt_f \lambda_f$. The revenue from forest harvested in period t but planted in a period $\bar{t}$ before period t is $\sum_f^l \sum_{\bar{t}}^T \left(pp_f \pi_f + pt_f \lambda_f \right) y_{f\bar{t}t} F_{if\bar{t}t}$. The production cost per unit of land in harvestable forest type f is C_f, and the total production cost from forest planted in period t and harvested at a later period $\tilde{t}$ is $\sum_f^l \sum_{\tilde{t}}^T C_f F_{ift\tilde{t}}$. The production cost per unit of land in permanent forest type p is C_p, and the total production cost from permanent forest planted in period t is $\sum_p^m C_p F_{ipt}$. There is no revenue from the land planted to permanent forest.

The objective is to maximize the present value of profits from farm production over the horizon T by choosing for each site and each period t the amount of land in an annual use, L_{ist}, the amount of land harvested from, $F_{if\bar{t}t}$, and planted to, $F_{ift\tilde{t}}$, forest type f, the amount of land planted to permanent forest type p, FP_{ipt}, and the amount of groundwater pumped for the irrigation of crops, GW_{it} (Eq. 23):

$$\max_{\substack{L_{ist}, F_{if\bar{t}t}, F_{if\bar{t}\tilde{t}},\\ FP_{ipt} GW_{it}}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{w} \begin{pmatrix} \sum_s^k (p_s y_{is} - C_s) L_{ist} + \sum_f^l \sum_{\bar{t}}^T (pp_f \pi_f + pt_f \lambda_f) y_{f\bar{t}t} F_{if\bar{t}t} \ldots \\ \ldots - \sum_f^l \sum_{\tilde{t}}^T C_f F_{if\bar{t}\tilde{t}} - \sum_p^m C_p FP_{ipt} - GC_{it} GW_{it} \end{pmatrix} \right). \tag{23}$$

A time horizon T is chosen to balance the study of the long run accumulation of carbon in harvestable and permanent forests, as well as the long run depletion of the aquifer, with the relevance of past prices, crop yields, and production costs. Optimization occurs subject to constraints on the spatial dynamics of land and irrigation from Equations 1 to 10 in addition to non-negativity constraints on land, groundwater pumping, and the aquifer. The carbon emissions and sequestration shown in Equations 11 to 22 are not constraints on the optimization but respond to the producer's choices to maximize profits. This problem is non-linear in the groundwater extraction costs, and the CONOPT solver in the Generalized Algebraic Modeling System (GAMS) 23.5.1 identifies the solution.

Subsidies and cost-effectiveness

We propose a government-funded scheme to increase sequestration via forests through subsidizing landowners. We take two approaches, one encouraging harvestable forests and the other encouraging permanent forests. The subsidy regimen considered in this paper is divided into three methods: cost share on production cost for harvestable or permanent forests (sub_f or sub_p), one-time flat-rate transfer to landowner at planting for permanent forest (tr_p) and one-time flat-rate transfer to landowner at harvest for harvestable forest (tr_f). The subsidy at harvest is limited to the amount of land that remains in forest for a minimum number of years (25 years) before harvest.

The subsidy regimen adjusts to have the change in net carbon sequestration from the subsidy roughly equal for all scenarios so that the cost-effectiveness is comparable across scenarios. Subsidies are applied per unit of land; they can be applied for either harvestable forest or permanent forest, but not both in the same scenario. The preferred subsidy is defrayed full or partial planting costs before moving to one-time flat-rate transfers. Eq. 24 shows the subsidies as part of the economic objective function Eq. 23 section relevant to forests

$$\max_{L_{ijt},GW_{it}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} ...[\left(y_{ifw} p_{fw} + y_{ift} p_{ft} + tr_f - (1 - sub_f) C_f \right) L_{ift}] + [(1 - sub_p)\left(C_p \right) L_{ift} - tr_p] \right) \quad (24)$$

The average cost of carbon is the sum of the increase in farm net returns with the subsidy minus the total subsidy (which is a cost to taxpayers) divided by the increase in the net carbon sequestration with the subsidy. The marginal cost of carbon is the increase in in farm net returns with the subsidy minus the total subsidy for sequestration of one additional unit of carbon.

Sensitivity analysis

Our model is dependent on many parameters that are subject to change in the future. After determining the initial results, we conduct sensitivity analyses of multiple exogenous variables using the most cost-effective treatment. These variables are crop margins (variance in annual land state revenues and/or outlays), groundwater aquifer depth, harvestable forest product prices, and harvestable forest product mix between pulpwood and saw timber.

Data

The study area consists of three eight-digit hydrologic unit code watersheds within eleven counties in the Arkansas portion of the Lower Mississippi River Basin (Fig. 1). We exclude land not under cultivation, such as public land and urban areas, from the study area (Johnson and Mueller). Spatial heterogeneity of crop production, yield, and below ground hydrologic conditions on the landscape are preserved by dividing the study area into 2,000 sites. Initial acreage for the annual crops of interest (corn, rice and soybeans) by site are drawn from the 2017 Cropland Data Layer (USDA NASS). Soybean acreage by site is divided into irrigated and non-irrigated categories using county level statistics over the past five years (USDA NASS). A real discount rate of 2% is set based on the yield of a 30-year Treasury Bond over the past thirty years (US Treasury).

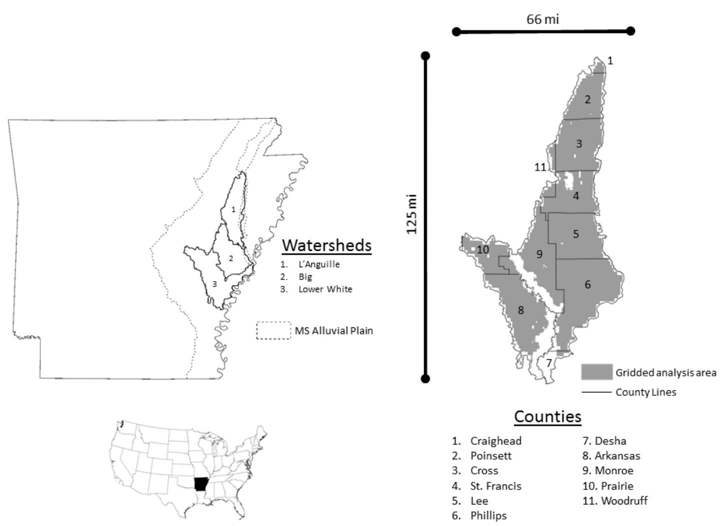

Figure 1. Three eight-digit hydrologic unit code watersheds and the eleven Arkansas counties wherein define the study area. Public lands and urban areas are excluded. The location of the study area within the State of Arkansas is shown.

Land cover production and irrigation

Annual crop yields at each site come from a county centroid interpolation of a five-year average of county yields from 2014 to 2018 (USDA NASS). Annual crop production costs (excluding irrigation) and crop irrigation requirements come from state level five-year averages from 2014 to 2018 (Flanders, Baker and Barber). Annual crop prices are fifty-year averages from 1969 to 2018 for harvest time contracts in the state (USDA NASS). Labor, fuel, lube and oil, and poly pipe for border irrigation plus the levee gates for the flood irrigation of rice all contribute to the costs of irrigation (Hogan et al., 2007). The wells, pumps, gearheads, and power units have purchase and maintenance costs that raise the per cubic-meter costs of irrigation water. The depth to the water table and the corresponding fuel needed to raise water determines the fuel cost per cubic meter from the aquifer. A 50 meter well requires about 65.5 liters of diesel per 1,000 cubic meters of water, and a 100 meter well requires about 131 liters of diesel per 1,000 cubic meters of water (Hogan et al., 2007). About 18 liters of diesel are necessary to pump 1,000 cubic meters of water to and from a reservoir (Hogan et al., 2007). EIA (2019) indicates $1 per liter of diesel and we add 10% to the fuel costs to account for oil and lube for irrigation equipment (Hogan et al., 2007). The majority of wells in the regions are diesel, but the proportion of electric wells is rising (USDA-NASS, 2014).

The estimate of biomass growth of forest uses the net merchantable bole volume of growing-stock trees per acre of timberland from 2013 to 2017 by forest type and stand age in five-year intervals (Forest Inventory EVALIDator web-application). Volume of biomass converts to weight with the specific gravity of each tree type (Wagner Meters) and the biomass goes into pulpwood and saw timber based on the estimates of the biomass quality in the study area (Self). A cubic function estimates the biomass weight by five-year interval of stand age, and the coefficients for the cubic function for each forest type are shown in Table 1. Fixed rotations are 25 years for pine and 50 years for hardwood.

Forest production costs for loblolly pine are from a 2016 survey of the costs of forestry practices across the southeastern United States (Maggard and Barlow), and for mixed hardwood forests from estimates of projects by the USDA Natural Resource Conservation Service (Childress). Stumpage prices, which account for harvesting costs, for pulpwood and saw timber are a twenty-five year average from 1992 to 2016 of the southern Arkansas region (Prestemon) with adjustments for the Delta region (Pelkki). Finally, the ratio of pulpwood and saw timber for each forest type were set at conservative estimates for the growing region.

Carbon Emissions and Sequestration

For forests, emissions from production and decay of wood products from harvested land are modeled in the manner adopted by (Smith, Heath and Skog). Parameters for the proportion of carbon emitted at each step of processing relate to Table 6 in Smith et al.

Table 1 Economic and Hydrologic Data and Parameters for Forest Land States

Parameter	Definition	Value
pp_{pine}, pt_{pine}	Stumpage price of pine [pulpwood, saw timber] ($/ton)	5, 20
$pp_{hardwood}$, $pt_{hardwood}$	Stumpage price of hardwood [pulpwood, saw timber] ($/ton)	7, 33.86
$a3, a2, a1, a0$ for y_{ftt}	Coefficients for cubic function estimate of pine biomass growth as function of the stand age, and the coefficient number refers to the corresponding power of the term in the polynomial	0.002, -0.0318, 2.0564, -6.0942
$b3, b2, b1, b0$ for y_{ftt}	Coefficients for cubic function estimate of hardwood biomass growth as function of the stand age, and the coefficient number refers to the corresponding power of the term in the polynomial	0.00006, -0.0054, 0.8096, -2.8753
π_f, λ_f	Ratio of [pulpwood, saw timber] in growing stock volume for pine and hardwood	0.7, 0.3
C_f and C_p for pine, hardwood	Production cost of harvestable and permanent [pine, hardwood] ($/ac)[a]	305, 348
k_{pine}, $k_{hardwood}$	Fixed rotation length of [pine, hardwood] in periods and, shown in brackets, in years	5 [25], 10 [50]
E_f, E_p	Carbon emissions per acre from production of [harvestable, permanent] forest for pine and hardwood (tons/ac)	0.46, 0.31
v_{pine}, $v_{hardwood}$	Proportion of total carbon in [pine, hardwood] taken off site for processing	0.74, 0.835
u_{pine}, $u_{hardwood}$	Proportion of carbon in [pine, hardwood] released at processing off site	0.186, 0.606
x_{pine}, $x_{hardwood}$	Proportion of the present value of carbon released from the decay of pulp products from [pine, hardwood]	0.756, 0.741
z_{pine}, $z_{hardwood}$	Proportion of the present value of carbon released from the decay of saw timber products from [pine, hardwood]	0.568, 0.624
TCM_{pine}, $TCM_{hardwood}$	Maximum carbon sequestration by permanent [pine, hardwood] forest (tons/ac)	55.54, 81.38

[a] Production cost of pine is generated from the following production practices: hand planting of bareroot loblolly pine at the specified rate and seedling cost over all land types for the entire study area; chemical application for site preparation via aerial methods for the Northern Coastal Plain; chemical application for herbaceous weed control via all methods for the Northern Coastal Plain; fertilization via all methods and all fertilizer types for the entire study area; timber cruising via all methods for the Northern Coastal Plain; and custodial management for boundary line maintenance and/or road construction/maintenance for the Northern Coastal Plain.

Soil carbon sequestration from above- and below-ground biomass is influenced by county-level annual crop yields, the ratio of root-to-shoot biomass, carbon content in residues, and carbon content in roots (Popp, Nalley and Fortin). The soil carbon adjusts according to local tillage practices and soil texture (Popp, Nalley and Fortin). Tables A1 – A3 in the appendix have the parameters for the carbon emission and sequestration for the annual land states.

The carbon emissions from the fuel, fertilizer and chemical applications for annual crops come from the translation of production practices in the crop enterprise budgets between 2012 to 2018 (Flanders, Baker and Barber) to carbon equivalents (DataSmart 2016 Life Cycle Inventory). Additional emissions come from production practices identified through interviews with crop specialists (Roberts & Norsworthy 2019; Purcell & Norsworthy, 2019; Norman, 2019). Methane byproduct emissions from rice cultivation come from the weighted prevalence of specific production practices (EPA). Emissions from irrigation fuel combustion change in response to the model outcome for the depth to the aquifer.

Aquifer

The initial water table depth and saturated thickness of the Alluvial aquifer is from the Arkansas Natural Resources Commission (2014; 2015). The aquifer volume at site *i* comes from multiplying the site acreage by the saturated thickness of the aquifer. Natural recharge (nr_i) comes from the precipitation and the contributions by local streams and connected aquifers (Reed).

Results

The study contains results from eight core model structures. There are two options each for three structural components: forest rotations can be fixed or flexible, aquifer depletion can be bathtub or spatial, and carbon subsidy preference can be for harvestable forests or permanent forests. These options are represented in Fig. 2 below.

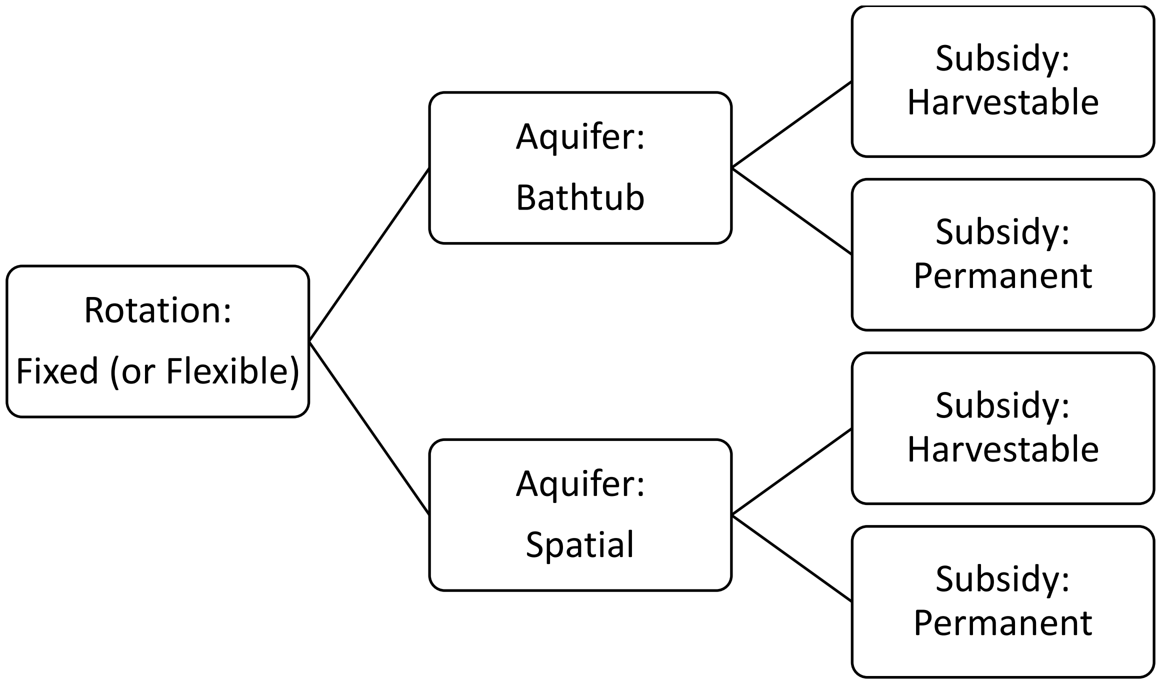

Figure 2. Representation of the eight core models for which cost-effectiveness of carbon sequestration is calculated in this study.

Table 2 shows results for all combinations of the fixed rotation treatment after application of subsidies to achieve ~100 million more tons of carbon sequestered over the study period. All net returns were constant between baseline and treatment for each aquifer depletion type. The optimal solution for bathtub aquifer depletion with harvestable subsidy showed $1,057 billion in net returns (present value) and 130 million metric tons of carbon sequestered over 50 years. Comparing to the baseline seen in Table A4, ~1,600 acres shifted from irrigated soybeans to harvestable pine to increase overall sequestration. The subsidy rate required for this transition was full defrayed planting cost ($305 per acre for pine) and an additional one-time payment at harvest of $4,659 per acre for all harvestable forest acreage. The present value of all carbon subsidies was $9,236,000, leading to an average cost of additional carbon abated of $92.12 per ton.

The optimal solution for bathtub aquifer depletion with permanent subsidy showed $1,057 billion in net returns and 133 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, ~480 acres moved from irrigated soybeans to permanent pine (92%) and permanent hardwood (8%) to increase overall sequestration. The subsidy rate required for this transition was full defrayed planting cost and an additional one-time payment at planting of $732.50 per acre for all permanent forest acreage. The present value of all carbon subsidies was $1,866,000, leading to an average cost of additional carbon abated of $18.08 per ton.

The optimal solution for spatial aquifer depletion with harvestable subsidy showed $1,053 billion in net returns and 1,955 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, significant acreage shifted from permanent pine forest to harvestable pine forest and from dryland soybeans to corn to increase overall sequestration. The subsidy rate required for this transition was full defrayed planting cost and an additional one-time payment at harvest of $1,500 per acre for all harvestable forest acreage. The present value of all carbon subsidies was $55,348,000, leading to an average cost of additional carbon abated of $557.32 per ton.

The optimal solution for spatial aquifer depletion with permanent subsidy showed $1,053 billion in net returns and 1,953 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, significant acreage moved from fallow and harvestable pine to permanent pine to increase overall sequestration. The subsidy rate required for this transition was 10% defrayed planting cost for all permanent forest acreage. The present value of all carbon subsidies was $911,000, leading to an average cost of additional carbon abated of $9.37 per ton.

Table 2 Crop, environmental, and economic conditions for landscape with harvestable or permanent subsidies and with bathtub or spatial aquifer depletion under fixed rotation treatment

Land use, environmental, and economic conditions	Bathtub aquifer with harvestable subsidy	Bathtub aquifer with permanent subsidy	Spatial aquifer with harvestable subsidy	Spatial aquifer with permanent subsidy
Land use conditions[a] (acres)				
Rice	273,200	273,200	272,250	272,250
Irrigated corn	202,400	202,400	193,300	192,640
Irrigated soybeans	534,700	535,820	480,300	481,060
Non-irrigated soybeans	-	-	25,966	27,935
Fallow	-	-	3,938	2,304
Harvestable pine	1,639	-	30,123	5,348
Harvestable hardwood	-	-	-	-
Permanent pine	-	445	6,107	30,434
Permanent hardwood	-	38	-	-
Environmental conditions[b] (million tons of carbon)				
Net carbon sequestration	130	133	1,955	1,953
Change in net carbon sequestration from the subsidy[c]	100	103	99	97
Aquifer stock (thousand acre-feet)	32,157	32,099	35,544	35,544
Economic conditions				
Present value farm net return ($ billions)	1,057	1,057	1,053	1,053
Subsidy for percentage of planting costs	100%	100%	100%	10%
Subsidy at planting ($)	N/A	732.5	N/A	-
Subsidy at harvest ($)	4,659	N/A	1,500	N/A
Present value of carbon subsidy ($ thousands)	9,236	1,866	55,348	911
Average cost of carbon ($/ton)[d]	92.12	18.08	557.32	9.37

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period. [c] The subsidy adjusts to have the change in net carbon sequestration from the subsidy roughly equal for all scenarios so that the cost-effectiveness is comparable across scenarios. [d] The average cost of carbon is the sum of the increase in farm net returns with the subsidy minus the total subsidy (which is a cost to taxpayers) divided by the increase in the net carbon sequestration with the subsidy.

Table 3 shows results for all combinations of the flexible rotation treatment after application of subsidies to achieve ~100 million more tons of carbon sequestered over the study period. All net returns were constant between baseline and treatment for each aquifer depletion type. The optimal solution for bathtub aquifer depletion with harvestable subsidy showed $1,057 billion in net returns (present value) and 132 million metric tons of carbon sequestered over 50 years. Comparing to the baseline seen in Table A5, ~1,600 acres shifted from irrigated soybeans to harvestable pine to increase overall sequestration. The subsidy rate required for this transition was full defrayed planting cost and an additional one-time payment at harvest of $4,675 per acre for all harvestable forest acreage. The present value of all carbon subsidies was $9,366,000, leading to an average cost of additional carbon abated of $92.41 per ton.

The optimal solution for bathtub aquifer depletion with permanent subsidy showed $1,057 billion in net returns and 134 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, ~400 acres moved from irrigated soybeans to permanent pine (50%) and permanent hardwood (50%) to increase overall sequestration. The subsidy rate required for this transition was full defrayed planting cost and an additional one-time payment at planting of $731 per acre for all permanent forest acreage. The present value of all carbon subsidies was $1,595,000, leading to an average cost of additional carbon abated of $15.45 per ton.

The optimal solution for spatial aquifer depletion with harvestable subsidy showed $1,053 billion in net returns and 1,561 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, significant acreage shifted from permanent pine and fallow to harvestable pine forest to increase overall sequestration. The subsidy rate required for this transition was 45% defrayed planting cost for all harvestable forest acreage. The present value of all carbon subsidies was $6,688,000, leading to an average cost of additional carbon abated of $50.39 per ton.

The optimal solution for spatial aquifer depletion with permanent subsidy showed $1,053 billion in net returns and 1,525 million metric tons of carbon sequestered over 50 years. Comparing to the baseline, significant acreage moved from fallow and harvestable pine to permanent pine to increase overall sequestration. The subsidy rate required for this transition was 15% defrayed planting cost for all permanent forest acreage. The present value of all carbon subsidies was $104,000, leading to an average cost of additional carbon abated of $1.08 per ton.

Table 4 shows results for sensitivity analysis of crop margins (doubled and halved) and groundwater depth (doubled and halved) for the most cost-effective option from the previous results (flexible rotation of spatial aquifer depletion with permanent forest subsidy preference). All treatments were less cost-effective than the baseline, but still well below the average cost of additional carbon abated for the seven other core model structures.

Table 5 shows results for sensitivity analysis of forest product prices and forest product mixes for the most cost-effective option from the previous results. The final treatment (adjusting product mix to 85% pulpwood and 15% timber) lead to a lower average cost. The optimal solution for product mix 85/15 showed $1,053 billion in net returns and 1,515 million metric tons of carbon sequestered over 50 years. Comparing to the baseline in appendix Table (11), significant acreage moved from fallow and harvestable pine to permanent pine to increase overall sequestration. The subsidy rate required for this transition was 6% defrayed planting cost for all permanent forest acreage. The present value of all carbon subsidies was $41,000, leading to an average cost of additional carbon abated of $0.40 per ton. This was the overall lowest average cost of any model structure.

Table 3 Crop, environmental, and economic conditions for landscape with harvestable or permanent subsidies and with bathtub or spatial aquifer depletion under flexible rotation treatment

Land use, environmental, and economic conditions	Bathtub aquifer with harvestable subsidy	Bathtub aquifer with permanent subsidy	Spatial aquifer with harvestable subsidy	Spatial aquifer with permanent subsidy
Land use conditions[a] (acres)				
Rice	273,200	273,200	272,250	272,250
Irrigated corn	202,400	202,400	192,740	192,720
Irrigated soybeans	534,700	535,900	480,940	480,980
Non-irrigated soybeans	-	-	27,889	27,934
Fallow	-	-	5,857	5,588
Harvestable pine	1,639	-	32,293	31,002
Harvestable hardwood	-	-	-	-
Permanent pine	-	203	-	1,510
Permanent hardwood	-	203	-	-
Environmental conditions[b] (million tons of carbon)				
Net carbon sequestration	132	134	1,561	1,525
Change in net carbon sequestration from the subsidy[c]	101	103	133	97
Aquifer stock (thousand acre-feet)	32,157	32,095	35,544	35,544
Economic conditions				
Present value farm net return ($ billions)	1,057	1,057	1,053	1,053
Subsidy for percentage of planting costs	100%	100%	45%	15%
Subsidy at planting ($)	N/A	731	N/A	-
Subsidy at harvest ($)	4,675	N/A	-	N/A
Present value of carbon subsidy ($ thousands)	9,366	1,595	6,688	104
Average cost of carbon ($/ton)[d]	92.41	15.45	50.39	1.08

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period. [c] The subsidy adjusts to have the change in net carbon sequestration from the subsidy roughly equal for all scenarios so that the cost-effectiveness is comparable across scenarios. [d] The average cost of carbon is the sum of the increase in farm net returns with the subsidy minus the total subsidy (which is a cost to taxpayers) divided by the increase in the net carbon sequestration with the subsidy.

Table 4 Crop, environmental, and economic conditions for landscape with or without permanent forest subsidies, spatial aquifer depletion, and flexible rotation for crop margin and groundwater depth variance

Land use, environmental, and economic conditions	Crop margin double	Crop margin half	Groundwater depth double	Groundwater depth half
Land use conditions[a] (acres)				
Rice	272,250	272,250	272,250	272,250
Irrigated corn	192,230	193,300	193,100	192,390
Irrigated soybeans	481,750	401,200	447,830	481,560
Non-irrigated soybeans	27,388	107,250	60,836	27,590
Fallow	4,032	5,772	5,322	5,723
Harvestable pine	27,697	29,991	30,870	30,908
Harvestable hardwood	-	-	-	-
Permanent pine	6,610	2,204	1,753	1,534
Permanent hardwood	-	-	-	-
Environmental conditions[b] (million tons of carbon)				
Net carbon sequestration	1,771	1,522	1,538	1,521
Change in net carbon sequestration from the subsidy[c]	95	98	96	94
Aquifer stock (thousand acre-feet)	35,532	39,498	37,178	35,532
Economic conditions				
Present value farm net return ($ billions)	2,109	525	1,052	1,054
Subsidy for planting costs	10%	43%	16%	16%
Subsidy at planting ($)	-	-	-	-
Present value of carbon subsidy ($ thousands)	275	344	117	109
Average cost of carbon ($/ton)[d]	2.89	3.50	1.21	1.15

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period. [c] The subsidy adjusts to have the change in net carbon sequestration from the subsidy roughly equal for all scenarios so that the cost-effectiveness is comparable across scenarios. [d] The average cost of carbon is the sum of the increase in farm net returns with the subsidy minus the total subsidy (which is a cost to taxpayers) divided by the increase in the net carbon sequestration with the subsidy.

Table 5 Crop, environmental, and economic conditions for landscape with permanent forest subsidies, spatial aquifer depletion, and flexible rotation for tree price and product mix variance

Land use, environmental, and economic conditions	Tree price alternative	Tree product mix (45 p/55 t)	Tree product mix (85 p/15 t)
Land use conditions[a] (acres)			
Rice	272,250	272,250	272,250
Irrigated corn	192,730	192,720	192,720
Irrigated soybeans	480,950	480,980	480,980
Non-irrigated soybeans	27,897	27,912	27,944
Fallow	5,452	5,516	5,588
Harvestable pine	31,161	30,947	30,838
Harvestable hardwood	-	-	-
Permanent pine	1,527	1,661	1,665
Permanent hardwood	-	-	-
Environmental conditions[b] (million tons of carbon)			
Net carbon sequestration	1,537	1,549	1,515
Change in net carbon sequestration from the subsidy[c]	101	101	104
Aquifer stock (thousand acre-feet)	35,544	35,544	35,544
Economic conditions			
Present value farm net return ($ billions)	1,053	1,053	1,053
Subsidy for planting costs	28%	26%	6%
Subsidy at planting ($)	-	-	-
Present value of carbon subsidy ($ thousands)	197	193	41
Average cost of carbon ($/ton)[d]	1.94	1.92	0.40

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period. [c] The subsidy adjusts to have the change in net carbon sequestration from the subsidy roughly equal for all scenarios so that the cost-effectiveness is comparable across scenarios. [d] The average cost of carbon is the sum of the increase in farm net returns with the subsidy minus the total subsidy (which is a cost to taxpayers) divided by the increase in the net carbon sequestration with the subsidy.

The model shows that aquifer levels are largely dependent upon the structure (bathtub or spatial) used to define them, yet some changes occur with the addition of other treatment options, such as crop margin and depth variance.

Discussion and Conclusion

The results suggest that the landscape can sequester additional carbon through afforestation of marginal agricultural land. This transition is enticed by the presence of subsidies for harvestable or permanent forests to keep farm net returns on par with traditional agricultural crops. This comes at an overall cost to society in the amount of the subsidy to change landowner decisions. The most cost-effective regimen was the flexible rotation scheme with spatial aquifer depletion and permanent forest subsidy preference. Moreover, multiple regimens gave average cost values well below the results from previous studies (van Kooten, Eagle and Manley). While this may be an indicator that the model is too optimistic, and future iterations could include more nuance in assumptions of landowner willingness to transition based purely on economic analysis, this may also be attributed to addressing the issue from new treatment perspectives.

A key motivation for the study area was the rapidly depleting groundwater levels in the Arkansas Delta. The model tracked aquifer levels through the baseline, eight core model structures and sensitivity analyses. Even in the baseline results, we see a dramatic difference in aquifer levels. When the landowner is asked to consider their access to water as spatially-limited, she conserves more water than in the version where the aquifer is common property. This follows from what we know of resource management in private versus common property scenarios. Since the landowner is already more water conscious in spatial aquifer depletion, the addition of a subsidy does not change the aquifer totals. The situation is different when bathtub aquifer depletion is assumed: landowners are enticed to switch land from irrigated agricultural crops to non-irrigated forests and thus see a decrease in water usage overall. Future work could address the combination of gains from additional carbon sequestered and water conserved via forest subsidies.

The flexible rotation scheme with spatial aquifer depletion and permanent forest subsidy preference is the most cost-effective option for multiple reasons. First, the landowner is already more prone to non-irrigated options due to an intrinsic desire to conserve water. Second, the landowner is more likely to allocate land to harvestable forests because they are allowed to choose the rotation length. We find landowners mostly choose to extend the rotation length past 25 years; while it is seen, few choose a shorter time span. Finally, the presence of the permanent forest subsidy pulls more land into permanent forests where carbon is sequestered indefinitely, as opposed to the re-emission that happens for a large share of harvested wood end-use products.

This model can be extended and further refined. As with annual crops, forest yield would be better approximated by including site-specific information in the calculations. As biomass yield estimates improve, so will carbon sequestration and emissions information by site. Other considerations in forest sequestration are natural disasters that disrupt the landscape; examples are wildfires (where stored carbon is released through combustion) and hurricanes (where growing trees die and start to decay). Other research opportunities include changing the scope to investigate how the time horizon impacts land use decisions and ultimately the average cost of additional carbon abated.

As carbon emissions continue to accumulate in the atmosphere, policies aimed at offsetting pollution will increase in importance. Developing a spatially-explicit optimization programming model for carbon sequestration through afforestation provides insight into optimal policymaking decisions.

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Appendix

Table A1 Economic and Hydrologic Data and Parameters for Annual Land States

Parameter	Definition	Value
pr_{rice}	Price of rice ($/cwt)	17.48
pr_{corn}	Price of corn ($/bushel)	5.25
pr_{soy}	Price of soybeans ($/bushel)	12.68
ca_{rice}	Annual production cost of rice ($/ac)	459
ca_{corn}	Annual production cost of corn ($/ac)	485
$ca_{irr\ soy}$	Annual production cost of irrigated soybeans ($/ac)	354
ca_{dsoy}	Annual production cost of non-irrigated soybeans ($/ac)	328
	Annual production cost of fallow ($/ac)	22
wd_{rice}	Annual irrigation per acre of rice (acre-feet)	2.7
wd_{corn}	Annual irrigation per acre of corn (acre-feet)	1.17
wd_{isoy}	Annual irrigation per acre of soybeans (acre-feet)	1.0
c^p	Cost to raise an acre-foot of water by one foot ($/foot)	0.55
δ_t	Discount factor	0.95
ξ_i,	Soil factor, fraction of carbon lost to respiration due to soil related microbial activity	0.72

Table A2 Carbon Sequestration Data and Parameters for Annual Land States

Parameter	Definition	Value
λ_{rice}	Yield conversion for rice from cwt/ac to kg/ac	45.5
λ_{corn}	Yield conversion for corn from bu/ac to kg/ac	25.4
λ_{isoy}	Yield conversion for irrigated soybeans from bu/ac to kg/ac	27.2
λ_{dsoy}	Yield conversion for non-irrigated soybeans from bu/ac to kg/ac	27.2
λ_{dsorg}	Yield conversion for non-irrigated sorghum from bu/ac to kg/ac	25
α_{rice}	Moisture content (wet basis) of rice	0.13
α_{corn}	Moisture content (wet basis) of corn	0.155
α_{isoy}	Moisture content (wet basis) of irrigated soybeans	0.13
α_{dsoy}	Moisture content (wet basis) of non-irrigated soybeans	0.13
α_{dsorg}	Moisture content (wet basis) of non-irrigated sorghum	0.14
H_{rice}	Harvest index (grain weight to aboveground biomass) of rice	0.45
H_{corn}	Harvest index (grain weight to aboveground biomass) of corn	0.43
H_{isoy}	Harvest index (grain weight to aboveground biomass) of irrigated soybeans	0.45
H_{dsoy}	Harvest index (grain weight to aboveground biomass) of non-irrigated soybeans	0.45
H_{dsorg}	Harvest index (grain weight to total aboveground biomass) of non-irrigated sorghum	0.39
β_{rice}	Crop residue C content of rice (g/kg)	360
β_{corn}	Crop residue C content of corn (g/kg)	410
β_{isoy}	Crop residue C content of irrigated soybeans (g/kg)	430
β_{dsoy}	Crop residue C content of non-irrigated soybeans (g/kg)	430
β_{dsorg}	Crop residue C content of non-irrigated sorghum (g/kg)	420
δ_{low}	Aboveground C remaining in the soil with low tillage	0.40
$\delta_{conventioal}$	Aboveground C remaining in the soil with conventional tillage	0.70
η_{low}	Belowground C remaining in the soil with low tillage	0.45
$\eta_{conventional}$	Belowground C remaining in the soil with conventional tillage	0.40
χ_{rice}	Root C content of rice (g/kg)	350
χ_{corn}	Root C content of corn (g/kg)	420
χ_{isoy}	Root C content of irrigated soybeans (g/kg)	430
χ_{dsoy}	Root C content of non-irrigated soybeans (g/kg)	430
χ_{dsorg}	Root C content of non-irrigated sorghum (g/kg)	380
ϕ_{rice}	Root/shoot ratio (belowground/aboveground biomass) of rice	0.16
ϕ_{corn}	Root/shoot ratio (belowground/aboveground biomass) of corn	0.19
ϕ_{isoy}	Root/shoot ratio (belowground/aboveground biomass) of irrigated soybeans	0.16
ϕ_{dsoy}	Root/shoot ratio (belowground/aboveground biomass) of non-irrigated soybeans	0.16
ϕ_{dsorg}	Root/shoot ratio (belowground/aboveground biomass) of non-irrigated sorghum	0.08
σ_g	Conversion factors to track the carbon emitted from fuel combustion to lift an acre-foot of water one foot	10.37

Source: Popp et al. (2011)

Table A3 Carbon Emission Data and Parameters for Annual Land States

Parameter	Definition	Value
E_{rice}	GHG emissions from rice production	621
E_{corn}	GHG emissions from corn production	852
E_{isoy}	GHG emissions from irrigated soybean production	169
E_{dsoy}	GHG emissions from dryland soybean production	137
E_{fallow}	GHG emissions from fallow production	23
$E_{methane}$	GHG emissions from methane release of rice production	1211

Table A4 Crop, environmental, and economic conditions for landscape at baseline conditions with bathtub and spatial aquifer depletion under fixed and flexible rotation treatment

Land use, environmental, and economic conditions	Fixed rotation with bathtub aquifer	Fixed rotation with spatial aquifer	Flexible rotation with bathtub aquifer	Flexible rotation with spatial aquifer
Land use conditions[a] (acres)				
Rice	273,200	272,250	273,200	272,250
Irrigated corn	202,400	192,620	202,400	192,730
Irrigated soybeans	536,300	481,090	536,300	480,960
Non-irrigated soybeans	-	27,941	-	27,934
Fallow	-	3,502	-	6,510
Harvestable pine	-	6,435	-	31,400
Harvestable hardwood	-	-	-	-
Permanent pine	-	28,140	-	192
Permanent hardwood	-	-	-	-
Environmental conditions[b] (million tons of carbon)				
Net carbon sequestration	30	1,856	30	1,428
Aquifer stock (thousand acre-feet)	32,075	35,544	32,075	35,544
Economic conditions				
Present value farm net return ($ billions)	1,057	1,053	1,057	1,053

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period.

Table A5 Crop, environmental, and economic conditions for landscape at baseline conditions presuming spatial aquifer depletion and flexible rotation treatment for crop margin and groundwater depth variance

Land use, environmental, and economic conditions	Crop margin double	Crop margin half	Groundwater depth double	Groundwater depth half
Land use conditions[a] (acres)				
Rice	272,250	272,250	272,250	272,250
Irrigated corn	192,260	193,300	193,110	192,380
Irrigated soybeans	481,730	401,210	447,830	481,580
Non-irrigated soybeans	27,409	107,240	60,835	27,592
Fallow	4,642	6,715	6,163	6,532
Harvestable pine	30,017	31,251	31,578	31,437
Harvestable hardwood	-	-	-	-
Permanent pine	3,663	-	204	190
Permanent hardwood	-	-	-	-
Environmental conditions[b] (million tons for carbon)				
Net carbon sequestration	1,677	1,423	1,442	1,427
Aquifer stock (thousand acre-feet)	35,532	39,498	37,178	35,532
Economic conditions				
Present value farm net return ($ billions)	2,109	525	1,052	1,054

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period.

Table A6 Crop, environmental, and economic conditions for landscape at baseline conditions presuming spatial aquifer depletion and flexible rotation treatment for tree price and product mix variance

Land use, environmental, and economic conditions	Tree price alternative	Tree product mix (45 p/55 t)	Tree product mix (85 p/15 t)
Land use conditions[a] (acres)			
Rice	272,250	272,250	272,250
Irrigated corn	192,730	192,730	192,720
Irrigated soybeans	480,940	480,960	480,980
Non-irrigated soybeans	27,889	27,926	27,939
Fallow	6,100	6,225	6,569
Harvestable pine	32,048	30,053	31,334
Harvestable hardwood	-	1,832	-
Permanent pine	-	-	192
Permanent hardwood	-	-	-
Environmental conditions[b] (million tons of carbon)			
Net carbon sequestration	1,436	1,448	1,412
Aquifer stock (thousand acre-feet)	35,544	35,544	35,544
Economic conditions			
Present value farm net return ($ billions)	1,053	1,053	1,053

[a] Land uses are annual averages. [b] Net carbon sequestration is a present value total in millions of tons and the aquifer stock is the level in the final period.