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# Afforestation for carbon sequestration in the Lower Mississippi River Basin of Arkansas, USA: Does modeling of land use at fine spatial resolution reveal lower carbon cost?

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ABSTRACT

We use optimization of a structural dynamic model to evaluate the cost of carbon sequestration when afforestation subsidies are used to encourage private landowners to switch from cropland to forestry. Our model allows for the planting of either softwood or hardwood forest types with flexible rotation lengths, in addition to irrigated crops. We apply the model to a portion of the Lower Mississippi River Basin in Arkansas where groundwater overdraft lowers the profitability of irrigated crops. In our baseline model with a 5% discount rate, a subsidy for afforestation from $1000 to $4500 per acre increases pine plantings, aquifer volume, and carbon sequestration above the levels without a subsidy. The average cost to sequester a ton of carbon increases from $13 ($3.55 per ton CO2eq) at the lowest subsidy to $36 ($9.84 per ton CO2eq) at the highest. Lower costs are achievable when soybeans are prominent on the landscape and high costs result when rice and corn dominate. Reducing the discount rate from 5% to 2% changes the afforestation type from fast growing softwoods to slow growing hardwoods, and this substantially lowers the cost of carbon sequestration. Delaying the implementation of an afforestation subsidy until irrigation costs rise from groundwater scarcity will increase the costs of carbon sequestration because many landowners will choose forest types with longer rotations without a subsidy. A carbon credit scheme leads to only afforestation by no harvest hardwoods.

## 1. Introduction

Sequestration of atmospheric carbon from forests in United States is significant. In 2015, all the forest land in southern Alaska and the coterminous 48 states sequestered with forest growth, 2090 Tg C (571 Tg CO2eq), based on the 2017 Inventory of U.S. Greenhouse Gas Emissions and Sinks (U.S. Environmental Protection Agency, 2017). All carbon emissions in the U.S. in 2015 were 24,107 Tg C (6,586.7 Tg CO2eq), and the forest growth in the U.S. therefore sequestered nearly 9% of the emissions from the U.S. that year. Because of the potential to offset greenhouse gas emissions, forest carbon sequestration has long been of interest to policy makers and researchers concerned about the threat of global climate change (National Academy of Sciences, 1992).

Policy makers have proposed financial and other incentive programs to increase forest carbon sequestration (Lewandrowski et al., 2004). The aim of these incentive programs are broadly to enhance the management for nonindustrial forest lands, increase afforestation of marginal agricultural lands, and prevent development of private forest land (McKinley et al., 2011). Researchers have examined costs and benefits such programs (e.g., Newell and Stavins, 2000; Stavins and Richards, 2005; Murray et al., 2005; Latta et al., 2013, 2016). For example, recent estimates of forest carbon sequestration for the U.S. during the period 2015–2050 consider a baseline scenario and compare this to three policy scenarios (Haight et al., 2020). One policy would reduce stand-replacing wildfires; the second policy encourages reforestation of understocked federal forests in the western US and afforestation of marginal cropland in the eastern US, and the third is a reduction in deforestation through land-use policy. The policy with greatest increase in carbon benefit, far exceeding policy cost, is afforestation and reforestation based on their results.

One promising region for an afforestation program is the Mississippi River Delta where most of the agricultural region was forested wetland prior to European settlement (Gardnier, 2015). Much of the cropland in the region depends on groundwater for irrigation from an alluvial

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aquifer with significant declines (Konikow, 2013). The long term agricultural profitability depends on the cost of irrigation, and groundwater overdraft may lower agriculture land value and make afforestation a cost-effective sequestration option. We examine the potential for increasing carbon sequestration through a joint afforestation subsidy and deforestation tax (ST) program that allows private landowners to simultaneous choose the land to afforest, the forest species, the rotation length of the harvestable forest, and access to declining irrigation resources. The cost-effectiveness of the ST is the increase in social cost divided by the increase in the net carbon sequestration with the afforestation ST. The social cost of the ST is the increase in cost to taxpayers from the subsidy less the increase in revenue to taxpayers from the taxes collected less the difference in farm net returns with and without the policy.

We perform our economic analysis using optimization of a structural-dynamic model. Optimization-based approaches model the net economic returns of different land uses (i.e., agriculture and forestry) on the basis of the costs of inputs into the production processes and the market prices of the outputs (Sedjo and Sohngen, 2012). Differences in the net returns of agriculture and forestry are used to estimate the subsidy required for land use conversion from agriculture to forestry (assuming agricultural land use has higher value). Optimization models may include a wide range of forestry options that vary by species composition and rotation age. Our optimization model differs from earlier structural dynamic modeling in our attention to spatial detail in land use and groundwater conditions. Soil suitability and aquifer conditions can vary substantially over space making the use of county averages a potentially poor approximation of the opportunity costs associated with irrigated crops. In previous work, Smith et al. (2012) analyze carbon sequestration with loblolly pine for the state of Arkansas at the county level through a structural dynamic model but do not endogenously address alternative forest species, rotation length, or aquifer declines. Applications of the Forest and Agricultural Sector Optimization Model (FASOM) and the Global Timber Model (GTM) allow for price endogenous land use and management choice (Adams et al., 1999; Murray et al., 2004; Latta et al., 2013; Tian et al., 2018), but the models are built from multi-state blocks that prevent an examination of spatially fine scale opportunity costs.

We note that researchers also use reduced form econometric models to analyze afforestation programs for carbon sequestration (e.g., Lubowski et al., 2006). In contrast to the optimization-based approaches like the one we use, econometric models are used to estimate land use transition probabilities and simulate land use changes and carbon dynamics under different levels of an afforestation subsidy based on historical land use decisions. The disadvantage of this approach is that evolving environmental and social concerns about land use, such as growing concern about groundwater scarcity in the study area, may not be reflected in transition probabilities estimated from historical behavior (Sedjo and Sohngen, 2012). As a result, the predicted land use changes from an econometric model my understate owners' willingness to transition from agriculture to forestry because of increasing water costs.

## 2. Methods

Our structural dynamic analysis is an examination of the essential relationships that landowners make about annual crops, harvestable forest species and rotation lengths for those species, non-harvestable forest species, and groundwater pumping for irrigation at a square mile resolution. The objective of the optimization problem is the present value of the sum of net economic returns from annual crop and forest production less the irrigation costs associated with groundwater pumping over a 150-year time horizon. The time horizon $T$ of 150 years allows for at least two rotations of harvestable hardwood and observable aquifer depletion while keeping recent prices, crop yields, and production costs relevant. We report model outcomes for only the first 100 years because the model assumption of no more value after 150 years leads to unrealistic land allocations near the end of the time horizon. The land use choices have ramifications for carbon emissions and sequestration, and the landowners respond to several types of policies to encourage the net sequestration of carbon. To examine the cost-effectiveness of carbon sequestration policies, the baseline model supposes no policy, and we compare model outcomes to a policy that varies the afforestation subsidies/deforestation taxes. Sensitivity analyses examine the responsiveness of policy outcomes to the discount rate, water abundance conditions, and fluctuating market conditions that influence the margins of annual crops and harvestable forest species.

### 2.1. Land cover

There are $n$ possible land covers that 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 $L_{ist}$, $L_{ift}$, $L_{ipt}$, 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 for same species of loblolly pine and mixed hardwood forest. Any annual land use can become another land cover in the subsequent period up to a maximum based on the historical variation in each land cover and site.. The initial amount of land in land cover $j$ at site $i$, $L_{ij0}$, multiplied by a value greater than one based on historical variation in land cover $j$ at each site $i$, $\phi_{ij}$, sets the upper bound for land cover $j$ at site $i$, $\phi_{ij}L_{ij0}$. 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)),

$$\sum_{s}^{k} L_{ist} + \sum_{f}^{l} L_{ift} + \sum_{p}^{m} L_{ipt} = \sum_{j}^{n} L_{ijt} = \sum_{j}^{n} L_{ij0} \tag{1}$$

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 $\widetilde{t}$ after period $t$, is $F_{ift\widetilde{t}}$. 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)):

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

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 $\widetilde{t}$, $\sum_{\widetilde{t}}^{T} F_{ift\widetilde{t}}$, 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 for a rotation length chosen within the model (Eq. (4)):

$$F_{ift\widetilde{t}} \leq m_{t\widetilde{t}} \sum_{j}^{n} L_{ij0} \tag{4}$$

where $m_{t\widetilde{t}}$ takes a value of zero if $\widetilde{t} < t$, meaning harvest occurs in a period before planting, and a value of one if $\widetilde{t} > t$ which indicates that harvest occurs in a period after planting. Eq. (4) indicates 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.

### 2.2. Irrigation and the model of the aquifer

We supplement precipitation with average annual irrigation for land cover $j$ represented by $wd_j$. The pumping of groundwater from wells, $GW_{it}$, provides the irrigation water (Kovacs and Durand-Morat, 2020). Rather than deficit irrigate, we assume farmers apply a constant $wd_j$ based on highly inelastic demand for irrigation water from empirical studies (Wang and Segarra, 2011). The water extracted from the wells equals the irrigation water applied to the crops (Eq. (5)),

$$\sum_{j}^{n} wd_j L_{ijt} = GW_{it} \tag{5}$$

Groundwater cannot flow laterally across sites, and the change in the depth to the aquifer, $AQ_{it}$, at each site is different in response to the groundwater extraction and the site level natural recharge, $nr_i$, that occurs from precipitation, streams, and underlying aquifers (Eq. (6)),

$$AQ_{it} = AQ_{it-1} - GW_{it} + nr_i \tag{6}$$

The cost to lift a unit of water by a distance unit, $c^p$, along with the depth of the well initially, $dp_i$, determine the groundwater pumping cost at a site, $GC_{it}$. The increase in the depth to the aquifer depends on the bathtub aquifer volume depletion, $AQ_0 - AQ_t$, that is divided by the area of the landscape, $\sum_i^W \sum_j^n L_{ij0}$. We account for the capital costs from drilling and pumps in response to the decline of the aquifer with $c^c$, measured per unit of water pumped (Eq. (7)).

$$GC_{it} = c^c + c^p \left( dp_i + \frac{(AQ_0 - AQ_t)}{\sum_i^m \sum_j^n L_{ij0}} \right) \tag{7}$$

### 2.3. 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 carbon emissions go to the farm gate for annual land covers, but the forest land covers assess carbon emissions to the mill and beyond to compare permanent and harvestable forest. Omitting the emissions from annual crops beyond the farm gate makes the emissions from annual crops lower than they actual are and the cost of carbon from afforestation greater than it actually is.

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. (8)).

$$EL_{it} = \sum_{s}^{k} E_s L_{ist} + \sum_{f}^{l} \sum_{\tilde{t}}^{T} E_f F_{if\tilde{t}t} + \sum_{p}^{m} E_p FP_{ipt} \tag{8}$$

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. (9)),

$$EG_{it} = GW_{it} \left( dp_i + \frac{(AQ_{i0} - AQ_{it})}{\sum_j^n L_{ij0}} \right) \sigma_g \tag{9}$$

where $\sigma_g$ is a scalar that converts the diesel[1] 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. (10) indicates the carbon emission, $EP_{it}$, from the processing of harvestable forest types at time $t$ and site $i$.

$$EP_{it} = \sum_{f}^{l} \sum_{\tilde{t}}^{T} u_f v_f TC_{f\tilde{t}t} F_{if\tilde{t}t} \tag{10}$$

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 $\pi_f$ and saw timber products is $\lambda_f$. Eq. (11) 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 $t$ and site $i$.

$$ED_{it} = \sum_{f}^{l} \sum_{\tilde{t}}^{T} \left( x_f \pi_f + z_f \lambda_f \right) \left( 1 - u_f \right) v_f TC_{f\tilde{t}t} F_{if\tilde{t}t} \tag{11}$$

Eq. (12) indicates the present value of emissions, $ET_{it}$, from all land covers at time $t$ and site $i$.

$$ET_{it} = \delta_t (EL_{it} + EG_{it} + EP_{it} + ED_{it}) \tag{12}$$

where the discount factor, $\delta_t$, 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; Kovacs et al., 2017). The carbon sequestered by aboveground biomass per acre for crop $j$ in site $i$, $AGB_{ij}$, is

$$AGB_{ij} = Y_{ij} \lambda_j \left( 1 - \alpha_j \right) \left( \frac{1}{H_j} - 1 \right) \kappa_j \eta_j \beta_j \tag{13}$$

where the yield $Y_{ij}$ in per acre conventional units converts, with $\lambda_j$, into tons per acre and finally into dry mass by adjusting with $\alpha_j$ for the moisture content (Eq. (13)). The proportion of biomass aboveground left after the harvest, in the form of stems and leaves, depends on the harvest index, $H_j$. The remaining parameters in Eq. (13) to determine the biomass aboveground that is sequestrated include the carbon concentration of the biomass, $\beta_j$, the fraction of carbon left in soil after decomposition by microbes, $\eta_j$, and the fraction of plant residue within the soil based on the tillage method, $\kappa_j$.

For the belowground biomass, the carbon sequestrated per acre, $BGB_{ij}$, comes from

$$BGB_{ij} = Y_{ij} \lambda_j \left( 1 - \alpha_j \right) \left( \frac{\phi_j}{H_j} \right) \eta_j \chi_j \tag{14}$$

where, like in Eq. (8), the dry mass of the yield in tons per acre is determined with $Y_{ij}$, $\lambda_j$, and $\alpha_j$ (Eq. (14)). The shoot/root ratio $\phi_j$ divided by the harvest index $H_j$ converts the yield to belowground biomass of which only a fraction, $\eta_j$, with tillage affecting microbial decomposition

[1] A rapidly growing number of pumps are electric in the study area, but the majority remain diesel.

of incorporated plant residue with an estimated carbon concentration of $\chi_j$.

The soil factor, $\xi_i$, 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. (15) indicates the carbon sequestration for annual land covers, in period *t* carbon values, in period *t* and site *i* ($SA_{it}$).

$$SA_{it} = \sum_{s}^{k}[(AGB_{is} + BGB_{is})\xi_i]L_{ist} \tag{15}$$

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. (16) indicates the carbon sequestration, in planting period $\bar{t}$ values, from harvestable forest types in period *t* and site *i* ($SF_{it}$).

$$SF_{it} = \sum_{f}^{l}\sum_{\tilde{t}}^{T}\sum_{\bar{t}}^{T}\left(TC_{f\bar{t}t} - TC_{f\bar{t}(t-1)}\right)m_{t\tilde{t}}F_{if\bar{t}\tilde{t}} \tag{16}$$

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. (17) indicates the carbon sequestration, in planting period $\bar{t}$ values, from permanent forest in period *t* and site *i* ($SP_{it}$).

$$SP_{it} = \sum_{p}^{m}\sum_{\bar{t}}^{T}\left(TC_{p\bar{t}t} - TC_{p\bar{t}(t-1)}\right)FP_{ip\bar{t}} \tag{17}$$

Eq. (18) indicates carbon sequestration for all land covers in present values in period *t* and site *i* ($S_{it}$),

$$S_{it} = \delta_t SA_{it} + \delta_{\bar{t}}(SF_{it} + SP_{it}) \tag{18}$$

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. The sequestration from annual crops and harvestable forest types chosen after the study period do not count because the decision to plant those occurs after the time horizon. 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. (19) indicates the carbon sequestration, in present values, from permanent forest that occurs after the end of the study horizon at site *i* ($SPM_i$).

$$SPM_i = \sum_{p}^{m}\sum_{\bar{t}}^{T}\delta_{\bar{t}}\left(TCM_p - TC_{p\bar{t}T}\right)FP_{ip\bar{t}} \tag{19}$$

## 2.4. Farm net returns objective

We suppose a constant 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. To avoid the use of unusually high or low profitability estimates we use five averages for production cost and county yield for several production methods for each crop.

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. (20))

subject to:

$$\max_{\substack{L_{ist},F_{if\bar{t}t},F_{ift\tilde{t}}\\ FP_{ipt},GW_{it}}} : \pi = \sum_{t=1}^{T}\delta_t\left(\sum_{i=1}^{w}\left(\begin{array}{l}\sum_{s}^{k}(p_s y_{is} - C_s)L_{ist} + \sum_{f}^{l}\sum_{\bar{t}}^{T}\left(pp_f\pi_f + pt_f\lambda_f\right)y_{f\bar{t}t}F_{if\bar{t}t}\ldots\\ \ldots - \sum_{f}^{l}\sum_{\tilde{t}}^{T}C_f F_{ift\tilde{t}} - \sum_{p}^{m}C_p FP_{ipt} - GC_{it}GW_{it}\end{array}\right)\right) \tag{20}$$

$$\phi_{ij}L_{ij0} \geq L_{ijt} \geq 0, GW_{it} \geq 0, AQ_{it} \geq 0 \tag{21}$$

Profitability differences across policy option then allow estimates of cost per ton of carbon sequestered which will differ based on profitability of land use choices across space and time as well as deployment cost of the policy.

Optimization occurs subject to constraints on the spatial dynamics of land and irrigation from Eqs. (1) to (7) in addition to non-negativity constraints on land, groundwater pumping, and the aquifer shown in Eq. (21). The model outcomes reported are only for two-thirds of the entire time horizon because there is a distortion in the land use choices toward the end of the time horizon without good information about resource salvage values. The agricultural land available at site *i* and the historical variation in land cover *j* on the landscape determines the value greater than one, $\phi_{ij}$, for setting the upper bound for each land cover. The spatial variation in the model comes from aquifer thickness, natural recharge of the aquifer, depth to groundwater, the upper bound constraint on the amount of land cover *j*, and the crop yield.

The carbon emissions and sequestration shown in Eqs. (8) to (19) are not constraints on the optimization but respond to the producer's choices to maximize net returns. This problem is non-linear in the groundwater extraction costs, and the CONOPT solver from AKRI Consulting and Development in the Generalized Algebraic Modeling System (GAMS)

24.5.6 finds the solution. Since the algorithm for the CONOPT solver searches for local optima, we seed the problem with alternative start values. The model runs led to the same optimal solution, providing us with confidence in our approach.

### 2.5. Policies for increasing carbon sequestration and sensitivity analyses

We consider several types of policies to increase sequestration through forests. The main approach is a two-part policy that combines a subsidy on newly forested land with a tax on newly deforested land (Stavins, 1999). A subsidy on new land in harvestable forest alone creates the incentive for landowners to harvest current forest and replant to forest next year for the subsidy, and a tax only on deforested land offers no incentive to increase harvestable forest land above the baseline. We incorporate the two-part policy by having the subsidy per acre augment net returns if the land in harvestable forest rises and the tax per acre diminish net returns if the land in harvestable forest decreases. The mathematical term to represent the two-part policy, which is added to the terms within the double parentheses in the objective (Eq. (20)), is $ST\left(\sum_f^l L_{ift} - \sum_f^l L_{if(t-1)}\right)$. The value $ST$ represents a per acre subsidy the landowner receives by increasing the area of harverstable forest when $\sum_f^l L_{ift} - \sum_f^l L_{if(t-1)} > 0$ and a per acre tax the landowner incurs by decreasing area in harvestable forest when $\sum_f^l L_{ift} - \sum_f^l L_{if(t-1)} < 0$. Gradually increasing the subsidy/tax (ST), where the size of the subsidy and tax is the same, causes the harvestable forest land to increase above the baseline.

Two other policies we consider include 1) a subsidy per acre for new permanently forested land and 2) a carbon payment per ton of carbon for net sequestration. The mathematical term added inside the double parentheses of Eq. (20) to represent the subsidy landowners receive from planting permanent forest is $SP\sum_p^m FP_{ipt}$ where $SP$ is the per acre subsidy on permanent forest. A subsidy on permanently forested land encourages forest that never loses its stored carbon through harvest but also does not provide revenue to the landowner. A carbon payment directly incentivizes the sequestration of the carbon, but this policy involves greater administrative burden and political will on the behalf of government to track the carbon accumulation and reward landowners. The carbon subsidy has two components in the Eq. (20) objective. One component is the net carbon sequestration in period $t$ for site $i$ within the double parentheses of the objective, $P_C(S_{it} - ET_{it})$, where the per ton carbon payment is $P_C$. The second component of the subsidy comes from carbon sequestered by permanent forest after the end of the study period, and this term that is added to Eq. (20) outside the double parentheses is $\delta_T P_C \sum_{i=1}^{w} SPM_i$.

The cost-effectiveness of any policy is the increase in social cost divided by the increase in the net carbon sequestration with the policy. We measure the social cost of a policy as the increase in cost to taxpayers from the subsidy less the increase in revenue to taxpayers from the taxes collected less the difference in farm net returns with and without the policy. Mathematically, the cost-effectiveness for the two-part policy is $\frac{\left(ST\left(\sum_f^l L_{ift} - \sum_f^l L_{if(t-1)}\right) - \left(\pi_{policy} - \pi_{no\_policy}\right)\right)}{SNC_{policy} - SNC_{no\_policy}}$ where $SNC$ is the sum of the present value of net carbon sequestration from all the land uses chosen over time horizon. We also include the present value of carbon beyond the study horizon for the permanent forest types.

Sensitivity analyses illustrate the usefulness of a structural dynamic model for evaluating the effectiveness of afforestation as carbon sequestration approach. The sensitivity analyses include how the discount rate, water scarcity conditions, annual crop margins, stumpage prices, forest production costs, and spatially variable productivity in harvestable forest influence cost-effectiveness and other model outcomes. The discount rate is crucial to any land use decision (e.g. the policy of the Federal Reserve Board and the price of housing). A recommendation by the US Office of Management and Budget (OMB) is to use low- and high-end discount rates to represent social and market

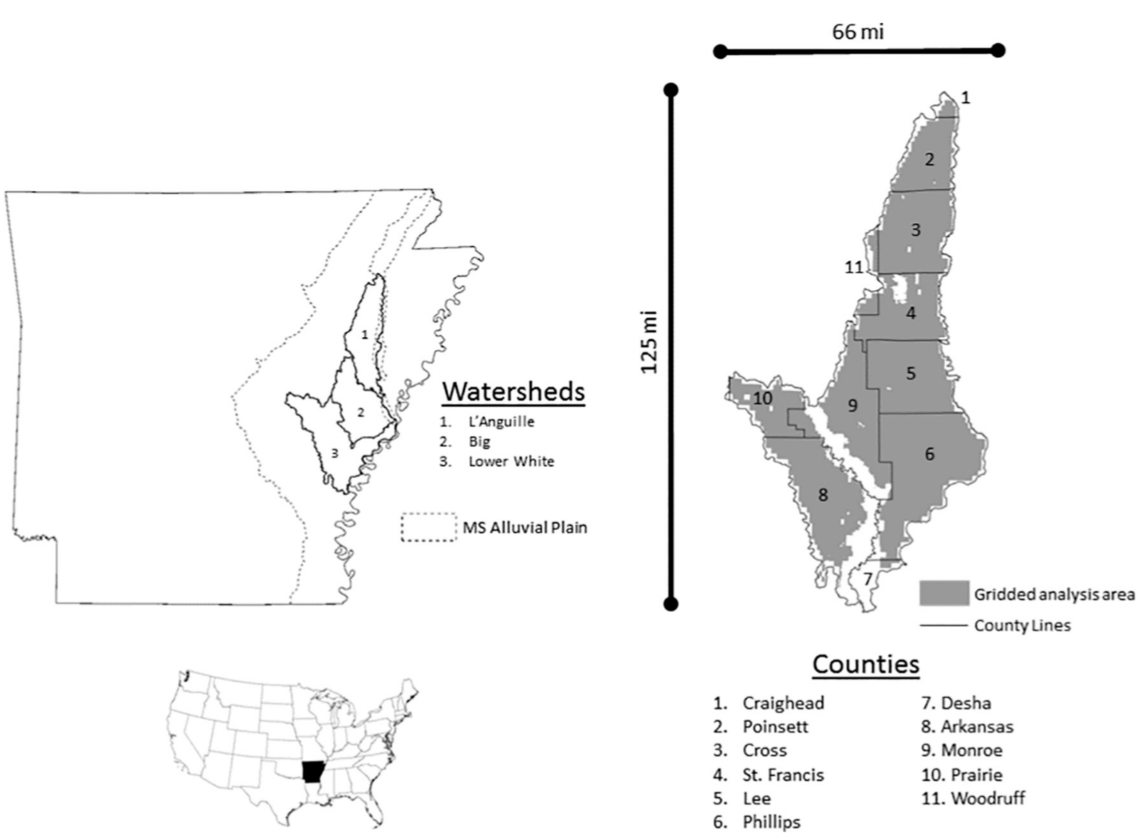


**Fig. 1.** Three eight-digit hydrologic unit code watersheds in Arkansas, excluding public land and urban areas define the region for a two thousand cell grid. One hundred randomly chosen cells within the grid represent the study area for the analysis.

**Table 1**
Parameters for the economic and carbon model components related to forest types.

| Parameter | Definition | Value |
|---|---|---|
| $pp_{pine}$, $pt_{pine}$ | Stumpage price of pine pulpwood and saw timber ($/ton) | 5, 20 |
| $pp_{hardwood}$, $pt_{hardwood}$ | Stumpage price of hardwood pulpwood and saw timber ($/ton) | 7, 33.86 |
| $a3, a2, a1, a0$ for $y_{pine,\bar{t}t}$ | Coefficients for cubic polynomial estimate of pine biomass as function of the stand age (ton/year$^3$, ton/year$^2$, ton/year, ton) | 0.0002, −0.0318, 2.0564, −6.0942 |
| $b3, b2, b1, b0$ for $y_{hardwood,\bar{t}t}$ | Coefficients for cubic polynomial estimate of mixed hardwood biomass as function of the stand age (ton/year$^3$, ton/year$^2$, ton/year, ton) | 0.00006, −0.0054, 0.8096, −2.8753 |
| $\pi_f, \lambda_f$ | Proportion of pulpwood and saw timber, respectively, for pine and hardwood | 0.7, 0.3 |
| $C_f$ | Production cost of harvestable pine and hardwood, respectively ($/ac)[a] | 305, 348 |
| $C_p$ | Production cost of permanent pine and hardwood, respectively ($/ac) | 196, 225 |
| $E_f$, $E_p$ | 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 comes 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 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.

time preferences, respectively (Office of Management and Budget (OMB), 2003). The water scarcity sensitivities (50%, 75%, 125%, and 150% of baseline) represent the role of uncertainty in climate conditions on the irrigation costs of annual crops. Annual crop margin, stumpage price, and harvestable forest production cost sensitivities (50% and 150%) represent the fluctuating market conditions that influence the output and input prices. We also consider spatially variable productivity in harvestable forest based on the county level variation in dryland soybean yields (USDA NASS, 2017a) and the forest productivity variation by site quality in Cunningham et al. (2012).

## 3. Data

The region for a grid of two thousand one square mile cells is three eight-digit hydrologic unit code watersheds that overlay eleven counties in the Lower Mississippi River Basin portion of Arkansas (Fig. 1). The grid cells (or sites) represent the spatial heterogeneity of crop production, yield, and below ground hydrologic conditions on the landscape. We randomly select 100 sites from the entire grid for the analysis. The land in annual crops (corn, rice and soybeans) for each site come from the 2017 Cropland Data Layer (USDA NASS, 2017b). The proportion of soybeans that are irrigated or non-irrigated soybean come from county estimates from the past five years (USDA NASS, 2017c). Land use other than annual crops in the 2017 Cropland Data Layer, such as public land and urban areas, we do not include in the study area. We use a 5% real discount rate to represent the average of real discount rates between the low- and high-end estimates from the OMB to reconcile the choice between social and market time preferences (Office of Management and Budget (OMB), 2003).

### 3.1. Annual crop and harvestable forest production

Annual crop yields by site from a five year average of county yields (Division of Agriculture, University of Arkansas, 2018) are in Table A1. The Division of Agriculture, University of Arkansas (2018) has the Crop Cost of Production estimates used for the costs of production by crop excluding irrigation costs for the past five years, and these farm production parameters are in Table A2. The crop prices come from the U.S. baseline outlook projections for agricultural and biofuel markets for all crops (Food and Agriculture Policy Research Institute at the University of Missouri (FAPRI), 2019). The average irrigation over the course of the growing season excluding natural rainfall comes from the Division of Agriculture, University of Arkansas (2018). 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, and the power units, pumps, and wells all have purchase and maintenance costs that further raise the cost of irrigation water (Hogan et al., 2007). Adjusting for inflation, the ownership and maintenance charges for the wells and the costs of production for all crops are constant over time.

The biomass growth by forest species and five year stand age comes from the net merchantable bole volume of growing-stock trees per acre of timberland in Arkansas drawn from 2013 to 2017 data collected through the USDA Forest Service Forest Inventory and Analysis program (USDA Forest Service, 2019). Forest Inventory and Analysis data come from permanent sample plots randomly located on public and private land throughout Arkansas, and the silvicultural treatments on the plots presumably are typical for the timberland species in the state. Volume of biomass converts to weight with the specific gravity of each species (Miles and Smith, 2009), and a cubic polynomial function for a yield curve was fit to the biomass weight by stand age and forest species (Table 1). The loblolly-short leaf pine yield curve is similar to the classic sigmoidal shape, but the oak-gum-cypress (i.e. hardwood) yield curve is roughly linear (Fig. A1).[2] The proportion of the biomass that becomes pulpwood or saw timber depends on the biomass quality of each forest type (Cunningham et al., 2012; Cunningham and Walkingstick, 2012). Forest production costs are from a 2018 survey of the cost of forestry practices across the southeastern United States for loblolly pine (Maggard and Barlow, 2019) and from estimates of restoration agreements through wetland reserve easements for mixed hardwood (USDA NRCS, 2017). Based on the most common forestry practices in the region, the costs include those for hand planting, chemical applications, prescribed burning, timber cruising, and custodial management. Even-aged stand management with limited pre-commercial thinning is typical for the region (Maggard and Barlow, 2019). Stumpage prices for pulpwood and saw timber for the five year average ending in 2016 are for the southern Arkansas region (TimberMart-South (TMS), 2018). We do not use

[2] "There are 5669 sample plots across Arkansas within the Forest Inventory and Analysis program (USDA Forest Service, 2020). The cross-sectional variation in biomass stand growth is therefore satisfactory, but only five year increments for biomass within a stand are available. This leaves just twenty observations to fit a cubic polynomial for our study horizon. The fit of the yield curve polynomial may improve with estimates for stand biomass every two years."

stumpage prices from farther back in time because those prices do not reflect structural changes in the timber market likely to continue into the future.

### 3.2. Carbon emissions and sequestration

Carbon sequestration by forest species for afforestation in the South Central region come from Smith et al. (2005). Separate cubic polynomials are fit to carbon accumulation by five year stand age for soil and non-soil carbon accumulation. The non-soil carbon sequestration includes the carbon in live trees, standing dead trees, understory, down dead wood, and forest floor. Annual crops sequester carbon in the soil from above- and belowground biomass, and parameters for the annual crop yields, the ratio of root-to-shoot biomass, and the carbon content in residues and roots are in Table A3 (Popp et al., 2011). The soil carbon for the annual land types adjust according to tillage practices and county estimates of soil texture.

The production of harvestable forest products generates carbon equivalent emissions through site preparation, herbicide application, fertilization, thinning, and final harvest (Smith, 2010). Permanent forest production releases carbon from similar categories except there are no emissions from thinning and final harvest. Annual crop carbon equivalent emissions based on Table A4 come from fuel, fertilizer, and chemical applications using the production practices in the crop enterprise budgets (Division of Agriculture, University of Arkansas, 2018) with adjustments according to interviews with crop specialists. Emissions related to fuel combustion from irrigation wells depend on the power units and pumps for those wells (Hogan et al., 2007).

The decay of the slash from harvest and eventually the decay of the forest products leads to a release of the sequestered carbon in the forest into the atmosphere. The proportion of non-soil carbon emitted at harvest by forest species come from the Appendix C tables in Smith et al. (2005). The proportion of harvested wood that ultimately decays and releases carbon back to the atmosphere rather than being permanently sequestered in landfills come from the Smith et al. (2005) tables on the disposition of carbon by forest species for pulp or sawlog products.

### 3.3. Aquifer properties and natural recharge

The Arkansas Natural Resources Commission has the initial saturated thickness and depth to the water table of the alluvial aquifer (Arkansas Natural Resources Commission (ANRC), 2018). Spatially coarse pilot points determine the proportion of water within the water bearing material of the aquifer, known as the storability (Clark et al., 2013). The product of the land area of each site with the saturated thickness of the aquifer and the storability determines the initial volume of groundwater beneath each site. The amount of water available for irrigation from the aquifer is sum of the volume of groundwater beneath the sites. The natural recharge from precipitation and surface water bodies was adopted from calibrated modeling by Reed (2003) between 1994 and 1998.

## 4. Results

A subsidy for afforestation and an equivalent tax on deforestation from $1000 to $4500 per acre increases pine plantings, aquifer volume, and carbon sequestration above the levels without a ST (Table 2). The 5% discount rate makes the delayed returns from harvestable hardwood forest not competitive with harvestable pine forest. The rotation length for harvestable pine is between forty to fifty years at the beginning of the study horizon and closer to forty years later in the study horizon (Fig. 2). The large planting in a single period shown in Fig. 2 is unrealistic and a consequence of not accounting for unobservable differences across farms that would lead to variation in the responsiveness to a ST throughout the beginning of the time horizon. The actual planting and harvest in response to the policy are likely to be more evenly distributed than the model indicates. The timing of the carbon sequestration closely follows the harvestable pine rotation schedule (Fig. A2). The rotation length on the newly afforested sites is longer than for intensively managed pine plantations because we project lower stem quality and less intensive management than on pine plantations. Longer rotations are also a way for landowners to rebuild the groundwater stock and thus lowering pumping cost by being able to draw from water resources closer to the surface to maintain the profitability of irrigated agriculture. The average cost to sequester a ton of carbon is $12.59 ($3.44 per ton CO2eq) at the lowest ST amount and increases to $36.34 ($9.93 per ton CO2eq) at the highest ST amount.

The baseline model, without an afforestation ST, land use and aquifer for the average over the study period and for three select time frames are in Table A5. The baseline model has 27,314 acres of soybeans in the initial period, but with the $1000 ST, the initial period has only 18,638 soybean acres. At the lowest ST, mostly soybean acres where groundwater is scarce switch to harvested pine (11,411 acres), and there are gains in carbon sequestration and groundwater savings (Fig. 3a). The average aquifer volume in the baseline model is 1557 thousand acre-feet

**Table 2**
Afforestation and carbon sequestration for an afforestation subsidy/tax on harvested forest with baseline discount rate of 5%.

| Afforestation subsidy/tax ($/acre) | Harvested pine greater than baseline[a] (acres) | Aquifer volume greater than baseline (thousand acre-feet) | Carbon sequestration greater than baseline (thousand tons C) | Average cost of carbon sequestration[b] ($/ton C) |
|---|---|---|---|---|
| 1000 | 11,411 | 324 | 394 | 12.59 |
| 1500 | 14,670 | 567 | 637 | 16.17 |
| 2000 | 16,928 | 695 | 757 | 18.10 |
| 2500 | 21,278 | 966 | 987 | 22.54 |
| 3000 | 27,582 | 1332 | 1298 | 27.80 |
| 3500 | 34,490 | 1708 | 1619 | 32.95 |
| 4000 | 36,577 | 1861 | 1719 | 34.62 |
| 4500 | 38,533 | 2057 | 1813 | 36.34 |

[a] Baseline forestation is 685 acres of pine and 62 tons of carbon sequestration out of 100 mile$^2$ or 64,000 acres. Mixed hardwood acres decline by 50 acres for all subsidy/tax levels.

[b] The average cost of carbon is the subsidy less the increase in farm net returns above the baseline divided by the increase in the sequestration with the subsidy.

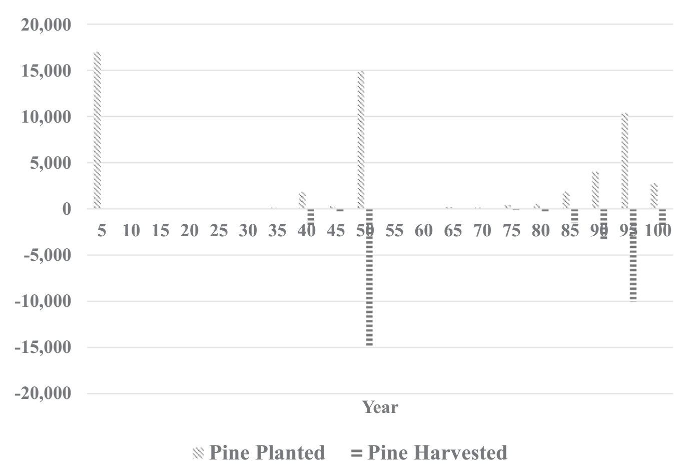


**Fig. 2.** Landscape acreage of loblolly pine planted and harvested over the study horizon for the baseline model with an afforestation subsidy/tax of $2000. The figure displays harvest and planting in five year increments. For example, there is a large harvest and immediate planting that both occur in the fiftieth period.

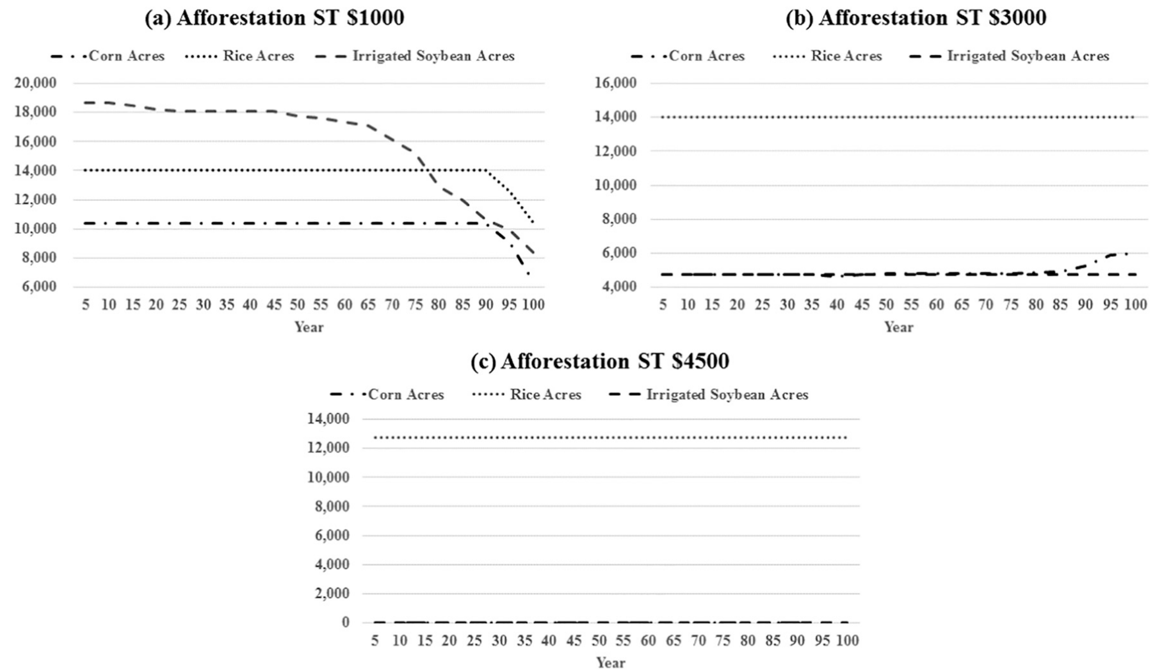


**Fig. 3.** Landscape acreage in corn, rice, and irrigated soybean over the study horizon for an afforestation ST of (a) $1000, (b) $3000, and (c) $4500.

(Table A5), and the $1000 ST increases this by 324 thousand acre-feet or nearly 21%. At the $2500 ST, there is some shift of corn acres to harvested pine but mostly more soybean acres. There is a faster rise in the average cost of carbon sequestration between the $2500 and $4000 ST, as the planting of pine replaces corn, because corn sequesters more carbon than other crops (Fig. 3b). High-value rice acres begin to transition to harvested pine at the $4000 ST, and soybean acres transition entirely. At the highest ST, all corn and soybean acres shift to harvested pine, and only about 90% of the baseline rice acres remain (Fig. 3c). Less land transitions to forest at $4000 ST and higher since most rice production has greater value than forest even at the high afforestation ST.

**Table 3**
Afforestation and carbon sequestration for an afforestation subsidy/tax on harvested forest for 2% and 8% discount rate.

| Afforestation subsidy/tax ($/acre) | Harvested pine greater than baseline[a] (acres) | Harvested mixed hardwood greater than baseline (acres) | Carbon sequestration greater than baseline (thousand tons C) | Average cost of carbon sequestration[b] ($/ton C) |
|---|---|---|---|---|
| 2% discount rate | | | | |
| 2000 | 2901 | 10,243 | 1497 | 5.84 |
| 3000 | 4230 | 11,193 | 2035 | 7.79 |
| 4000 | 5795 | 12,126 | 2334 | 10.13 |
| 8% discount rate | | | | |
| 2000 | 20,121 | −14 | 986 | 20.27 |
| 3000 | 38,890 | 103 | 1505 | 27.74 |
| 4000 | 43,016 | 36 | 1661 | 36.13 |

[a] Average baseline forestation over the study period for the 2% discount rate is 1169 acres of pine and 808 acres of mixed hardwood, and baseline carbon sequestration is 621 thousand tons. Average baseline forestation over the study period for the 8% discount rate is 128 acres of pine and 25 acres of mixed hardwood, and baseline carbon sequestration is 6 thousand tons.

[b] The average cost of carbon is the subsidy less the increase in farm net returns above the baseline divided by the increase in the net carbon sequestration with the subsidy.

There is a diminishing increase in aquifer conservation and carbon sequestration because less land transitions to forest, but there is also a diminishing rise in the average cost of carbon sequestration since rice is the largest emitter of carbon equivalents among the crops.

The use of a lower discount rate (2%) decreases the number of irrigated acres that transition to harvested forest in response to each afforestation subsidy amount, but most of the transitioning acres are now harvested mixed hardwood rather than harvested pine leading to substantially greater and more cost-effective carbon sequestration (Table 3). This occurs because a lower discount rate places greater weight on future returns, increasing the profitability of the slower growing but more valuable hardwood forest. The afforestation subsidy that is least cost-effective ($4000) in this scenario generates carbon sequestration at a cost of $10.13 per ton C ($2.78 per ton CO2eq), making it cheaper than even the most cost-effective subsidy with the baseline 5% discount rate. A higher discount rate (8%) increases the number of acres that transition to harvested forest, and nearly all of the new forest is harvested pine. High discounting of future returns favors pine forest because pine growth exceeds hardwood growth. There is more pine afforestation with an 8% discount rate than at a 5% discount rate at each ST because pine grows faster than 8% in the early years of growth while the returns from annual crops are steady through time. The greater displacement of annual crops by pine for a given ST means the cost of carbon is less at the 8% discount rate than the 5% discount rate when there is land to afforest. At the highest ST and an 8% discount rate, nearly all the land is in pine. When there is no more land to put into forest, the 8% discount rate only lowers the present value of carbon sequestration and increases the average cost of carbon.

The results shown in Table 4 indicate how water abundance conditions influence afforestation. The starting aquifer volume and the rate of natural recharge range from 50% to 150% of the baseline, and the afforestation subsidy adjusts to achieve an equivalent amount of net carbon sequestration (757 thousand tons) in each water scenario. A $2000 ST adjusts to $2785 under the 50% water abundance condition, and harvested pine increases to 36,306 acres from 17,103 acres at the 100% condition (Table 4). At 50% water abundance and no afforestation ST, there is a significant shift out of rice and into corn, soybeans, and hardwoods that sequester more carbon. As a consequence, an afforestation ST has to induce a lot of pine acres at a 50% water abundance to

**Table 4**
Influence of water abundance conditions on the afforestation of harvested forest and carbon sequestration.

| Water abundance conditions (% of water baseline)[a] | Afforestation subsidy/tax ($/acre)[b] | Harvested pine greater than no subsidy/tax (acres) | Aquifer volume greater than no subsidy/tax (thousand acre-feet) | Average cost of carbon sequestration[c] ($/ton C) |
|---|---|---|---|---|
| 50% | 2785 | 36,306 | 237 | 28.85 |
| 75% | 2141 | 24,638 | 373 | 18.20 |
| 100% | 2000 | 16,928 | 695 | 18.10 |
| 125% | 1789 | 15,854 | 825 | 17.35 |
| 150% | 1755 | 15,883 | 834 | 17.10 |

[a] The water baseline refers to the baseline estimates of aquifer abundance and natural recharge at each site. Thus, 150% of the water baseline refers to the use of 150% of the baseline estimates of aquifer abundance and natural recharge at each site.

[b] The afforestation subsidy/tax on harvested forest is set to achieve about 757 thousand tons of carbon for each water abundance condition.

[c] The average cost of carbon is the subsidy less the increase in farm net returns above the baseline divided by the increase in the net carbon sequestration with the subsidy.

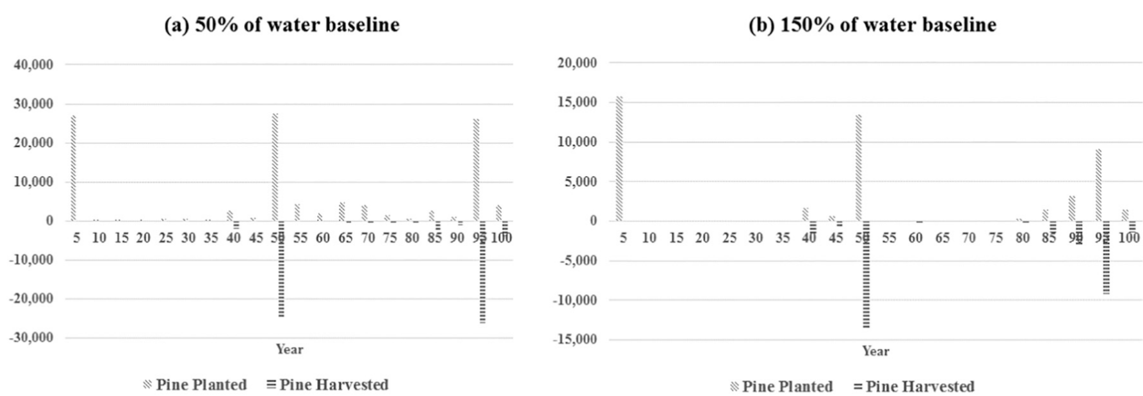


**Fig. 4.** Landscape acreage of loblolly pine planted and harvested over the study horizon with an afforestation ST set to obtain 757 thousand tons of carbon sequestration for model runs with (a) 50% of the water baseline and (b) 150% of the water baseline. The water baseline refers to the baseline estimates of aquifer abundance and natural recharge at each site. The 150% of the water baseline refers to the use of 150% of the baseline estimates of aquifer abundance and natural recharge at each site.

achieve an increase in net sequestration equivalent to that in the 100% water condition. This makes carbon sequestration less cost-effective at the 50% water abundance condition, and sequestration becomes more cost-effective as initial aquifer volume and natural recharge increase. The 150% water abundance condition has a $1755 subsidy and 15,883 acres of harvested pine. The cost of sequestering a ton of carbon does not change linearly with the water abundance condition, and in fact jumps substantially between the 75% condition and the 50% condition, going from $18.20 to $28.85 ton C ($4.97 to $7.88 per ton CO2eq). This occurs because rice acres are much less viable under the 50% condition without an afforestation ST and begin to transition to other land covers early in the study period. Pine plantings occur throughout the study horizon with the 50% water baseline, especially later in the study horizon as groundwater supplies become critically low (Fig. 4a). The pine plantings occur principally at forty to fifty year intervals when water is abundant (Fig. 4b).

We also vary the annual crop margins, stumpage prices, and harvested forest production costs to 50% and 150% of baseline (Table 5), adjusting the afforestation ST to have an equivalent net carbon sequestration (757 thousand tons) in each model run. We also consider spatially variable productivity in the harvestable forest to achieve the same net carbon sequestration target. With low crop margins, even a small ST of $1131 triggers significant transition away from each irrigated crop into harvested pine (33,195 acres). The significant acres of pine that must be planted is because low crop margins and no ST already embody a landscape where annual crops shift to uses with greater sequestration. High crop margins necessitate a large $3393 ST, but less land in harvestable pine is necessary to reach the carbon sequestration target because the no ST scenario has land in permanent pine with baseline crop margins but the no ST scenario has none of the permanent pine with high crop margins. The cost of a sequestered ton of carbon is $14.46 ($3.95 per ton CO2eq) with 50% crop margins and $35.41 ($9.67 per ton CO2eq) with 150% crop margins. Thus, lower crop margins lower the cost of carbon sequestration while higher margins increase the cost of carbon sequestration.

The opposite effect is true of stumpage prices as low stumpage prices increase the cost of carbon sequestered while high stumpage prices lower the cost of carbon sequestered. This occurs because low stumpage prices predictably mean that a higher afforestation ST is necessary to achieve an equivalent net sequestration (Table 5). The lower ST in the high stumpage price scenario leads to 14,852 acres transitioning to harvested pine. The high stumpage price scenario achieves equivalent net sequestration with fewer acres of harvested pine because the no ST scenario with high stumpage prices has no land in hardwoods but the no ST scenario with baseline stumpage prices has land in hardwoods.

Low harvested forest production costs lead to relatively cost-effective carbon sequestration, $11.97 per ton C ($3.27 per ton CO2eq), through a modest shift of soybean acres into harvested forest (10,209 acres of harvested pine). High forest production costs are offset by a higher ST making it profitable to convert more acres of soybean as well as some acres of corn. The low forest production cost scenario achieves equivalent net sequestration with the fewest acres of harvested pine because the no ST scenario with low forest production costs has almost no land in permanent forest but the no ST scenario with baseline forest production costs has land in permanent pine. Allowing for spatially variable forest productivity increases the average cost of carbon and more cropland has

**Table 5**
Influence of annual crop margins, stumpage price, harvested forest production costs, and spatially variable productivity on the afforestation of harvested forest and carbon sequestration.

| Sensitivity analysis (% of forest parameter baseline)[a] | Afforestation subsidy/tax ($/acre)[b] | Harvested pine greater than no subsidy/tax (acres) | Harvested mixed hardwood greater than no subsidy/tax (acres) | Average cost of carbon sequestration[c] ($/ton C) |
|---|---|---|---|---|
| Baseline | 2000 | 16,928 | −50 | 18.10 |
| Annual crop margins | | | | |
| 50% | 1131 | 33,216 | −3052 | 14.46 |
| 150% | 3393 | 15,084 | −718 | 35.41 |
| Stumpage prices | | | | |
| 50% | 2274 | 19,364 | 213 | 23.34 |
| 150% | 1643 | 14,852 | 0 | 14.74 |
| Harvested forest production costs | | | | |
| 50% | 1480 | 10,209 | −17 | 11.97 |
| 150% | 2435 | 20,046 | 0 | 26.61 |
| Spatially variable forest productivity | 2176 | 18,331 | −43 | 20.56 |

[a] The annual crop margins baseline refers to the baseline difference between crop revenue and all other production costs. Thus, 150% of the annual crop margins baseline refers to the use of 150% of the baseline estimates annual crop margins at each site.

[b] The afforestation subsidy/tax on harvested forest is set to achieve about 757 thousand tons of carbon for each crop margin, stumpage price, or harvested forest production cost condition.

[c] The average cost of carbon is the subsidy less the increase in farm net returns above the baseline divided by the increase in the net carbon sequestration with the subsidy.

**Table 6**
Afforestation and carbon sequestration for a subsidy on permanent mixed hardwoods and for a payment for sequestered carbon.

| Permanent mixed hardwood afforestation subsidy ($/acre) | Carbon sequestration greater than baseline[a] (thousand tons C) | Average cost of carbon sequestration[b] ($/ton C) | Payment for carbon sequestration ($/ton C) | Carbon sequestration greater than baseline (thousand tons C) | Average cost of carbon sequestration ($/ton C) |
|---|---|---|---|---|---|
| 1000 | 1456 | 3.21 | 5 | 1843 | 3.29 |
| 1500 | 2388 | 4.10 | 10 | 3475 | 5.23 |
| 2000 | 3023 | 4.72 | 15 | 6268 | 8.55 |
| 2500 | 3853 | 5.84 | 20 | 7082 | 9.52 |
| 3000 | 5005 | 7.21 | 25 | 7764 | 10.67 |
| 3500 | 6294 | 8.65 | 30 | 8546 | 12.16 |
| 4000 | 6592 | 8.99 | 35 | 9337 | 13.89 |
| 4500 | 7057 | 9.57 | 40 | 9397 | 14.03 |

[a] Average baseline forestation over the study period is 685 acres of pine, 50 acres of mixed hardwood, and baseline carbon sequestration is 62 tons.

[b] The average cost of carbon is the subsidy less the increase in farm net returns above the baseline divided by the increase in the net carbon sequestration with the subsidy.

to convert to forest, relative to the baseline, because the average productivity of the forest is less when varying productivity across site quality. For each sensitivity analysis in Table 5, the size of the ST to achieve the carbon sequestration target is a major driver of differences in the cost-effectiveness of carbon sequestration.

In addition to an afforestation ST, we compare results for two other policy scenarios: a subsidy targeting only permanent mixed hardwood[3] and a direct payment for carbon sequestration (Table 6). Direct payments for carbon range from $5 to $40 per ton of carbon ($1.37 to $10.93 per ton CO2eq) in increments of $5. To produce equivalent levels of carbon sequestration, direct payments for carbon are slightly more cost-effective than an afforestation subsidy for permanent forest. For example, to sequester 7057 tons of carbon requires a $4500 subsidy and cost $9.57 per ton C ($2.61 per ton CO2eq) under the permanent forest subsidy. A direct carbon payment of $20 per ton of carbon ($5.46 per ton CO2eq) induced slightly more sequestration (7082 acres in permanent mixed hardwoods) at a slightly lower average cost of $9.52 per ton C ($2.60 per ton CO2eq). However, a subsidy on permanent hardwood forest is probably easier to administer than a payment system for carbon sequestration. Since the social costs of the hardwood subsidy are about $700 thousand more than the direct payment for carbon sequestration for an equivalent amount of carbon,[4] the additional administration costs for a direct carbon payment could be justified. The cost-effectiveness of these policies depends on the willingness of landowners to convert land into permanent forest. Typically, landowners may be reluctant to give up the flexibility to put their land into other uses as possible with annual crops. The inefficiency of the harvestable pine afforestation ST for

[3] A subsidy targeting permanent pine is much more costly for carbon sequestration than a subsidy targeting permanent mixed hardwoods. A mature pine forest contains much less carbon than a mature mixed hardwood forest even though the pine accumulates the carbon faster.

[4] Here we compare the social costs of carbon with a no harvest hardwood subsidy of $3500 to the social costs of carbon with a direct carbon payment of $15.

carbon (nearly $60 million higher social costs for an equivalent amount of carbon[5]) means that more attention should go toward understanding the additional incentives farmers need to permanently set aside land for hardwoods.

## 5. Discussion and conclusion

We use a model of land use and water conditions at the one square mile level of spatial resolution to evaluate the cost effectiveness of afforestation to sequester carbon with endogenously chosen forest species and rotation lengths. When mostly soybean transitions to pine between the $1000 to $3000 afforestation ST, the rise in the average cost of carbon is slower than the rise in the afforestation ST. However, when corn and rice transition to pine between the $3000 to $4500 afforestation ST, the average cost of carbon rises faster, namely at the same pace as the afforestation ST. A landscape that is predominantly soybean has a lower cost of carbon, and the cost of carbon sequestration rises slower than a landscape with mostly corn or rice. The crop types and the proportions of land in each crop, which change with market conditions, in turn influence the cost-effectiveness of the afforestation ST.

The forest species chosen and the land planted to forest is quite sensitive to the discount rate, which in turn can have large ramifications for the cost of carbon sequestration. A 2% discount rate makes the slower growing hardwood forest with greater long term sequestration potential more profitable to landowners, and the choice of hardwood forest at any given afforestation ST significantly increases carbon sequestration and lowers the cost of carbon. A higher discount rate than 5% means that afforestation employs pine given their faster growth compared to hardwoods. However, the pine forest is more profitable relative to annual crops, and land in pine increases for any given afforestation ST, which also increases carbon sequestration and lowers the cost of carbon. The effectiveness of carbon sequestration through afforestation is also sensitive to water scarcity. Holding the carbon target to be sequestered constant, greater scarcity of water increases the afforestation ST required, the land in forest, and the average cost of carbon. Water scarcity also lengthens the pine forest rotation since more land enters than leaves pine throughout the study period compared to the baseline water conditions. Since the average cost of carbon using an afforestation ST increases with water scarcity, policy makers should consider the afforestation ST soon and thereby before the costs of irrigation rise.

The annual crops margins and harvest production costs are also considerations for an afforestation policy. A 50% increase in annual crops margins nearly doubles the average cost of carbon, and a 50% decline in harvestable forest production costs cuts the average cost of carbon by a third. Only a fall in the discount rate lowers the average cost of carbon more than the reduction in forest production costs. The most cost-effective afforestation policy would be a permanent easement on land to plant permanent hardwood through an afforestation subsidy or a direct carbon payment. However, permanent easements may be undesirable to the operators of farming operations who want to maintain flexibility in making annual land use choices.

The comparability of our results on the cost of carbon with previous studies is a challenge because our 100 site study area is substantially smaller than the land area in other studies. Stavins (1999) whose analysis is also in the Mississippi Delta States finds that an afforestation ST of $60 per acre per year induces nearly five million acres of new forest on 10.6 million agricultural acres at an average cost of carbon of $38 per ton carbon ($10.38 per ton CO2eq). Scaling our study to a similar size landscape as Stavins (1999), using an afforestation ST similar to the $60 per acre per year, leads to more than 5.6 million acres of new forest at an average cost of $28 per ton carbon ($7.65 per ton CO2eq). Comparison with Stavins (1999) has limits because the opportunity costs of annual crops have changed, and the Stavins study uses reduced form econometrics while we use structural dynamic modeling. However, the lower average cost of carbon could be attributable to the use of detailed information about the types of crops grown, groundwater availability, and endogenously chosen forest types and harvestable forest rotation lengths.

Newell and Stavins (2000) using the techniques and study area in Stavins (1999) find an average cost of carbon of $16 ($4.37 per ton CO2eq) for permanent mixed stand forest while we find a $4 average cost of carbon ($1.09 per ton CO2eq) for permanent hardwoods. Our lower average cost of carbon is partly because hardwoods sequester more carbon than mixed stands, but the alternative model assumptions we use in relation to Stavins (1999) mentioned above likely also have a role. Our sensitivity analysis with the discount rates reveals the importance of allowing forest species selection at low discount rates, which was not seen in Newell and Stavins (2000) where forest types are exogenously set. At a discount rate near 2% our study shows a switch to hardwood forest that substantially lowers the average cost of carbon. A rise in annual crop prices in Newell and Stavins (2000) increases the average cost of carbon slightly while a fall in annual crop prices decreases the average cost of carbon substantially. This is because the afforestation ST in Newell and Stavins (2000) prevents deforestation with higher annual crops prices as much as an increase in new land in forest. We find the opposite because there is minimal existing land to deforest in the baseline without the ST. An increase in annual crop prices just makes afforestation more difficult because the opportunity cost of land is higher. A decrease in annual crop margins and no ST results in ample hardwood forest. The pine afforestation with the ST then has to be substantial to exceed the sequestration from the hardwoods. The net result is that the average cost of carbon falls, but not quickly, as the annual crop margins fall.

Methodologically our model is closer to FASOM, but the spatial unit in FASOM is multiple state regions to evaluate forestry policies for the entire United States. Adams et al. (1999) find an average cost of carbon of $17 ($4.64 per ton CO2eq) from an increase of seven million acres of forest on land previously used for agriculture, and this is less than our $28 per ton carbon ($7.65 per ton CO2eq) estimate for 5.6 million acres. The much larger region in Adams et al. (1999) should mean greater opportunities for low cost carbon sequestration through afforestation than in our small but spatially detailed study area. Similar to Adams et al. (1999), we find that hardwood species are important for minimum cost strategies, but our model indicates that hardwood planting only occurs if the discount rate is close to 2% or the policy is a direct payment for carbon sequestration. One advantage of a model with a large study area, like FASOM, is the ability to evaluate how afforestation might result in commodity and land market changes that reduce management intensity of existing forests or increase deforestation, and we do not account for these leakages in our current model framework (Murray et al., 2004).

There are extensions to this work that would be beneficial to policy makers who want to understand how landowners react to an afforestation ST or an alternative policy for carbon sequestration. Greater computing power could expand the application of our model to a larger area, potentially the entire Lower Mississippi River Basin or the southern United States. Modifications to our model that include endogenous prices and leakage would be necessary to evaluate afforestation policies for the entire southern United States. We could then confirm whether a larger area results in the afforestation and the average cost of carbon we predict by scaling upward. The responsiveness of a landowner to an afforestation ST will vary depending on the awareness and landowner characteristics amenable to a policy change. The model could incorporate a differential reaction to the policy, which would alleviate the substantial forest planting in the initial period observed in Fig. 2. The typical forestry management for the region we assume in this model could be supplanted by alternative management techniques, which

[5] Here we compare the social costs of carbon with an afforestation ST of $4500 to the social cost of carbon with a direct carbon payment of $5.

change the yield curves and production costs, to examine whether our major findings would change. One way to develop this extension would be through the use of the Forest Vegetation Simulator that can simulate the growth and yield associated with a wide range of silvicultural treatments for most tree species, forest types, and stand conditions (Shaw and Gagnon, 2020).

Another line of research could follow Stavins (1999) use of reduced form econometrics but includes land use change at greater spatial resolution that accounts for endogenously chosen forest types and groundwater pumping. A comparison could then be made between the relative merits of the reduced form econometrics and structural dynamic modeling for policy analysis (Obembe and Hendricks, 2020). Allowing for the endogenous choice of alternative management of the harvestable forest types to increase site level productivity in even and uneven aged forest stands could also offer insights (Olschewski and Benítez, 2010; Parajuli and Chang, 2012). The inclusion of uncertainty about forest growth and the timber and annual crop markets along with risk aversion by landowners may change the afforestation choices (Johnston and Withey, 2017). Broadening the scope of profit making opportunities for landowners to include biofuel markets, alternative carbon crediting schemes, and credits for ecosystem services other than carbon are other directions for research on afforestation (Köthke and Dieter, 2010; Price and Willis, 2011).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Appendix

The appendix has four tables. Table A1 has the mean and standard deviation of the site level data inputs for the model. Table A2 has the farm production and irrigation parameters for the model. The carbon sequestration parameters for the annual crops are in Table A3, and the carbon emission parameters for the land and irrigation fuel combustion are in Table A4. Table A5 indicates the baseline, i.e. no afforestation ST, land use and aquifer conservation outcomes for three time frames and the average of the study period. Fig. A1 shows the yield curve estimates for loblolly-short leaf pine (left) and oak-gum cypress (right) based on biomass estimates for five stand age increments from USDA Forest Service (2019). Fig. A2 indicates the undiscounted carbon sequestration over the study horizon for an afforestation ST of (a) $1000, (b) $3000, and (c) $4500.

**Table A1**
Descriptive statistics of the spatial data across sites of the study area.

| Variable | Definition | Mean | Std. Dev. |
|---|---|---|---|
| $L_{i,rice}$ | Initial acres of rice | 95.34 | 121.03 |
| $L_{i,corn}$ | Initial acres of irrigated corn | 43.87 | 73.96 |
| $L_{i,isoy}$ | Initial acres of irrigated soybean | 306.85 | 119.19 |
| $L_{i,dsoy}$ | Initial acres of dry land soybean | 73.65 | 56.43 |
| $y_{i,rice}$ | Annual rice yield (cwt per acre)[1] | 65.41 | 3.06 |
| $y_{i,corn}$ | Annual corn yield (bushels per acre) | 180.13 | 10.77 |
| $y_{i,isoy}$ | Annual irrigated soybean yield (bushels per acre) | 49.36 | 4.04 |
| $y_{i,dsoy}$ | Annual dry land soybean yield (bushels per acre) | 34.37 | 3.76 |
| $dp_i$ | Depth to water (feet) | 62.82 | 34.22 |
| $AQ_i$ | Initial aquifer thickness (feet) | 82.97 | 29.47 |
| $nr_i$ | Annual natural recharge of the aquifer per acre per year (feet) | 0.43 | 0.20 |
| $\xi_i$ | Soil factor, fraction of carbon lost to respiration due to soil related microbial activity | 0.72 | 0.05 |

Note: Number of all sites is 100. The mean and the standard deviation of the county yields come from the 11 counties in the study area.

**Table A2**
Value of the farm production and irrigation model parameters.

| Parameter | Definition | Value |
|---|---|---|
| $pr_{rice}$ | Price of rice ($/cwt) | 11.70 |
| $pr_{corn}$ | Price of corn ($/bushel) | 3.69 |
| $pr_{soy}$ | Price of soybeans ($/bushel) | 9.54 |
| $ca_{rice}$ | 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 |
| $\delta_t$ | Discount factor | 0.95 |

**Table A3**
Carbon sequestration parameters for the annual crops.

| Parameter | Definition | Value |
|---|---|---|
| $\lambda_{rice}$ | Yield conversion for rice from cwt/ac to kg/ac | 45.5 |
| $\lambda_{corn}$ | Yield conversion for corn from bu./ac to kg/ac | 25.4 |
| $\lambda_{isoy}$ | Yield conversion for irrigated soybeans from bu./ac to kg/ac | 27.2 |
| $\lambda_{dsoy}$ | Yield conversion for non-irrigated soybeans from bu./ac to kg/ac | 27.2 |
| $\lambda_{dsorg}$ | Yield conversion for non-irrigated sorghum from bu./ac to kg/ac | 25 |
| $\alpha_{rice}$ | Moisture content (wet basis) of rice | 0.13 |
| $\alpha_{corn}$ | Moisture content (wet basis) of corn | 0.155 |
| $\alpha_{isoy}$ | Moisture content (wet basis) of irrigated soybeans | 0.13 |
| $\alpha_{dsoy}$ | Moisture content (wet basis) of non-irrigated soybeans | 0.13 |
| $\alpha_{dsorg}$ | 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 for irrigated soybeans | 0.45 |
| $H_{dsoy}$ | Harvest index for non-irrigated soybeans | 0.45 |
| $H_{dsorg}$ | Harvest index for non-irrigated sorghum | 0.39 |
| $\beta_{rice}$ | Crop residue C content of rice (g/kg) | 360 |
| $\beta_{corn}$ | Crop residue C content of corn (g/kg) | 410 |
| $\beta_{isoy}$ | Crop residue C content of irrigated soybeans (g/kg) | 430 |
| $\beta_{dsoy}$ | Crop residue C content of non-irrigated soybeans (g/kg) | 430 |
| $\beta_{dsorg}$ | Crop residue C content of non-irrigated sorghum (g/kg) | 420 |
| $\delta_{low}$ | Aboveground C remaining in the soil with low tillage | 0.40 |
| $\delta_{conventioal}$ | Aboveground C remaining in the soil with conventional tillage | 0.70 |
| $\eta_{low}$ | Belowground C remaining in the soil with low tillage | 0.45 |
| $\eta_{conventional}$ | Belowground C remaining in the soil with conventional tillage | 0.40 |
| $\chi_{rice}$ | Root C content of rice (g/kg) | 350 |
| $\chi_{corn}$ | Root C content of corn (g/kg) | 420 |
| $\chi_{isoy}$ | Root C content of irrigated soybeans (g/kg) | 430 |
| $\chi_{dsoy}$ | Root C content of non-irrigated soybeans (g/kg) | 430 |
| $\chi_{dsorg}$ | Root C content of non-irrigated sorghum (g/kg) | 380 |
| $\phi_{rice}$ | Root/shoot ratio (belowground/aboveground biomass) of rice | 0.16 |
| $\phi_{corn}$ | Root/shoot ratio (belowground/aboveground biomass) of corn | 0.19 |
| $\phi_{isoy}$ | Root/shoot ratio for irrigated soybeans | 0.16 |
| $\phi_{dsoy}$ | Root/shoot ratio for non-irrigated soybeans | 0.16 |
| $\phi_{dsorg}$ | Root/shoot ratio for non-irrigated sorghum | 0.08 |

Source: Popp et al. (2011).

**Table A4**
Carbon emission parameters for the annual land uses and irrigation fuel combustion.

| Parameter | Definition | Value |
|---|---|---|
| $E_{rice}$ | GHG emissions from rice production (tons/acre) | 1.55 |
| $E_{corn}$ | GHG emissions from corn production (tons/acre) | 2.13 |
| $E_{isoy}$ | GHG emissions from irrigated soybean production (tons/acre) | 0.42 |
| $E_{dsoy}$ | GHG emissions from dryland soybean production (tons/acre) | 0.34 |
| $E_{fallow}$ | GHG emissions from fallow production (tons/acre) | 0.06 |
| $E_{methane}$ | GHG emissions from methane release of rice production | 3.03 |
| $\sigma_g$ | Conversion factors to track the carbon emitted in tons from fuel combustion to lift an acre-foot of water one foot | 0.00042 |

Source: Division of Agriculture (2018); Popp et al. (2011); Hogan et al. (2007).

**Table A5**
Baseline (no afforestation ST) land use and aquifer conservation outcomes for select time frames.

| Baseline model outcomes | Average of first hundred years | First year | Fiftieth year | Hundredth year |
|---|---|---|---|---|
| Land use allocation (acres) | | | | |
| Corn | 9510 | 10,394 | 10,394 | 5187 |
| Rice | 12,253 | 14,032 | 14,032 | 4089 |
| Irrigated soybean | 20,814 | 27,314 | 26,664 | 5649 |
| Dryland soybean | 1519 | 0 | 397 | 5813 |
| Fallow | 15 | 0 | 0 | 121 |
| Harvestable pine | 685 | 0 | 0 | 4009 |
| Harvestable hardwood | 50 | 1 | 1 | 163 |
| Permanent pine | 7123 | 229 | 482 | 26,931 |
| Permanent hardwood | 2 | 0 | 0 | 7 |
| Aquifer volume (thousand acre-feet) | 1557 | 3954 | 1503 | 110 |

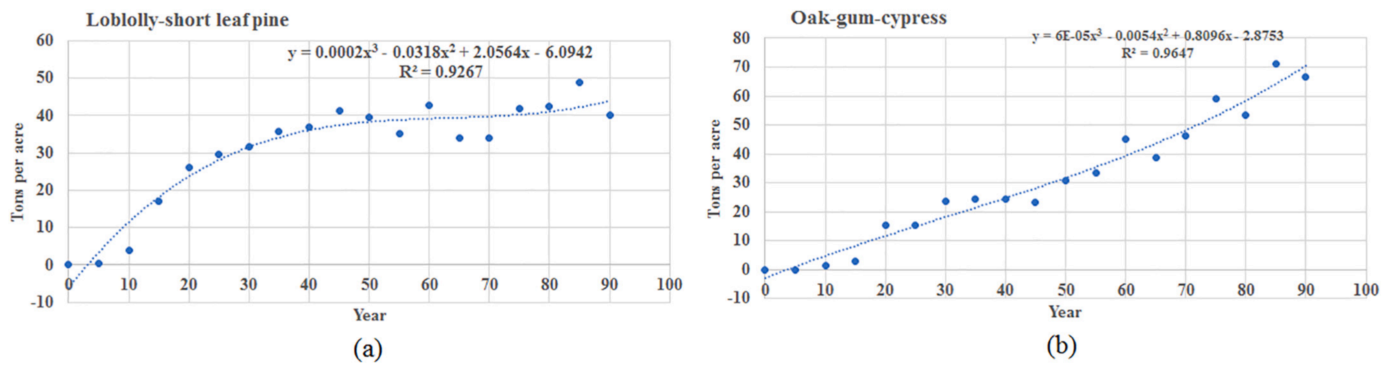


**Fig. A1.** Yield curve estimates for loblolly-short leaf pine (left) and oak-gum cypress (right) based on biomass estimates for five stand age increments from USDA Forest Service (2019).

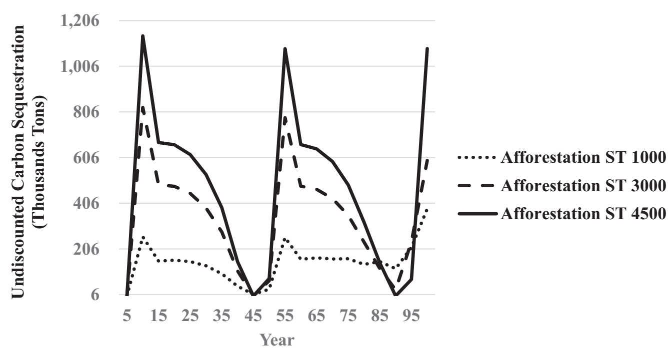


**Fig. A2.** Undiscounted carbon sequestration over the study horizon for an afforestation ST of (a) $1000, (b) $3000, and (c) $4500.

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