Marginal Cost of Carbon Abatement through Afforestation of Agricultural Land in the Mississippi Delta

Karli A. Moore[1]
kam034@uark.edu

Kent F. Kovacs[1]
Tel: (479) 575-2323
kkovacs@uark.edu

[1] University of Arkansas
Department of Agricultural Economics and Agribusiness
216 Agriculture Building
Fayetteville, AR 72701

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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 Department of Agriculture (USDA) administers voluntary, incentive-based programs to encourage landowners to adopt production practices with positive environmental outcomes. This policy can be used to increase transition from marginal agricultural land to forests, thereby creating new carbon sinks. We analyze an eleven-county study area in the Mississippi Delta region of Arkansas 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 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. The product of this effort, a marginal cost curve for carbon abatement, will assist policymakers in allocating limited resources to programs for greenhouse gas mitigation.

Keywords: Afforestation, Carbon Sequestration, Land

JEL Classifications: Q15, Q24, Q25

Introduction

Increasing accumulation of atmospheric carbon is the primary driver of climate change. Carbon dioxide emissions from human activities create a heat-trapping environment causing the Earth to warm at historically unprecedented rates (Santer, et al., 1996). Mitigating increasing levels of carbon in the atmosphere requires a reduction in emissions and/or escalation in sequestration. Emissions reduction comes from two avenues: energy efficiency through improved practices and/or technology, and transition from fossil fuel to renewable energy sources. Carbon sequestration can be categorized into engineered or natural processes. Engineered carbon sequestration is often referred to as carbon capture and sequestration (Talbot, 2014). In the natural world, carbon is sequestered by plants through the process of photosynthesis. One climate change abatement strategy is to sequester emissions by increasing terrestrial vegetation.

While all plants photosynthesize, a significant portion of the carbon captured is released upon harvest. For long-term carbon sequestration, perennial species with long or indefinite lifespans are key. Under this criteria, forests – especially those consisting of fast-growing tree species – have been identified as strong candidates for organized carbon sequestration efforts (Moulton & Richards, 1990). Surveying the current landscape, the most promising opportunities for afforestation are in privately-owned marginal agricultural land. This study will focus on the potential for atmospheric carbon abatement through afforestation in the Arkansas Delta (as defined by an eleven-county study region along the Mississippi River – Fig. 1).

The Arkansas Delta is a good candidate for afforestation for two reasons: an ideal environment for tree growth and increasingly tenuous groundwater situation affecting agricultural production. 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 costs of irrigation increase, it may be more profitable for landowners to adopt less water-intensive land cover, making afforestation attractive.

Previous literature on forestry carbon abatement is divided into two methodological strands. Optimization-based approaches model maximum net economic returns of various land uses (i.e., agriculture and forestry) utilizing exogenous parameters of input costs, yield expectations and market prices (Sedjo & Sohngen, 2012). Differences in the net returns of agriculture and forestry are used to estimate the subsidy required for conversion to land states with higher carbon sequestration. Our spatially-explicit optimization model allows for in-depth exploration of the impact of depleting groundwater, and subsequent irrigation cost increases, on optimal land use allocation. Other examples of optimization models for estimating carbon abatement cost curves include Moulton and Richards (1990) and more recently Sohngen and Brown (2008).

Econometric models of land use decisions allow researchers to develop carbon abatement cost curves from differentials in carbon price. Stavins (1999) and Newall and Stavins (2000) estimated costs of carbon sequestration associated with converting marginal agricultural land to loblolly pine plantations in the Delta states (Arkansas, Louisiana and Mississippi). They found converting cropland to forests could capture carbon at marginal costs up to $664 per ton CO_2e. This figure is aligned with the results from other carbon offset studies. A meta-analysis of fifty-five studies on the cost of abating carbon using forestry found averages between $117 and $1,407 per ton CO_2e (van Kooten, Eagle, Manley, & Smolak, 2004).

The following study seeks to add to the literature on forest carbon policy by estimating the marginal cost of carbon abatement from afforestation for land in representative counties of the

Arkansas Delta. It also accounts for groundwater dynamics and the cost of crop irrigation, important factors in an environment of rapidly depleting groundwater where water-intensive crops are the dominant land cover.

Methods

Land cover and irrigation models

Land uses are divided into annual states and perennial states. There are six annual land uses: corn, flood-irrigated rice, non-irrigated sorghum, non-irrigated soybean, furrow-irrigated soybean and fallow (CRP). There are two perennial (non-irrigated) land uses, loblolly pine plantations and mixed hardwood forests. Field crops, fallow land and perennial forests represent n possible land covers j for period t and site i as denoted by L_{ijt}. Any annual land cover j at period t can become another land cover in the subsequent year, but the perennial states are considered constant until harvest in the final period. The sum of land covers chosen for site i at any time t must equal the initial land availability (Eq. 1).

$$\sum_{j}^{n} L_{ijt} = \sum_{j}^{n} L_{ij0} \text{ , for } j = \text{crops, fallow, perennial forests} \qquad (1)$$

The fixed average annual irrigation that crop j receives to supplement precipitation, wd_j, is given in acre-feet. The groundwater stored in the aquifer beneath site i at the end of period t is AQ_{it}, and the water from well pumping is GW_{it}. There is recharge of the groundwater, nr_i, occurring naturally from precipitation, streams and underlying aquifers each period. The intensity of well pumping across the landscape influences aquifer depletion over space. The proportion of the underground flow into the aquifer at site k and out of site i when an acre-foot of water is pumped from a well at site k is p_{ik}, which depends on the distance and the lateral speed of underground water movement based on the soil profiles observed between sites. In response to declining groundwater availability, a farmer maximizing profit might switch land out of irrigated crops into non-irrigated, fallow or perennial states at the end of a period.

GHG value model

A life cycle assessment (LCA) up to the farm gate indicates the GHG emissions measured in carbon equivalents (CE) as kg per acre for land cover j (E_j). The LCA quantifies emissions associated with fuel use, manufacture of chemicals/fertilizer, methane release from rice production, and nitrous oxide emissions from nitrogen fertilizer application to the soil (Nalley et al. 2011). Emissions from groundwater pumping at site i (EG_{it}) is the depth of the well scaled by a conversion factor σ_g that identifies the carbon released from fuel combustion to lift an acre-foot of water by one foot and multiplied by the acre-feet of groundwater pumped, GW_{it}. Equation (2) indicates the total carbon emissions for time t at site i (E_{it}).

$$E_{it} = \sum_j^n E_j L_{ijt} + EG_{it} + ER_{it} \quad (2)$$

For annual states, the sequestration of aboveground biomass (AGB_{ij}) and belowground biomass (BGB_{ij}) depends on the soil texture and tillage practices (Popp et al. 2011). 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). The carbon sequestration, S_{it}, for time t at site i is shown in Equation (3) as

$$S_{it} = \sum_j^n \left[\left(AGB_{ij} + BGB_{ij} \right) \xi_i \right] L_{ijt} \quad (3)$$

Farm returns objectives

There is an assumption of no productivity growth over time for the yield of annual crop *j* per acre at site *i*, y_{ij}. The cost to produce an acre of the annual crop excluding the irrigation cost (C_j) and the price per conventional unit of the annual crop (pr_j) are constants in real terms. The net value for annual crop j is then pr_j - C_j per acre less irrigation costs.

The yield for a perennial forest land state is modeled as a cubic function with respect to rotation length. Forest products from a perennial land state can be sold in two forms, timber and pulpwood, which are percentages of the total yield from an acre. Therefore, the net value for perennial crop j is the stumpage price of pulp and timber minus production costs. The net value of fallow land is the conservation rental payment minus the cost to establish approved practices. The real discount factor, δ_t, converts all values to a standard time period for comparability in monetary terms.

The economic objective is to maximize the present value of farm profits over the fixed horizon T (50 years) by changing the amount of land in each annual crop, fallow land state or perennial forest (Equation 4). The time horizon does influence the results such that a shorter horizon leads to faster depletion of the aquifer and a longer horizon leads to slower annual depletion of the aquifer. The non-negativity constraints on land, water use, and the aquifer are shown in Equation 5.

$$\max_{L_{ijt}, RW_{it}, GW_{it}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \left(pr_j y_{ij} - ca_j \right) L_{ijt} - c^r L_{iRt} - c^{rw} RW_{it} - GC_{it} GW_{it} \right) \tag{4}$$

Subject to:

$$L_{ijt} \geq 0, RW_{it} \geq 0, GW_{it} \geq 0, AQ_{it} \geq 0, \quad (5)$$

and the spatial dynamics of land and irrigation.

Data

The study area consists of three eight-digit hydrologic unit code watersheds within eleven counties in the Arkansas Delta (Fig. 1). Land without crops (public and/or urban areas) are excluded from the study area (Johnson & Mueller, 2010).

Sites

Spatial heterogeneity of crop production, yield and irrigation opportunity on the landscape are preserved by dividing the study area into 2,724 sites. Of those, two hundred sites were randomly selected as representative samples for this study. Initial acreage for the annual crops of interest (corn, rice, sorghum and soybeans) by site are drawn from the 2015 Cropland Data Layer (Cropland Data Layer, 2017). Soybean acreage by site is divided into irrigated and non-irrigated categories using county level statistics (Arkansas Field Office - Soybean Irrigated and Non-Irrigated, 2017). Annual crop yields are calculated from five year averages at a county level (Arkansas Field Crop Enterprise Budgets, 2015). Perennial forest biomass yields are determined by a cubic function with respect to rotation length from the U.S. Forest Service EVALIDator (EVALIDator, 2015).

Groundwater

The initial water table depth and saturated thickness of the Alluvial aquifer is from the Arkansas Natural Resources Commission (Arkansas Groundwater Protection and Management Report for 2014, 2015). The aquifer volume at site *i* is calculated by multiplying the site acreage by the saturated thickness of the aquifer. Natural recharge (nr_i) comes from the precipitation and contributions by local streams and connected aquifers (Reed, 2003).

Annual Crop Revenue and Cost

Production costs (excluding irrigation) and irrigation water requirements by crop are from the 2014 Crop Cost of Production estimates (Flanders, et al., 2015). CRP payment rates per acre are indicated in USDA Farm Service Agency reports for Arkansas (Conservation Reserve Program Stastics, 2017). Annual crop prices are 10-year averages for harvest time contracts in Arkansas (National Agricultural Statistics Service Quick Stats, 2017). The real discount rate is set at 2% based on the yield of a 30yr Treasury Bond over the past thirty years (Interest Rate Statistics, 2017).

Perennial Crop Revenue and Cost

Production costs are derived from estimates of projects administered by the Natural Resource Conservation Service of the USDA (Childress, 2017). Stumpage prices, which account for harvesting costs, are shown as averages over 40 years in southern Arkansas (Prestemon, 2017).

Carbon Tracking

County-level annual crop yields influence the soil carbon sequestration in above- and below-ground biomass (Popp, Nalley, Fortin, Smith, & Brye, 2011). These values are adjusted based on localized tillage practices and soil texture. Emissions from fuel, fertilizer and chemical applications are tracked from crop enterprise budget estimates (Flanders, et al., 2015). Carbon sequestration by perennial crops is modeled by a cubic function with respect to rotation length (EVALIDator, 2015).

Results

The study contains results from three scenarios of the land use optimization model (Table 3). The first scenario is a baseline run with no subsidy for perennial plantings. The optimal solution showed $345,400,000 in net returns (present value) and 859,208 metric tons of carbon sequestered over 50 years. In the final period, land was distributed as follows: 6,861 acres of rice; 11,923 acres of irrigated soybeans; 14,655 acres of corn; 31,758 acres of non-irrigated sorghum; 5,346 acres of pine plantations; 169 acres of hardwood forests; and zero acres of non-irrigated soybeans and CRP.

The second scenario introduced a ten percent government subsidy on perennial (pine and hardwood) revenue. Present value of net returns increased slightly (0.31%) to $346,300,000 and the new land use pattern sequestered 1,086,754 metric tons of CO_2 (26% increase over the baseline) for a total subsidy cost of $1,120,155. Cost effectiveness for this scenario, additional economic returns less the subsidy divided by gains in carbon sequestration, is $0.96/metric ton CO_2e. With the ten percent subsidy, acreage decreased for rice (7%), corn (6%) and sorghum (3%), held constant for irrigated soybeans, and increased for pine (36%) and hardwood (130%).

The final scenario elevated the government subsidy to twenty percent of perennial revenue. Present value of net returns increased slightly (0.67%) over baseline with a corresponding 83% increase in carbon sequestration. Subsidies totaled $3,913,229, and lead to a cost effectiveness of $2.27/metric ton CO_2e. Mirroring the previous trend, acreage decreased for rice (14%), corn (18%), and sorghum (11%), held constant for irrigated soybeans, and increased for pine (122%) and hardwood (215%).

The site-level marginal cost of carbon sequestration is charted for a 10% subsidy and 20% subsidy (Figures 2a and 2b). With a 10% subsidy, 59 sites incorporate more perennial crops than in the baseline distribution. The cost of sequestering more carbon through additional trees ranges from a low of \$1.50/ac/metric ton CO_2e to a high of \$144.12/ac/metric ton CO_2e, with a median value of \$7.97/ac/metric ton CO_2e. Moving the subsidy to a higher level (20%) shifts acreage to trees on 82 sites. The marginal cost of sequestration in this scenario ranges from \$6.70/ac/metric ton CO_2e to \$37,793.10/ac/metric ton CO_2e, and the median value is \$17.03/ac/metric ton CO_2e.

Depleting groundwater is a major factor in the study area. The model shows that as more perennial crops enter the landscape, the aquifer rises. There is a 3% rise in aquifer levels given a 10% subsidy, and 9% rise with the 20% subsidy. This is initiated by the transition of water-intensive crops to non-irrigated options.

Discussion and Conclusion

The results suggest that the landscape can sequester additional carbon through the afforestation of marginal agricultural land. This transition is spurred on by the presence of revenue subsidies for perennial forests to keep farm net returns on par with traditional agricultural crops. While present value of economic farm returns increase with market intervention, there is an overall cost to society for the subsidy. The 10% subsidy was more cost effective, but both regimens were well below results from previous studies (van Kooten, Eagle, Manley, & Smolak, 2004). This may be an indicator that the model is too optimistic, and future iterations will include more nuance in production costs and carbon footprint of perennial land use.

The spatially-explicit nature of the model allows for examination of policy impacts on a site level. Results comparing a 10% subsidy to a 20% subsidy indicate that there is a differential in site participation. This is likely due to the quality of land impacted; higher quality land will have greater economic potential with conventional crops, and therefore will require the larger subsidy for conversion.

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, 10% subsidy and 20% subsidy scenarios. As the subsidies introduced more perennial crops, irrigated annual crop acreage fell resulting in higher aquifer levels. The inclusion of groundwater concerns could have contributed to the abnormally low costs for sequestering carbon. Spatially-detailed irrigation costs may have caused a transition from water-intensive and high emitting crops (i.e. rice) to non-irrigated and carbon abating options.

Marginal cost curves for carbon sequestration show the variation in cost over sites. In both subsidy scenarios, the range is skewed by outliers on the upper bound with most of the sites clustered together at the low-end of the range. Since policymakers are working with limited resources, they would be best served to target sites with lower marginal costs for carbon sequestration. To aid in this endeavor, a follow-up research topic could be to identify the land characteristics that produce low versus high marginal costs.

The model for carbon sequestration and land use distribution can be extended and further refined. As with annual crops, perennial forest yield can be better approximated by including site-specific information into the calculations. As biomass yield estimates improve, so will carbon sequestration and emission information by site. Currently, the model assumes that carbon stored in tree biomass is captured indefinitely. In reality, this detail is more nuanced and relies on information about the intended use of harvested material. Future iterations of the model can include multiple scenarios of wood use and identify the impact on the overall carbon sequestration goal. Other research opportunities include changing the scope to investigate how the time horizon impacts land use distribution.

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

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Table 1 Economic and Hydrologic Data and Parameters

Parameter	Definition	Value
pr_{rice}	Price of rice ($/cwt)	13.63
pr_{corn}	Price of corn ($/bushel)	4.99
pr_{soy}	Price of soybeans ($/bushel)	11.62
pr_{sorg}	Price of sorghum ($/bushel)	5.23
pr_{CRP}	Government payment for CRP	59.1
$pr_{pinepulp}$	Stumpage price of pine pulp ($/ton)	9.95
$pr_{pinetimber}$	Stumpage price of pine timber ($/ton)	30.11
$pr_{hardpulp}$	Stumpage price of hardwood pulp ($/ton)	11.71
$pr_{hardtimber}$	Stumpage price of hardwood timber ($/ton)	33.86
ca_{rice}	Annual production cost of rice ($/ac)	646
ca_{corn}	Annual production cost of corn ($/ac)	632
$ca_{irr\ soy}$	Annual production cost of irrigated soybeans ($/ac)	349
ca_{dsoy}	Annual production cost of non-irrigated soybeans ($/ac)	289
ca_{dsorg}	Annual production cost of non-irrigated sorghum ($/ac)	270
ca_{CRP}	Annual production cost of CRP ($/acre)	21
ca_{pine}	One-time production cost of pine ($/ac)	348
ca_{hard}	One-time production cost of hardwood ($/ac)	348
wd_{rice}	Annual irrigation per acre of rice (acre-feet)	2.5
wd_{corn}	Annual irrigation per acre of corn (acre-feet)	1.0
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 2 Carbon Data and Parameters

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 3 Optimization Model Results for Land Cover, Net Returns and Carbon Sequestration

Landscape conditions	Baseline	10% subsidy on stumpage price	20% subsidy on stumpage price
Land cover (thousand acres)			
Rice	6,861.83	6,362.72	5,917.24
Irrigated soybeans	11,922.88	11,922.88	11,922.88
Irrigated corn	14,655.94	13,834.51	12,068.42
Dryland soybeans	0	0	0
Dryland sorghum	31,758.15	30,947.23	28,407.70
Pine	5,346.56	7,259.33	11,866.63
Hardwood	168.72	387.42	531.21
CRP	0	0	0
Net Carbon Sequestration (metric tons)	859,208.27	1,086,754.47	1,569,544.94
Aquifer (thousand acre-feet)	1,373,847.16	1,413,793.66	1,504,191.54
Present value of economic Returns ($ thousands)	345,400	346,300	347,700
Present value of the subsidy ($ thousands)	--	1,120	3,913
Cost effectiveness ($/metric ton)	--	0.96	2.27

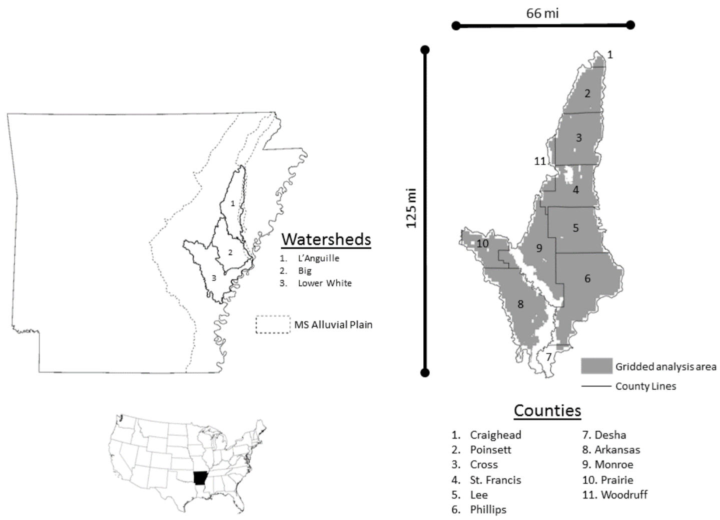

Figure 1. Three eight-digit hydrologic unit code watersheds and the eleven Arkansas counties wherein define the study area. Public lands and urban areas are excluded. The location of the study area within the State of Arkansas is shown.

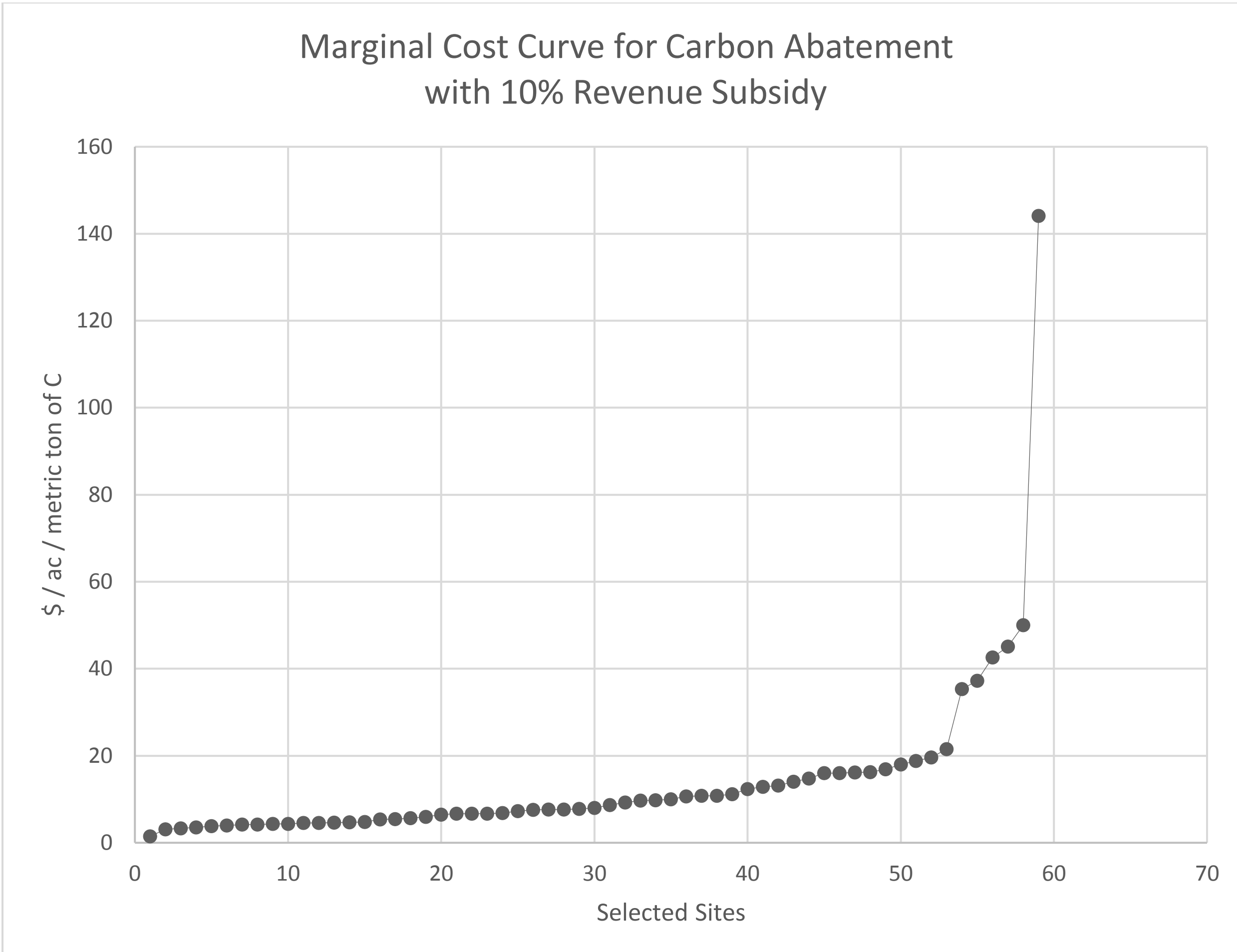

Figure 2a. Marginal cost curve for carbon sequestration from the cultivation of forested lots given a 10% subsidy on forest revenue

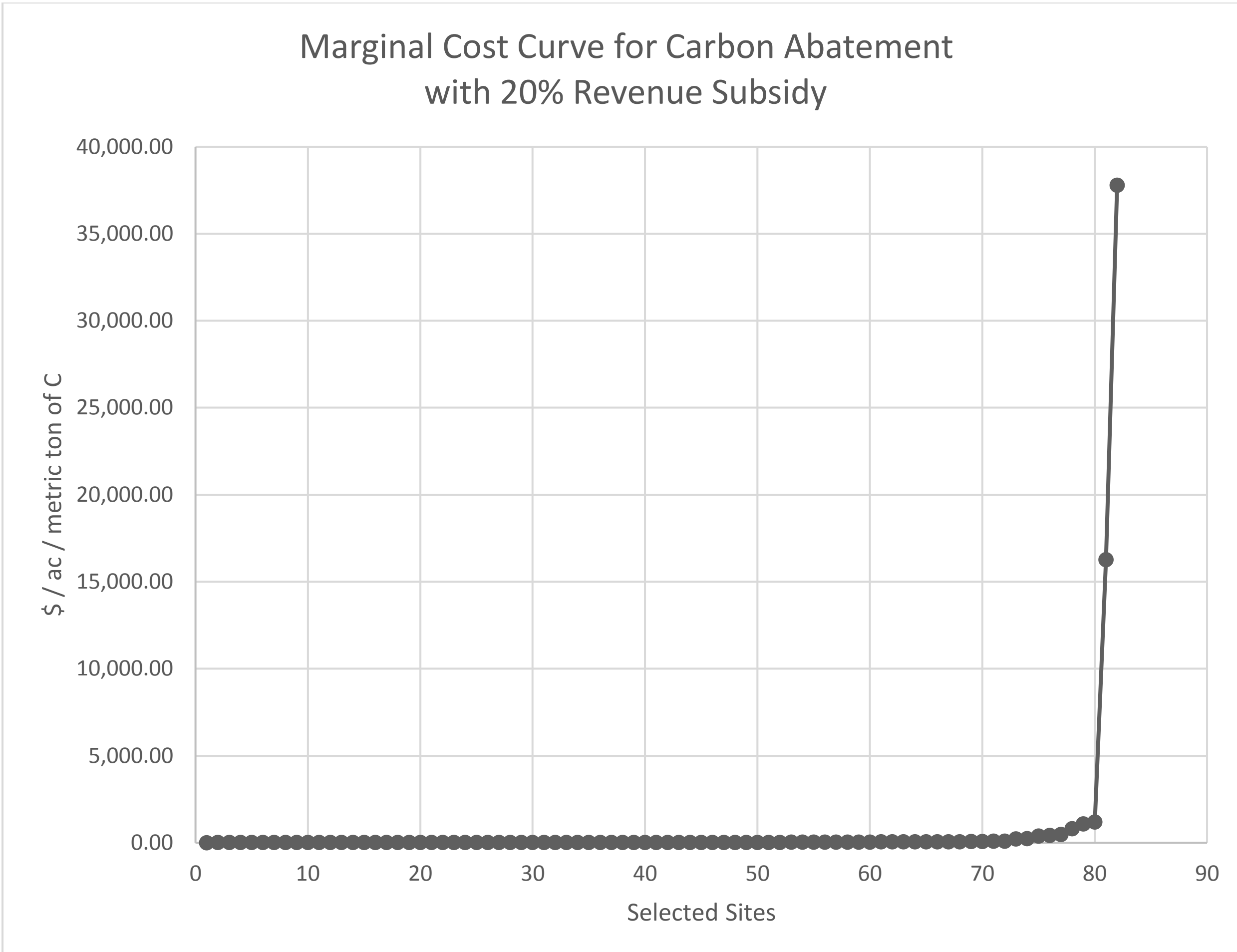

Figure 2b. Marginal cost curve for carbon sequestration from the cultivation of forested lots given a 20% subsidy on forest revenue