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Mitigating climate change through afforestation: New cost estimates for the United States

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ABSTRACT

We provide new cost estimates for carbon sequestration through afforestation in the U.S. We extend existing studies of carbon sequestration costs in several important ways, while ensuring the transparency of our approach. Our costs estimates have five distinguishing features: (1) we estimate costs for each county in the contiguous U.S., (2) we include afforestation of rangeland, in addition to cropland and pasture, (3) our opportunity cost estimates account for capitalized returns to future development (including associated option values) in addition to returns to agricultural production, (4) we develop a new set of forest establishment costs for each county, and (5) we incorporate data on Holdridge life zones to limit afforestation in locations where temperature and moisture availability prohibit forest growth. We find that at a carbon price of $50/ton, approximately 200 million tons of carbon would be sequestered annually through afforestation. At a price of $100/ton, an additional 100 million tons of carbon would be sequestered each year. Our estimates closely match those in earlier econometric studies for relatively low carbon prices, but diverge at higher carbon prices. Our results indicate a smaller, but still important, role for forest-based carbon sequestration in offsetting U.S. greenhouse gas emissions.

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1. Introduction

Concern about climate change has focused attention on the role of forests in the global carbon cycle. Trees and other forest plants convert carbon dioxide (CO_2) to carbon through photosynthesis, thereby reducing concentrations of CO_2 in the atmosphere. Because forests typically store more carbon than land in other uses (e.g., agriculture), expansion of forests onto non-forest lands (i.e., afforestation) has the potential to reduce CO_2 concentrations and mitigate effects of climate change. For the past several decades, economists have estimated the costs of carbon sequestration in forests to determine its competitiveness with other carbon mitigation and abatement strategies.

The first carbon sequestration cost studies appeared in the late 1980s (Marland, 1988; Sedjo, 1989; Dudek and LeBlanc, 1990), and provided point estimates of the average cost of forest carbon sequestration. The first detailed and comprehensive marginal cost estimates for the U.S. were provided by Moulton and Richards (1990) (hereafter, MR). Marginal costs are useful because they can be combined with cost estimates for other carbon mitigation and abatement approaches in order to identify the efficient portfolio of strategies. To estimate marginal costs, MR first estimated average costs of carbon sequestration for 10 U.S. regions and seven treatment types (afforestation on wet and dry cropland, afforestation on wet and dry pasture, and three forest management treatments). These estimates accounted for opportunity costs of the land, upfront treatment costs, and the total amount of carbon sequestered. MR constructed a marginal cost curve by ordering these costs from lowest to highest and then plotting them against cumulative carbon sequestration.

Following MR, economists have provided a number of refinements to the methodology for estimating marginal costs (Dempsey et al., 2010). Adams et al. (1993) recognized that a national afforestation policy would raise the marginal costs of carbon sequestration by restricting the supply of agricultural commodities, thus increasing their prices and the opportunity cost of conversion to forest. Similarly, more land in forest would increase the supply of wood products, diminishing these prices and the willingness of landowners to afforest. By combining models of the timber and agricultural sectors, these authors demonstrated that price feedbacks raise the marginal costs of carbon sequestration, particularly as the total amount of carbon sequestered increases.[1] Other studies that account for endogenous price feedbacks from forest carbon sequestration policies include Richards et al. (1993), Alig et al. (1997), Adams et al. (1999) and Lubowski et al. (2006).

A second refinement is to measure opportunity costs of land using econometric analysis, rather than bottom-up engineering methods, as in MR, or sectoral optimization models, as in the FASOM studies. The econometric approach involves analyzing historical data on the actual decisions by landowners facing returns to alternative uses. Once the relationship between land-use choices and net returns is identified, a policy simulation is conducted to estimate the response by landowners to incentives for afforestation and/or avoided deforestation. The econometric approach has the potential to account for factors that affect land-use decisions in practice but that are difficult to measure explicitly. These include option value related to holding land in its current use, as well as private non-market benefits (e.g., recreation) that landowners may derive from land in particular uses. Typically, marginal cost estimates from econometric analyses are higher than those produced with bottom-up engineering or optimization methods (Plantinga et al., 1999; Stavins, 1999; Lubowski et al., 2006). There have also been a few studies that estimate opportunity costs using a stated preference approach (e.g., van Kooten et al., 2002)

Three other innovations in the literature since MR deserve mention. The first relates to carbon accounting. MR compute the average annual increment in carbon over a 40-year project horizon. As Stavins (1999) points out, this ignores the time profile of carbon flows into and out of the forest. He proposed, as an alternative, discounting carbon flows and then annualizing the present value expression, an approach that has become standard practice in carbon sequestration studies. The second innovation has been to expand the scope of studies to other countries besides the U.S. Although the greatest number of estimates has been produced for the U.S., the review by Richards and Stokes (2004)

[1] The model in Adams et al. (1993) evolved into the Forest and Agricultural Sector Optimization Model (FASOM), which integrates the forest and agricultural sectors through competition for land (Adams et al., 1996).

includes global cost studies and estimates for a number of non-U.S. countries. Finally, recent forest carbon sequestration studies by Latta et al. (2011), Mason and Plantinga (2013) and Busch et al. (2012) have given more careful consideration to policy design and implementation and the effects this has on cost estimates.

This paper provides new cost estimates for carbon sequestration through afforestation in the U.S. The methodological advances since MR have helped to provide a more realistic assessment of the costs of a forest carbon sequestration policy. In particular, accounting for endogenous price effects and observed landowner behavior have revised upward the cost estimates reported in early studies. Unfortunately, the new methods have come at the cost of transparency. In MR, each point on the marginal cost curve can be traced to the underlying estimates of opportunity costs, converted land, treatment costs, and carbon uptake. In the newer studies, these variables are more complicated. For example, in a model with endogenous prices, the cost of carbon sequestration at each location is time-varying and dependent on many variables measured at other locations. As a result, it can be difficult to identify and understand the factors that lie behind a cost estimate for a particular location.

Our objective is to extend existing carbon sequestration cost estimates in several important ways, while ensuring that our methods and results remain transparent. As part of a longer version of this paper (Neilsen et al., 2013), we make available all of our data so that other researchers can reproduce our results as well as use the data for other purposes. Our costs estimates have five distinguishing features. First, we estimate costs for each county in the contiguous U.S., rather than for the aggregate regions used in MR and other studies. Second, our estimates include afforestation of rangeland, in addition to cropland and pasture.[2] Third, our opportunity cost estimates account for capitalized returns to future development in addition to returns to agricultural production. These estimates account for option value associated with holding land in agriculture while new information about the profitability of development becomes available. Fourth, we develop a new set of forest establishment costs for each county using data from the Conservation Reserve Program (CRP). Fifth, we incorporate data on Holdridge life zones to limit afforestation in locations where temperature and moisture availability prohibit forest growth. To keep the analysis simple, we do not account for endogenous prices and we assume that our cost estimates reflect all of the relevant factors affecting land-use choices. However, we compare our results to those in other studies to assess how our cost estimates would change were we to include these refinements.

In Section 2, we discuss the development of the data used in the study. Section 3 describes the procedure for computing marginal costs, and Section 4 presents results. A final section provides discussion and conclusions.

2. Data development

We need four key pieces of information to construct county-level estimates of the cost of sequestering carbon through afforestation. First, we measure average land prices in each county by use as an estimate of the opportunity cost of converting agricultural land to forest. Second, we estimate the cost of establishing forests in each county. Third, we use information on Holdridge Life Zones to identify the area of private land in each county that can feasibly be converted to forest. Lastly, we estimate the average carbon uptake by new forests in each county.

2.1. Land prices

We measure the opportunity costs of the land by constructing estimates of land prices for three uses (cropland, pasture, and rangeland) and each county. We start with the 1997 county average estimates of farmland value reported in the Census of Agriculture. These are self-reported estimates of the per-acre market value of farmland, where farmland includes all land that is part of a farm. Thus, it can

[2] Two other ways to sequester carbon in forests, changes in forest management and avoided deforestation, are not considered here. Earlier studies indicate that in the U.S. afforestation offers the greatest and lowest-cost opportunities for increase carbon sequestration in forests.

include cropland, pasture, rangeland, and forest.[3] We denote this value FARMVAL_i where i indexes counties. In an earlier study using these data, Plantinga et al. (2002) used econometric methods to decompose FARMVAL_i into components measuring near-term discounted returns to agriculture and future discounted returns to urban development. We denote the average capitalized development value per acre as DEVVAL_i. As explained in Plantinga et al. this estimate accounts for the option value associated with holding land in agricultural use in order to obtain forthcoming information about the profitability of development.[4] We assume that this development value is reflected in the returns to all private cropland, pasture, and rangeland in a county. This assumption is appropriate insofar as the average acre of a Census classified farm is representative of all private rural lands. The component of the per-acre farmland value due to agricultural production is $\text{AGVAL}_i = \text{FARMVAL}_i - \text{DEVVAL}_i$.

Suppose that the average farmland parcel in a county will be used for agricultural production for the next T_i years, after which time it will be converted to developed use. Assume that annual per-acre farm net revenues (FARMNR_i) are constant through time and that the discount rate in all counties is r. Then, we can write the agricultural value for county i as:

$$\text{AGVAL}_i = \text{FARMNR}_i \times \frac{(1+r)^{\text{T}_i} - 1}{r(1+r)^{\text{T}_i}} \tag{1}$$

We compute FARMNR_i using the 1997 Census of Agriculture statistics. For each county, farm net revenues equals the market value of agricultural products sold minus total farm production expenses plus total government payments.[5] We divide this figure by the area of land in farms to obtain an annual per-acre farm net revenue estimate. With estimates of AGVAL_i and FARMNR_i, we can estimate the discounting term in (1) for each county as:

$$\frac{(1+r)^{\text{T}_i} - 1}{r(1+r)^{\text{T}_i}} = \frac{\text{AGVAL}_i}{\text{FARMNR}_i} \tag{2}$$

This term implicitly accounts for the unobserved average time to development in each county, which we assume is the same for each use.

The final step is to estimate the land prices by use. Lubowski (2002) constructed county-level estimates of annual per-acre net revenues for each major land use. We use the 1997 estimates for crops, pasture, and range, which we denote CROPNR_i, PASTURENR_i, and RANGENR_i. Assuming these net revenues are constant through time, we can write land prices by use as:

$$\begin{aligned}
\text{CROPPRICE}_i &= \text{CROPNR}_i \times \frac{\text{AGVAL}_i}{\text{FARMNR}_i} + \text{DEVVAL}_i \\
\text{PASTUREPRICE}_i &= \text{PASTURENR}_i \times \frac{\text{AGVAL}_i}{\text{FARMNR}_i} + \text{DEVVAL}_i \\
\text{RANGEPRICE}_i &= \text{RANGENR}_i \times \frac{\text{AGVAL}_i}{\text{FARMNR}_i} + \text{DEVVAL}_i
\end{aligned} \tag{3}$$

If, on average, farm net revenues were unusually low, or even negative, in 1997, we can obtain either implausible large or negative price estimates. To address the first problem, we use FARMVAL_i as an upper bound on each of the price estimates. For the second problem, we replace the $\text{AGVAL}_i/\text{FARMNR}_i$ term with 20. If $r = 5\%$, then the left-hand side of (2) approaches 20 as T_i goes to infinity. This new price estimate is also bounded from above by FARMVAL_i.

[3] These estimates also include the value of farmland buildings (homesteads, barns, etc.). Unfortunately, there is no way to isolate only the land component of farmland value.

[4] Option values could also be associated with other land-use conversions (e.g., pasture to cropland). We account only for the option value arising from agriculture-to-development conversions, though we expect this to be the most important one. See, also, Schatzki (2003) for an examination of option values in the context of cropland to forest conversions.

[5] Our measure of government payments does not include subsidies provided to farmers enrolled in the CRP. To the extent that CRP payments reflect the foregone returns to cropping, and assuming that T_i occurs after the expiration of a CRP contract, the value in (1) also measures the price of land enrolled in the CRP.

For scenarios in which newly-established forests are periodically harvested, we subtract from each land price an estimate of the present discounted value of net revenues from timber harvesting. Using Lubowski's (2002) estimates of per-acre annualized forest net returns for each county, FORESTNR_i, we compute the present value of harvesting revenues as $\text{FORESTNR}_i/0.05$.

2.2. Establishment costs

We measure the costs of establishing forest on crop, pasture, or range land using estimates from the CRP during the period 1986–1993. During these first years of the CRP, the main objective of the program was to enroll large areas of erodible cropland, whereas in later years the program targeted parcels providing high levels of environmental benefits. The data from earlier years is, thus, more suited to measuring average establishment costs for all lands within a county. The CRP is a voluntary cropland retirement program under which land is converted to grass, trees, or other qualifying land covers. In exchange, the landowner receives an annual payment as well as up to 50% of the cost of establishing the alternative cover. We use the county average cost shares for trees, multiplied by two, to estimate forest establishment costs for each county. This implicitly assumes that costs of establishing forests on cropland are the same as for pasture and range. Because rangelands are typically found in arid regions, we may under-estimate the costs of forest establishment on these lands. However, as discussed below, this problem is mitigated to some degree because we exclude lands that cannot support forests due to climatic conditions. Finally, we assume that the cost estimates correspond to the costs of planting the existing mix of trees species found in each county. We adopt this assumption to allow for forests established through natural regeneration (e.g., hardwoods) as well as forests that are actively planted (e.g., softwood plantations). The CRP data provide a better measure of the costs of establishing plantations, which may lead us to overstate forest establishment costs.

Since the CRP focused on erodible cropland and was voluntary, the available observations of forest establishment costs are dependent on the geographic distribution of factors such as land quality and weather. As shown in the top panel of Fig. 1, observations of forest establishment costs are available for most counties in the eastern U.S., but unavailable for many of the western counties. To develop estimates for the missing counties, we regress observed CRP establishment costs on physiographic variables and use the estimated relationship to predict costs in the rest of the counties. Due to potential sample selection in the observed data arising from the non-random distribution of factors that affect the potential for afforestation (e.g., land quality, climatic factors), a 2-stage Heckman sample selection model was used.

The dependent variable in the cost model is the average per-acre forest establishment cost in each county (CRPCOST_i):

$$\text{CRPCOST}_i = \alpha + \beta' X_i + \delta D_i + \phi D_i G_i + \rho \hat{\lambda}_i + \varepsilon_i \tag{4}$$

where X_i is a vector of physiographic variables for county i; D_i is a dummy variable that takes the value 1 if a county is east of the 100th meridian, and 0 otherwise; G_i is a dummy for values of forest establishment costs that exceed \$500; $\hat{\lambda}_i$ is the estimated inverse Mills ratio from the first-stage estimation; and ε_i is a mean-zero random error term.

The physiographic variables include the share of total cropland in the county in Holdridge forest zones and the share of total CRP-eligible cropland in the county in Land Capability Classes (LCCs) IIe–Ve.[6] The cropland share in Holdridge zones was included to account for the potential for cropland in the county to be afforested. If a large share of cropland is located in Holdridge forest zones, it is expected that conversion costs would be relatively lower since more land is suitable for growing trees. CRP eligibility was generally limited to all cropland in LCC VI–VIII and cropland in classes IIe–Ve. We expect that forest establishment costs would be lower on higher quality land, and so a greater share of eligible cropland in classes IIe–Ve should be negatively related to costs.

[6] According to the LCC system, a lower Roman numeral indicates more productive land for agriculture and '*e*' indicates the land is subject to erosion. More details on the development of the land quality data used here are found in Neilsen et al. (2013).

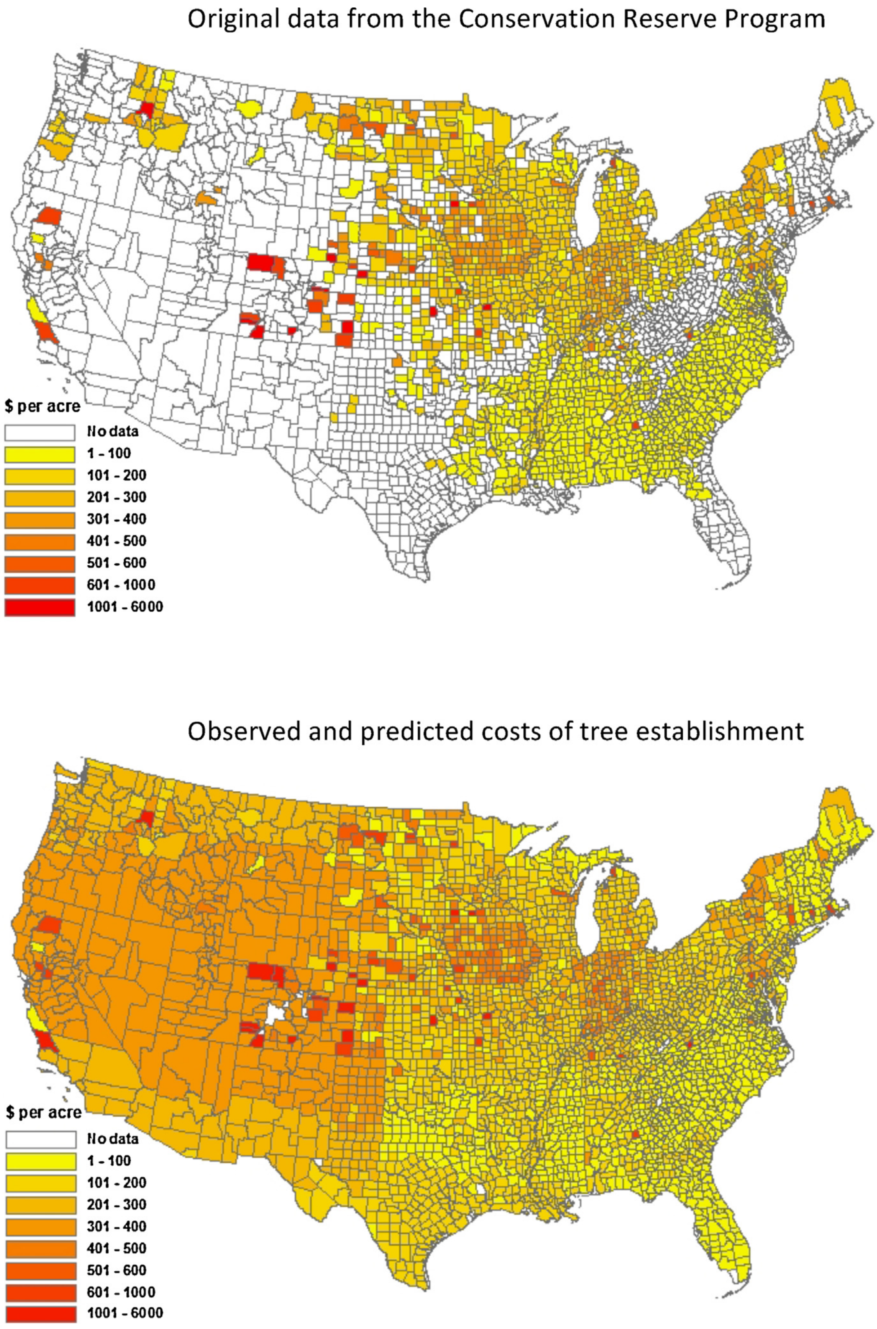

Fig. 1. Costs of tree establishment ($/acre).

To account for location-specific factors in each county, such as climate and types of trees that grow there, we include variables for the longitude and latitude of the county center as well as the squares of these variables. Further, a dummy variable for counties east of the 100th meridian is included to account for the east–west shift in precipitation that occurs at this longitude. We expect forest establishment costs to be lower in eastern counties due to greater rainfall. Finally, there are a small number of counties in the eastern U.S. with unusually high average costs. In these counties, it is likely that few CRP tree planting contracts were established. To limit the effects of outliers on the regression results, we include a dummy variable for costs in excess of $500 per acre interacted with the eastern dummy.

We only observe forest establishment costs for counties with a positive number of acres planted to trees under the CRP. The dependent variable in our selection equation is a binary variable that takes the value 1 if a county has positive CRP tree enrollment and 0 otherwise. The independent variables are physiographic variables that explain whether cropland in the county is likely to support trees. We include a dummy variable indicating if any of the cropland in the county is in the Holdridge forest zone. This variable is expected to have a positive effect on the likelihood of CRP tree enrollment.[7] Second, we include a measure of the acres of CRP-eligible cropland in a county. Not all eligible farmers participated in the CRP, but the likelihood that some did is likely to increase with the number of eligible acres. To control for climate, we include variables for longitude and latitude, as well as a measure of the annual precipitation. Greater rainfall is expected to increase the likelihood of tree planting under the CRP.

2.3. Holdridge life zones

The Holdridge life zone system is an ecosystem classification scheme for land (Holdridge, 1967). Four variables – precipitation, biotemperature, potential evapotranspiration, and elevation – are used to classify each land area as a distinct ecological unit. Lugo et al. (1999) map these variables for the contiguous U.S. and identify 38 life zones. For example, most of the contiguous U.S. east of the 100th meridian is comprised of three life zones: warm temperature moist forest, cool temperature moist forest, and cool temperature wet forest. Much more heterogeneity is found west of the 100th meridian. In total, 19 of the life zones correspond to a type of forest, which we refer to collectively as “Holdridge forest”. That a given location is classified as Holdridge forest does not necessarily mean that forests are found there; rather, the classification indicates that the climate at that location could support forests. This point is well demonstrated by the Corn Belt. This region is classified as Holdridge forest, though the majority of the land is in crops and other non-forest uses.

We use the Holdridge life zones to identify areas in the contiguous U.S. where there is potential for forest to be grown. The Holdridge classification emphasizes climatic factors, which have the potential to alter the structure, function, and geographic distribution of forests (Joyce and Birdsey, 2000). It does not account for soils, which can also limit where forests can grow. Although the Holdridge classification may not be perfectly suited for defining areas where trees can grow (Herrick et al., 2006), it is readily available and provides comprehensive coverage of the continental U.S. We overlay maps of Holdridge forest zones, land cover, and ownership to identify, for each county, the area of privately-owned crop, pasture, and range that can be converted to forest. Data is unavailable to identify land currently enrolled in the CRP. As such, we assume that CRP lands are available for conversion to forest under a hypothetical carbon sequestration policy (see footnote 5). More details on the data used in this step are found in Neilsen et al. (2013).

2.4. Carbon

Forest carbon is stored in biomass (e.g., live trees and understory vegetation), in standing dead trees, in fallen dead wood, and in floor litter and soils (Smith et al., 2006). At the time a forest stand is

[7] This variable is important for the identification of the model. The absence of any cropland in the Holdridge forest zone should be strongly correlated with the binary dependent variable for CRP tree enrollment, but would not explain differences across counties in observed establishment costs in counties with CRP tree enrollment.

established, most of the carbon will be found in the soils. However, as trees and other plants convert CO_2 to carbon through photosynthesis, in most forests the carbon stored in biomass will eventually exceed the carbon in soils. We use the tables in Smith et al. (2006) to measure carbon flows for the forest types found in each region.[8] A planning horizon of 85 years is assumed in each case. This is long enough so that carbon flows beyond this point have little effect on the present discounted value of carbon flows assuming a 5% annual rate. For each forest type, we compute the present value of carbon flows for the cases with no timber harvesting and periodic harvesting at rotation length specified in Smith et al. (2006). Following harvest, some carbon in the stand will be rapidly converted back to CO_2 through decomposition or burning for energy production.[9] Some portion of the carbon in the merchantable portion of trees will be fixed for decades in wood products (e.g., lumber, plywood) and, following disposal, in landfills.

The carbon yield for a representative forest stand in each county is constructed as a weighted average of the forest type-specific discounted flows. The weights reflect the composition of tree species currently found in each county. Species weights were obtained from U.S. Forest Service, Forest Inventory and Analysis studies conducted during the 1990s (Lubowski, 2002). In the cases where a species were not clearly represented by a forest type in Smith et al. (2006), we paired the species with a similar forest type within the region or the forest type from a neighboring region. The final result is the present value of discounted carbon flows (metric tons per acre) for a representative forest stand in each county. Separate values are produced for forests with and without periodic harvesting, though we do not distinguish among initial land uses due to lack of data.

3. Derivation of marginal costs

The first step in deriving a marginal cost curve is to compute the cost per ton of sequestering carbon for each initial land use (crop, pasture, range) and county. The per-acre opportunity cost of the land is the sum of the forest establishment cost and the land price corresponding to the initial use. If forests are periodically harvested, we use the land price net of harvesting revenues since these revenues decrease the opportunity costs of afforestation. The opportunity cost is then divided by the present discounted value of carbon corresponding to the respective no harvesting and harvesting cases. The result is an estimate of per-ton cost of sequestering carbon through afforestation for each county and initial land use. Implicit in this calculation is the assumption that land will be afforested today and remain in forest thereafter.

As described above, we have data on the area of privately-owned cropland, pasture, and range in each county that has the potential to be converted to forest. In each case, we multiply the land area by the annualized carbon flow per acre (assuming a 5% rate) for the corresponding county. The result is the annual amount of carbon that can be sequestered by county and initial land use for both the harvesting and no harvesting cases. Following Lubowski et al. (2006), a national-level marginal cost curve for carbon sequestration can be constructed by ordering the cost per ton estimates from smallest to largest and then plotting them against the cumulative annualized carbon sequestered.

4. Results

Before turning to the national-level marginal cost estimates, we discuss some of our intermediate results. Estimation results for CRP selection and cost equations are presented in Table 1. The estimates of the coefficients in the selection equation are consistent with expectations. The presence of cropland in the Holdridge forest zone, acres of eligible cropland, and annual precipitation all increase the likelihood of CRP tree planting. The coefficients on longitude and latitude are both positive, indicating that, all else equal, the likelihood of CRP tree planting increases as one moves north and east. All of the coefficient estimates are significantly different from zero at the 1% level.

[8] Forest type refers to the collection of dominant tree species in a forest.

[9] The substitution of biomass for fossil fuels does not generate a one-to-one emissions offset, but rather delays the release of carbon from fossil fuels. Accounting for the induced change in the time path of fossil fuel use and associated emissions is beyond the scope of our study.

Table 1
Estimation results for the cost and selection equations.

Cost equation		Selection equation	
Cropland share in Holdridge forest	.283^{+} (0.156)	Cropland in Holdridge forest	0.547** (0.104)
Cropland share in LCC IIe–Ve	−8.647 (25.919)	Precipitation	0.027** (0.003)
Longitude	−19.279* (8.243)	Acres of eligible cropland	0.290** (0.000)
Longitude squared	−0.095* (0.046)	Longitude	0.019** (0.003)
Latitude	149.796** (16.874)	Latitude	0.046** (0.006)
Latitude squared	−1.843** (0.219)	Constant	−1.497** (0.430)
East	−190.041** (31.530)		
East outlier	828.354** (45.584)		
Constant	−3699.582** (490.590)		
Inverse mills ratio	109.515** (34.863)		

$^{+}$ $p < 0.10$.
* $p < 0.05$.
** $p < 0.01$.

The results for the cost equation are mixed. The coefficient on the cropland share in Holdridge forest is positive, contrary to expectations, but significantly different from zero at only the 10% level. The share of CRP-eligible cropland in lower LCCs does not have a significant effect on forest establishment costs. The coefficient on the east dummy variable is significantly different from zero at the 1% level and indicates that costs are almost $200/acre lower in the east. All else equal, costs fall as one moves south and rise as one moves west, as reflected in the top panel of Fig. 1. The squared longitude and latitude variables are also significantly different from zero at the 1% level. Finally, the coefficient on the inverse Mills ratio is significantly different from zero, indicating a non-random distribution of observed CRP costs.

Using the estimated sample selection and cost equations, we predict forest establishment costs for the counties with missing observations, and plot the observed costs for those counties with CRP tree planting (bottom panel of Fig. 1). The results show considerably higher costs in western counties, as one would expect given that the climate is typically drier and, thus, less hospitable to trees.[10] Note that these estimates account only for stand establishment costs, and not any on-going costs of managing forests.

We summarize the county-level cost results by computing the average cost per ton of carbon in each county, using the land-use shares as weights. Fig. 2 show the cases without and with harvesting. Allowing harvesting affects both the carbon yields and opportunity costs of afforestation. As noted above, the effect on carbon uptake is ambiguous, varying with regional climatic conditions, forest species, and yields. In contrast, harvesting raises the value of land in forest, thereby lowering the opportunity cost of afforestation. The impact of harvesting on the national range of average carbon sequestration costs is minor: average costs are between $1.50 and $581 per metric ton with no harvesting and between $0.03 and $580 per metric ton with harvesting. However, the overall pattern revealed in Fig. 2 indicates that harvesting reduces per-ton costs in most counties.

The national-level marginal cost curve indicates the total carbon uptake per year that would result for given per-ton carbon payments (Fig. 3). With periodic harvesting, a carbon price of $50 per ton generates 200 million tons of carbon annually, corresponding to approximately 13% of the annual emissions of the US.[11] By comparison, with no harvesting a $50 per ton price yields only 127 million tons of carbon. At a $100 per ton price the sequestration level is 305 million tons of carbon with periodic harvesting, while further increases result in smaller incremental changes in the sequestration level (e.g., 351 tons at $150 per ton). After a price of $200 per ton, little remaining land is available for afforestation, and as a consequence further price increases have little effect on total carbon uptake.

[10] A referee points out that forest establishment costs in the western U.S. may also depend on baseline ecological conditions. For example, tree growth can be inhibited in grassland ecosystems.

[11] The estimated US net greenhouse gas emissions in 2009 were 1532 million tons of carbon equivalent (U.S. Environmental Protection Agency, 2011).

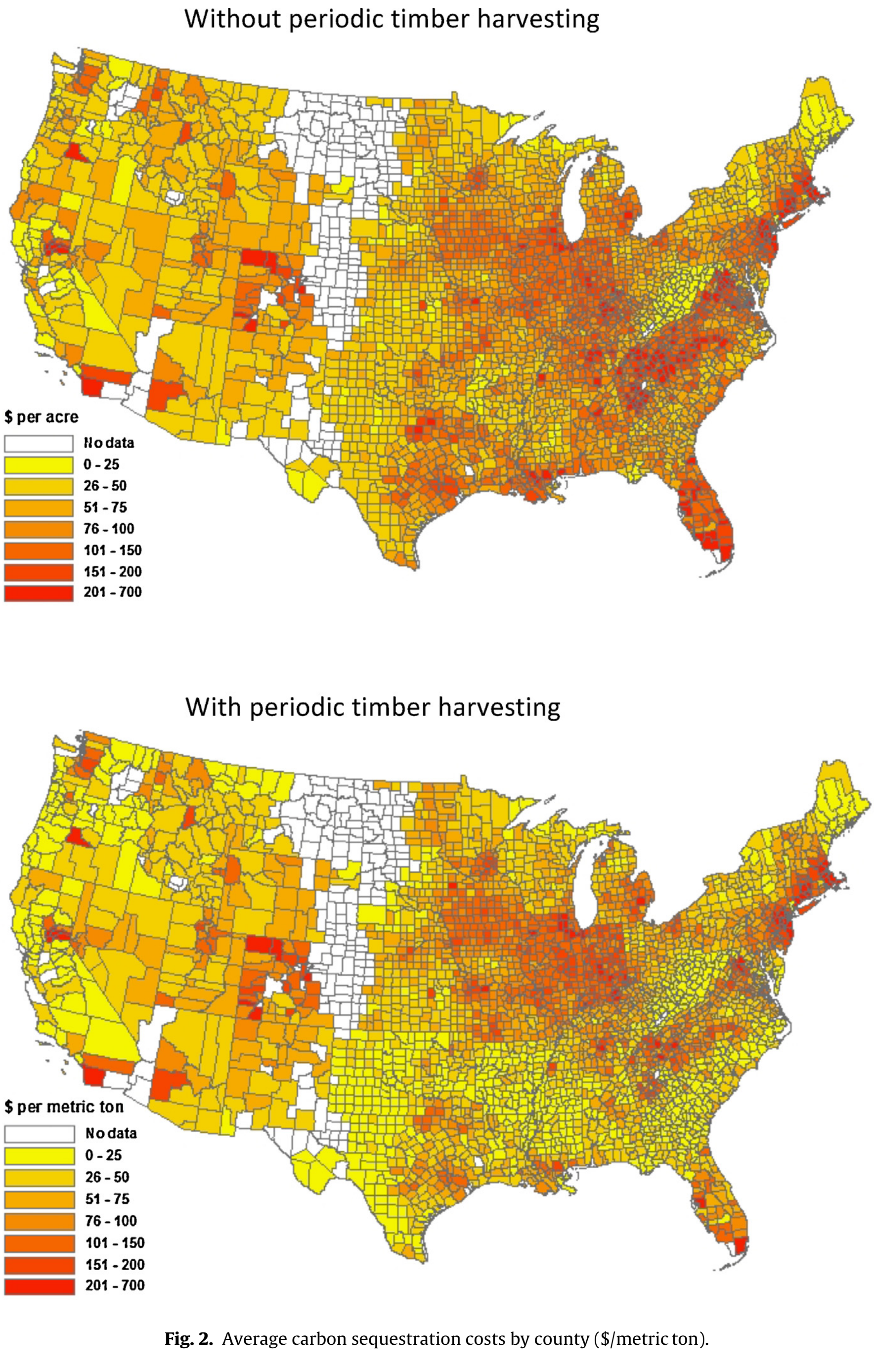

Fig. 2. Average carbon sequestration costs by county ($/metric ton).

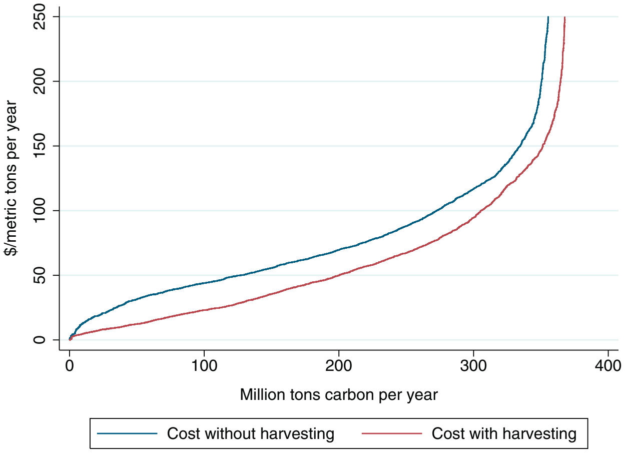

Fig. 3. Marginal costs of carbon sequestration through afforestation in the U.S. ($/metric ton/year).

Table 2
Summary of carbon sequestration cost results.

	Carbon prices ($/metric ton)		
	$50	$100	$150
Area afforested	Million acres		
Crops	79.2	158.0	206.6
Pasture	48.2	96.0	113.2
Range	118.4	138.4	141.7
Total	245.8	392.4	461.5
Carbon sequestration	Million tons as per		
Crops	63.8	119.7	150.1
Pasture	42.6	79.9	93.1
Range	93.7	105.9	108.1
Total	200.0	305.5	351.4
Opportunity costs	Billion dollars per year		
Crops	1.7	5.7	9.5
Pasture	1.2	3.8	5.4
Range	1.9	2.7	3.0
Total	4.8	12.3	17.9

For the rest of this section, we focus on results with periodic harvesting because this involves lower costs. Table 2 provides a breakdown of the results by land use for three carbon prices. The $50 carbon price results in the afforestation of 246 million acres with about one-half of this on rangeland. Increasing the carbon price to $100, the low cost range land is largely exhausted, and cropland contributes about 40% of the total 392 million afforested acres. The change from $50 per ton to $100 per ton doubles the area of afforested pasture. At a carbon price of $150 per ton, the largest contribution comes from cropland. Table 2 also reports the total carbon sequestered and the total opportunity cost of the policy for each land use and carbon price. The opportunity cost is measured as the total foregone rents plus establishment costs (or, equivalently, the area under the marginal cost curve). At $50 per ton, a large share of the total costs are associated with range land conversion. At higher carbon prices, the opportunity costs arise mostly from the afforestation of cropland.

Fig. 4 shows the geographic distribution of afforested acreage for carbon prices of $50 and $150 per metric ton. The most notable feature of these results is that increasing the carbon price from $50 to $150 has a large effect on the afforested acres in the section of the U.S. just east of the 100th meridian

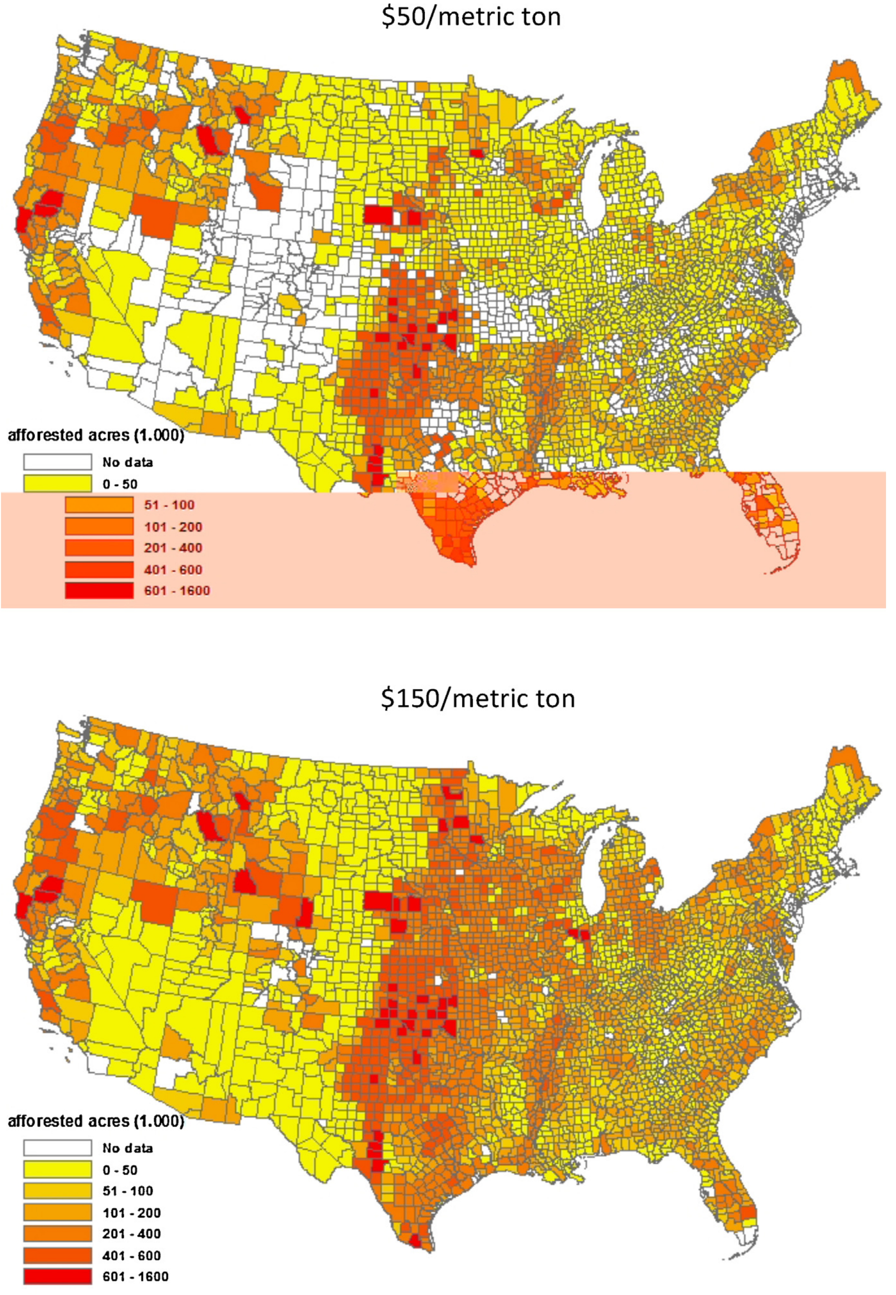

Fig. 4. Distribution of afforested acres at carbon prices of $50 and $150 per metric ton.

and, in particular, the Corn Belt region. Carbon sequestration costs are relatively high in this area, but there is a lot of available agricultural land that can be afforested when the carbon price is sufficiently high. In contrast, there is less of an effect on afforested acres in the western and eastern portions of the country, indicating that most of the opportunities for afforestation are exploited at relatively low carbon prices.

Table 3
Alternative estimates of total carbon sequestered (million tons per year) at different carbon prices.

	Carbon prices (per ton)					
	$25	$50	$75	$100	$125	$150
This study	125.0	200.0	280.0	305.5	340.0	351.4
This study (without Holdridge constraints)	200.0	345.0	440.0	480.0	510.0	530.0
Moulton and Richards	225.0	800.0				
Lubowski et al.	113.0	200.0	323.0	575.0	800.0	1050.0

Note: MR costs adjusted to 1997 values using the Consumer Price Index.

Incorporating the Holdridge forest zone constraints has large effects on the cost estimates. Without the constraints, the amount of available land increases from 490 million acres to 805 acres million acres, causing the annual sequestration potential to increase 370–560 Mt carbon annually. The increase in land availability lowers the marginal cost of carbon sequestration. At a $50 per ton carbon price, for instance, the sequestration supply increases from 200 to 336 Mt. annually.

4.1. Comparison to other studies

We compare our results to those in MR and Lubowski et al. (2006). Table 3 lists, for each study, the total carbon sequestered annually at different carbon prices. For a given carbon price, a larger value for total sequestered carbon indicates that the marginal cost curve lies farther to the right. At a price of $25 per ton, the estimates from this study are similar to those in Lubowski et al. (125 million tons compared to 113 million tons). Those in MR are similar to our estimates without the Holdridge constraints (225 million tons compared to 200 million tons). At a price of $50 per ton, however, the MR estimate diverges considerably from those in the other studies. While there are many factors involved, two important ones are that MR assumes a large stock of land available for afforestation and relatively low opportunity costs. In particular, the MR estimates do not account for foregone rents from future development. The results from this study closely match those in Lubowski et al. up to a carbon price of $75 per ton, but after that point our marginal cost curve turns up whereas the one in Lubowski et al. remains relatively flat. There are a number of potential reasons for this divergence. First, unlike Lubowski et al. we include Holdridge constraints (our estimates without Holdridge constraints continue to track those in Lubowski et al. up to a price of about $100 per ton). Second, our estimates of tree planting costs are likely to be higher than those in Lubowski et al. which are derived implicitly from observed land-use changes and, therefore, may partially reflect costs of establishing forests through natural regeneration. Third, our study only accounts for afforestation, while Lubowski et al. also include avoided deforestation. Finally, it is important to note that the Lubowski et al. estimates are based on an econometric model of land-use change and carbon prices above $100 per ton are likely to be outside the range of the historical data used to estimate the model.

5. Discussion and conclusions

At a carbon price of $50/ton, we estimate that approximately 200 million tons of carbon would be sequestered annually through afforestation. According to estimates in Lubowski et al. (2006), this corresponds to roughly one-half of the carbon abatement that would be undertaken in the U.S. energy sector at this price. If the carbon price were to rise to $100/ton, an additional 100 million tons of carbon would be sequestered each year, just over one-half of energy-based carbon abatement. Compared to earlier carbon sequestration costs studies, our estimates indicate a smaller, but still important, role for forest-based carbon sequestration in offsetting U.S. greenhouse gas emissions.

As noted in Section 1, for transparency we do not account for a number of factors included in recent cost studies, such as endogenous price feedbacks. We did, however, account for option value associated with conversion of land to developed uses. In this way, our approach includes elements of both bottom-up engineering studies and econometric analyses. For the factors that we did not account for, we can make comparisons between studies to infer the magnitude of these effects. Stavins and

Richards (2005) normalize the results from a number of U.S. carbon sequestration cost studies. Adams et al. (1993) and Richards et al. (1993) are two studies that account for endogenous price feedbacks and can be compared to MR, which ignores these effects. Up to about 200 million tons per year, the marginal costs of all three studies are similar. At 500 million tons, however, marginal costs in Adams et al. (1993) and Richards et al. (1993) are 40–60% higher than in MR. Lubowski et al. (2006) account for endogeous prices and employ an econometric approach that can account for unobservable factors. At 500 million tons, their estimate of marginal cost is approximately 100% higher than the estimate in MR (Stavins and Richards, 2005).

These comparisons suggest that, to be on the conservative side, our marginal cost estimates should be doubled at higher carbon sequestration levels to adjust for endogenous price feedbacks and unobservable landowner behavior. Even more important than these factors, however, may be climatic constraints on forests. Our marginal cost curve with Holdridge constraints is vertical well before 500 million tons, whereas when we ignore these constraints we obtain marginal cost estimates similar to those in Lubowski et al. (2006).

Our cost estimates incorporate conventional estimates of carbon storage in forests (Smith et al., 2006). These estimates are based on Forest Inventory and Analysis (FIA) data that are developed from surveys of current forests. In a region such as the Corn Belt, where most of the productive land is in agriculture, yields from current forests may understate the potential yield from new forests established on agricultural land. For the Corn Belt region, some preliminary studies have found that timber yields could be as much as double those found in FIA studies. Higher timber yields would have the effect of reducing cost estimates for carbon sequestration.

A study of a long-term carbon sequestration program must grapple with the possibility of climate change, even if avoiding climate change is the intention of the policy. Many of the components of our cost estimates would likely change in the future as the result of changes in climate, including commodity and carbon yields, the location of Holdridge forest zones, costs of forest establishment, and prices for timber, crops, and other commodities. A next step in this research would be to modify these cost components to determine how climate change would affect the level and geographic distribution of future carbon sequestration costs, using, for example, the IPCC climate change scenarios. In a related study, Haim et al. (2011) explored how changes in forest and agricultural yields and agricultural commodity prices would affect future patterns of land use in the U.S.

Our estimates of the marginal costs of carbon sequestration in forest are based on the opportunity costs of the land. In practice, there may be additional opportunity costs depending on the design of the carbon sequestration policy. If the government uses subsidies, for example, to encourage afforestation, then landowners may capture additional rents beyond the opportunity costs reflected in the cost estimates presented here. These payments to landowners can have opportunity costs if, for example, there are deadweight losses associated with the taxes levied to raise public funds. Mason and Plantinga (2013) find significant efficiency gains from the use of a contracting scheme that limits government payments for carbon sequestration.

While many factors can increase cost estimates for carbon sequestration, consideration of co-benefits can effectively reduce costs. Establishing new forests on agricultural lands can provide wildlife habitat, improve water quality by preventing erosion and reducing use of agricultural chemicals, among other benefits. Co-benefits of carbon sequestration have been estimated in earlier studies (e.g., Matthews et al., 2002; Plantinga and Wu, 2003) for specific regions in the U.S. Future work could focus on using these cost estimates in a national-scale evaluation of co-benefits. Withey et al. (2012) have begun this work by examining the returns to land conservation in terms of species preservation.

This discussion raises the broader issue of policy design, which our study does not directly address. The problems of additionality, permanence, and leakage have been widely discussed in the context of policies for carbon sequestration in forests (e.g., Richards and Andersson, 2001). These problems are now understood to be a symptom of the project-by-project approach to accounting for carbon credits. Plantinga and Richards (2010) discuss how national-level carbon accounting can be used to remedy these problems in the context of an international climate change treaty. Mason and Plantinga (2013) and Horowitz and Just (2013) examine policies that can address additionality in a domestic policy setting.

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