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# New Cost Estimates for Carbon Sequestration Through Afforestation in the United States

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Cover photograph by Frank Vanni.

## **Abstract**

**Nielsen, Anne Sofie Elburg; Plantinga, Andrew J.; Alig, Ralph J. 2014.** New cost estimates for carbon sequestration through afforestation in the United States. Gen. Tech. Rep. PNW-GTR-888. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

This report provides new cost estimates for carbon sequestration through afforestation in the United States. We extend existing studies of carbon sequestration costs in several important ways, while ensuring the transparency of our approach. We clearly identify all components of our cost estimates so that other researchers can reconstruct our results as well as use our data for other purposes. Our cost estimates have five distinguishing features: (1) we estimate costs for each county in the contiguous United States; (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. Accounting for climatic constraints on forest expansion has important effects on cost estimates.

Keywords: Carbon sequestration, afforestation, cost estimates.

To access county-level data on land prices, tree establishment costs, carbon uptake rates, and eligible land for conversion to forest, follow this link:  
[http://www.fs.fed.us/pnw/pubs/pnw\\_gtr888/county-level-data\\_nielsen2013.xlsx](http://www.fs.fed.us/pnw/pubs/pnw_gtr888/county-level-data_nielsen2013.xlsx)

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## **Introduction**

The first studies on the cost of sequestering carbon in forests appeared in the late 1980s (Dudek and LeBlanc 1990, Marland 1988, Sedjo 1989) and provided point estimates of the average cost of forest carbon sequestration. Moulton and Richards (1990) provided the first marginal cost estimates for the United States. Marginal costs are useful because they can be combined with cost estimates for other carbon mitigation and abatement approaches to identify the efficient portfolio of strategies. To estimate marginal costs, Moulton and Richards 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. Moulton and Richards constructed a marginal cost curve by ordering these costs from lowest to highest and then plotting them against cumulative carbon sequestration.

Following Moulton and Richards, 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.<sup>1</sup> 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 Moulton and Richards, or sectoral optimization models, as in the Forest and Agricultural Sector Optimization Model (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 or avoided deforestation. The econometric approach has the

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<sup>1</sup> 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).

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 nonmarket 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 (Lubowski et al. 2006, Plantinga et al. 1999, Stavins 1999). 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 Moulton and Richards deserve mention. The first relates to carbon accounting. Moulton and Richards 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 United States. Although the greatest number of estimates has been produced for the United States, the review by Richards and Stokes (2004) 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 (2011), and Busch et al. (2012) have given more careful consideration to policy design and implementation and the effects this has on cost estimates.

This report provides new cost estimates for carbon sequestration through afforestation in the United States. The methodological advances since Moulton and Richards 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 unobserved landowner behavior have revised upward the cost estimates reported in early studies. Unfortunately, the new methods have come at the cost of transparency. In Moulton and Richards, 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. Consequently, it can be difficult to identify and understand the factors that lie behind a cost estimate for a particular location.

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Richards study. Our results clearly identify all components of our cost estimates, and we make available all of the data so that other researchers can reconstruct 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 United States, rather than for the aggregate regions used in Moulton and Richards and other studies. Second, our estimates include afforestation of rangeland, in addition to cropland and pasture.<sup>2</sup> 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 use results from other studies to suggest how our cost estimates would change were we to include these refinements.

In the “Data Development” section, we discuss the development of the data used in the study, and in the “Cost Analysis and Results” section we present results.

## **Data Development**

We need four key pieces of information to construct 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. These data are combined, in this section, to produce cost estimates.

### **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

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<sup>2</sup> Moulton and Richards also evaluated forest management approaches, which we do not consider.

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 include cropland, pasture, rangeland, and forest.<sup>3</sup> We denote this value FARMVAL. In an earlier study using these data, Plantinga et al. (2002) used econometric methods to decompose FARMVAL 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. 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.<sup>4</sup> 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 owing to agricultural production is  $AGVAL = FARMVAL - DEVVAL$ .

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

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

We compute FARMNR 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. 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 and FARMNR, we can estimate the discounting term in (1) for each county as:

$$\frac{(1+r)^T - 1}{r(1+r)^T} = AGVAL / FARMNR \quad (2)$$

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

<sup>3</sup>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.

<sup>4</sup>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.

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, PASTURENR, and RANGENR. Assuming these net revenues are constant through time, we can write land prices by use as:

$$\begin{aligned} \text{CROPPRICE} &= \text{CROPNR} \times (\text{AGVAL} / \text{FARMNR}) + \text{DEVVAL} \\ \text{PASTUREPRICE} &= \text{PASTURENR} \times (\text{AGVAL} / \text{FARMNR}) + \text{DEVVAL} \\ \text{RANGEPRICE} &= \text{RANGENR} \times (\text{AGVAL} / \text{FARMNR}) + \text{DEVVAL} \end{aligned} \quad (3)$$

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 as an upper bound on each of the price estimates. For the second problem, we replace the AGVAL/FARMNR term with 20. If  $r = 5$  percent, then the left-hand side of (2) approaches 20 as  $T$  goes to infinity. This new price estimate is also bounded from above by FARMVAL. Maps showing per-acre prices for each use and county are found in the appendix (figs. 11 through 13).

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, we compute the present value of harvesting revenues as FORESTNR/0.05. Maps displaying the three land prices net of harvesting revenues are presented in the appendix (figs. 14 through 16).

**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 percent 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 underestimate the costs of

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forest establishment on these lands. However, as discussed below, this problem is mitigated to some degree because we exclude lands that cannot support forests owing to climatic conditions. Finally, we assume that the cost estimates correspond to the costs of planting the existing mix of tree 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, and so we are likely to overstate forest establishment costs.

Because 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 figure 1, observations of forest establishment costs are available for most counties in the Eastern United States, 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

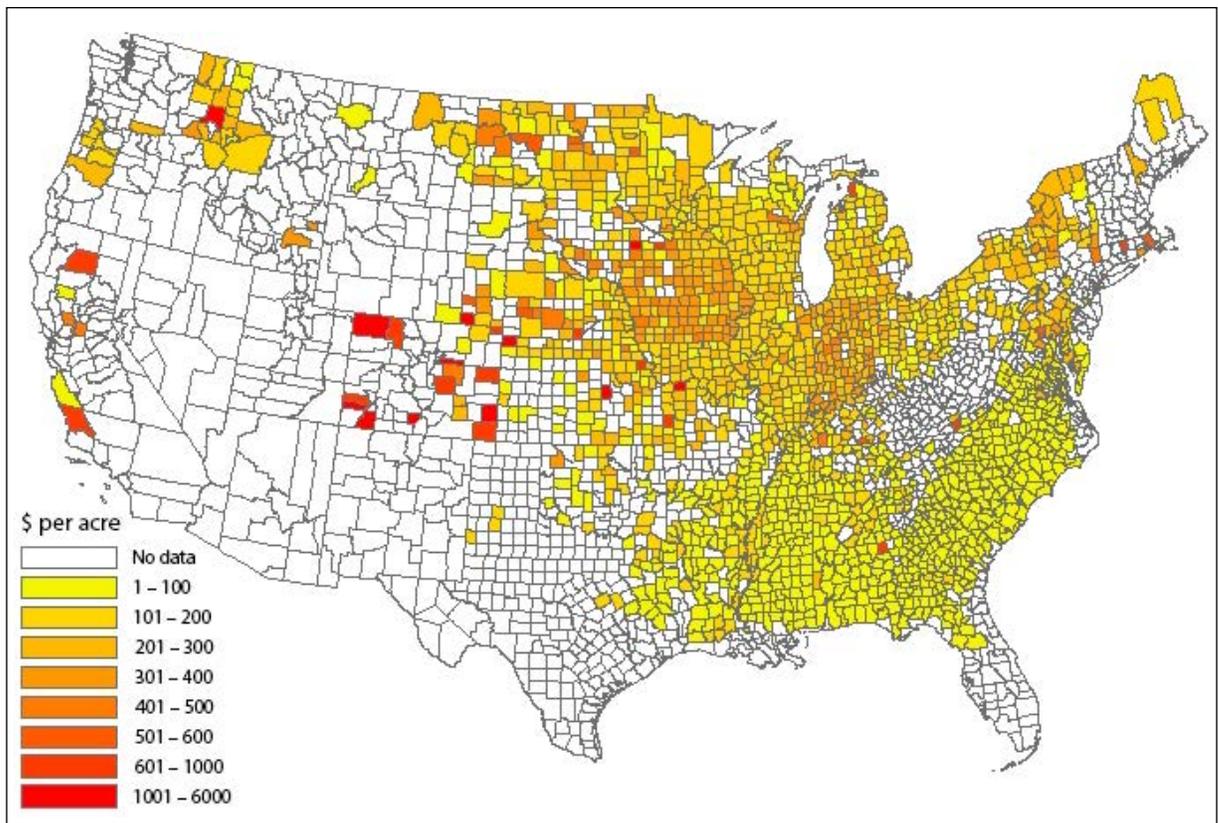


Figure 1—Original data from the Conservation Reserve Program on costs of tree establishment (\$/acre).

of the counties. Because of potential sample selection in the observed data arising from the nonrandom distribution of factors that affect the potential for afforestation (e.g., land quality, climatic factors), a two-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  $i$  ( $CRPCOST_i$ ):

$$CRPCOST_i = \alpha + \beta'X_i + \delta D_i + \phi D_i G_i + \rho \hat{\lambda}_i + \varepsilon_i \quad (4)$$

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 100<sup>th</sup> meridian, and 0 otherwise;  $G_i$  is a dummy for values of forest establishment costs that exceed \$500;  $\rho \hat{\lambda}_i$  is the estimated inverse Mills ratio from the first-stage estimation; and  $\varepsilon_i$  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. 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. The CRP eligibility was generally limited to cropland in LCC VI-VIII and erodable cropland in classes II-V, where a higher LCC class indicates lower soil productivity for agriculture. 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.<sup>5</sup>

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 100<sup>th</sup> 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 owing to greater rainfall. Finally, a small number of counties in the eastern United States have unusually high average costs. In these counties, it is likely that few CRP tree planting contracts were established. To

<sup>5</sup> We have estimates of the area of cropland by LCC in each county. These were obtained by overlaying an LCC map on the 2001 National Land Cover Database map. We obtained separate estimates of the breakdown of each LCC into subclasses (erodable, wet, etc.) for all land in the county. For LCC II-V, we multiplied the share of land in the erodable subclass by the cropland acres in the corresponding LCC to obtain an estimate of erodable cropland by LCC.

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.<sup>6</sup> 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 probability 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.

Estimation results 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-percent level.

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-percent 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-percent 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 figure 1. The squared longitude and latitude variables are also significantly different from zero at the 1-percent level. Finally, the coefficient on the inverse Mills ratio is significantly different from zero, indicating a nonrandom distribution of observed CRP costs.

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<sup>6</sup> 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.

**Table 1—Estimation results for the cost and selection equations**

Cost equation		Selection equation	
Cropland share in Holdridge forest	0.283+ (0.156)	Cropland in Holdridge forest	0.547** (0.104)
Cropland share in LCCa 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)		

Note: + p < 0.10, \* p < 0.05, \*\* p < 0.01.  
<sup>a</sup>LCC = land capability class.

Using the estimated cost equation, we predict forest establishment costs for the counties with missing observations (fig. 2). In figure 2, we also plot the observed average costs for those counties with CRP tree planting. 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. Note that these estimates account only for stand establishment costs, and not any ongoing costs of managing forests.

**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 United States and identify 38 life zones. For example, most of the contiguous United States east of the 100<sup>th</sup> 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 100<sup>th</sup> 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

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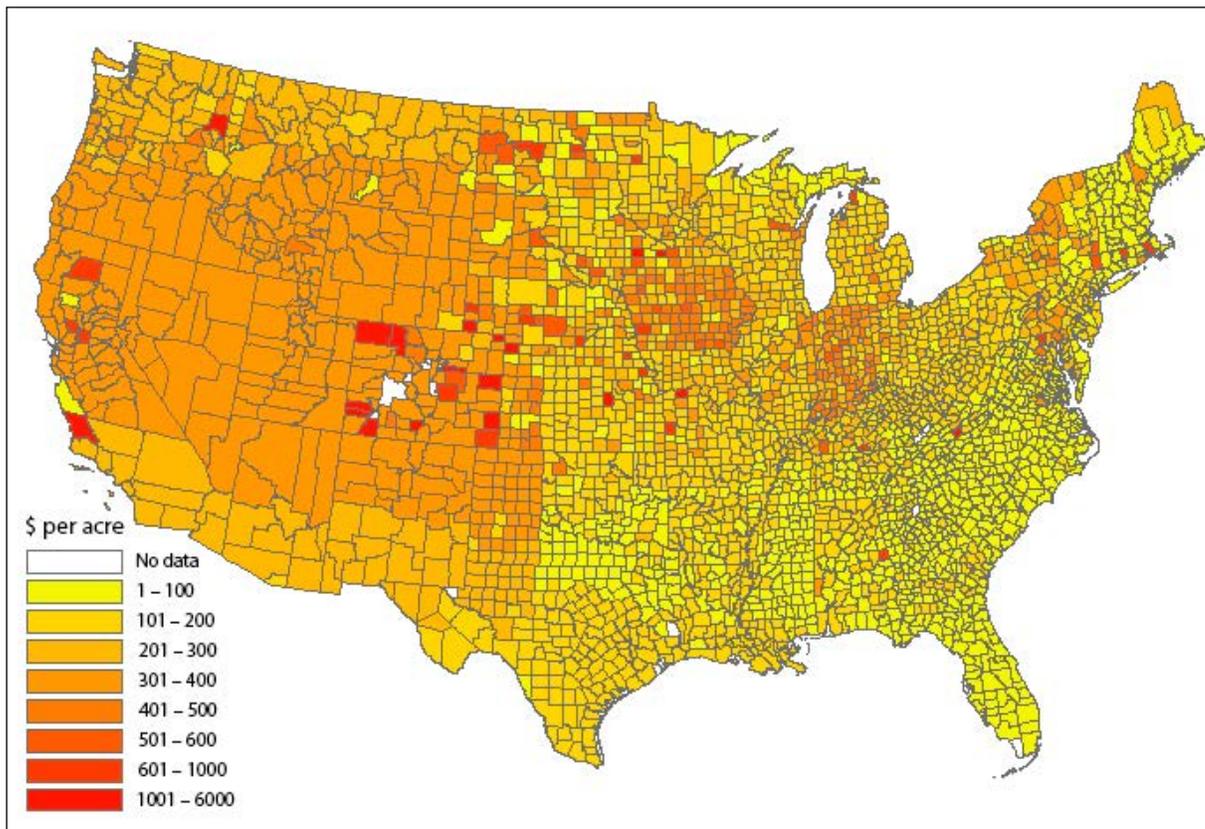


Figure 2—Observed and predicted costs of tree establishment (\$/acre).

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 nonforest uses.

We use the Holdridge life zones to identify areas in the contiguous United States where there is potential for forest to be grown. Specifically, 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 lands that can be converted to forest. Holdridge forest zones are identified using the map described in Lugo et al. (1999). The 2001 National Land Cover Database (NLCD) is used to identify crop, pasture, and range lands. Crop and pasture are defined by NLCD categories 82 (Cultivated Crops) and 81 (Pasture/Hay), respectively. West of the 100<sup>th</sup> meridian, we define range by categories 71 (Grassland/Herbaceous) and 52 (Shrub/Scrub) and, east of 100<sup>th</sup> meridian, only by category 71. The Shrub/Scrub category includes true shrubs as well as trees in an early successional stage. In the east, there are large

areas of land in the Shrub/Scrub category owing to the presence of young trees.<sup>7</sup> We treat these lands as already forested. Lands that are enrolled in a nonforest use under the CRP are likely to be found in categories 71 or 81. Finally, we use an ownership map from Conservation Biology Institute (2010) to identify private lands.

In the appendix, we present maps showing the share of each county in Holdridge forest zones by use (figs. 17 through 19).

### **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 established, most of the carbon will be found in the soils. However, as trees and other plants convert CO<sub>2</sub> 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.<sup>8</sup> 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 percent 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<sub>2</sub> through decomposition or burning for energy production.<sup>9</sup> 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 (FIA) studies conducted during the 1990s (Lubowski 2002). When a species was not clearly represented by a forest type in Smith et al. (2006), we paired the species

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<sup>7</sup> Our definition of rangeland is close to that used in the National Resources Inventory (NRI): “Rangeland is a land cover/use category on which the climax or potential plant cover is composed principally of native grasses, grasslike plants, forbs, or shrubs suitable for grazing and browsing, and introduced forage species that are managed like rangeland.” By the NRI definition, there is very little rangeland in the Eastern United States. In contrast, if we define rangeland to include Shrub/Scrub in the Eastern United States, the NLCD implies a large amount of rangeland.

<sup>8</sup> Forest type refers to the collection of dominant tree species in a forest.

<sup>9</sup> 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.

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 harvesting, though we do not distinguish among initial land uses owing to lack of data.

Results are shown in figures 3 and 4. Without harvesting, carbon uptake is greatest in the Lake states, Northeast and Pacific coast regions. With harvesting, carbon uptake in the South increases, while it drops in parts of the North. Yields decline more quickly over time in the South compared to the North, which explains the lower carbon uptake without harvesting. With periodic harvesting, carbon uptake increases in the South as average yields increase and carbon is accumulated in wood products pools. In the North, the loss of carbon at the first harvest lowers the present value of carbon flows.

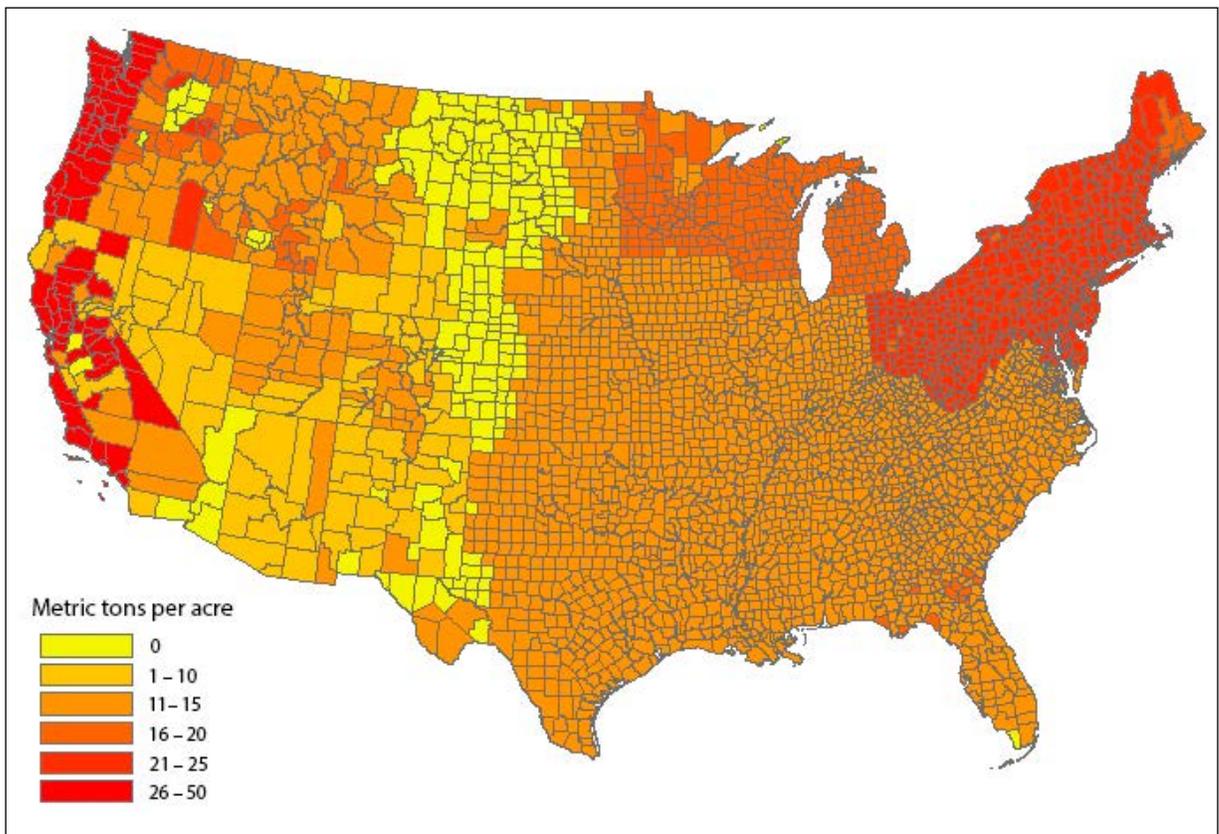


Figure 3—Carbon uptake without periodic harvesting (present value metric tons/acre).

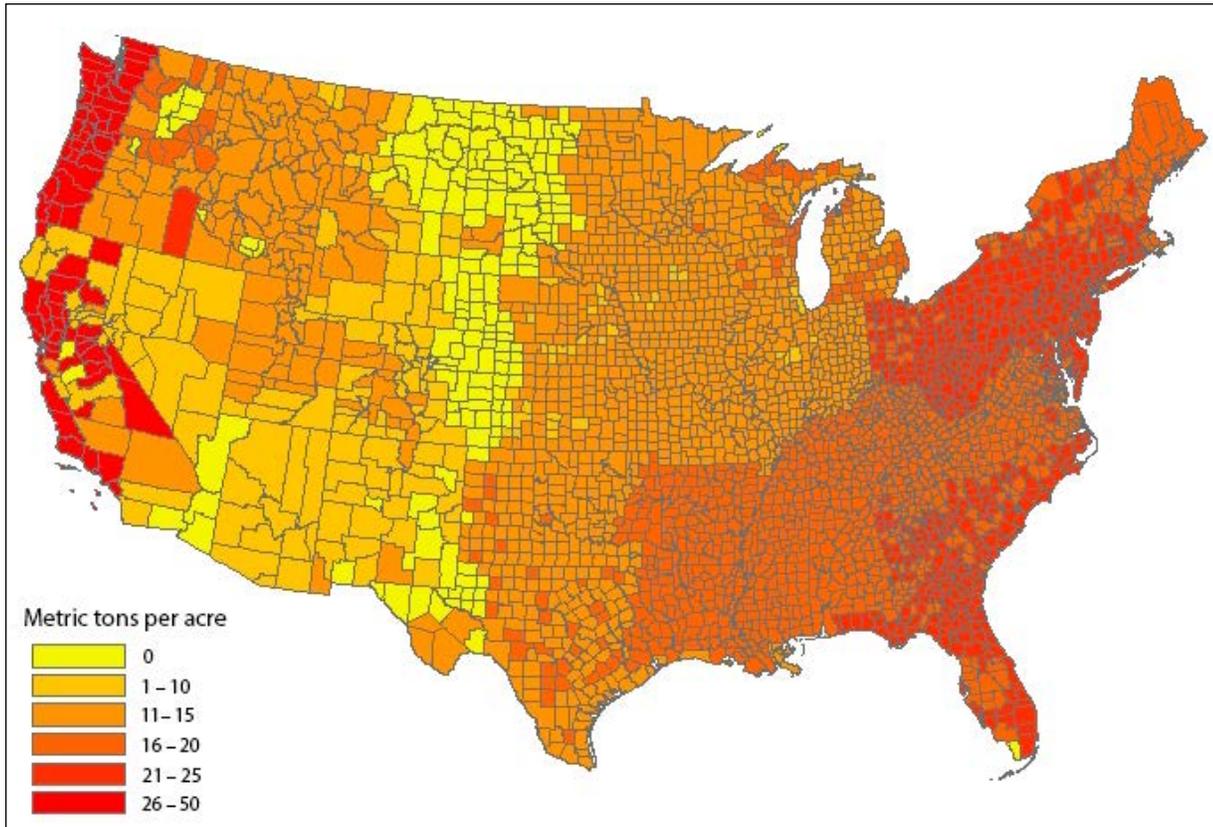


Figure 4—Carbon uptake with periodic harvesting (present value metric tons/acre).

## Cost Analysis and Results

Using the above information, we compute the cost per ton of carbon for each land use and county. The opportunity cost of the land is the sum of the 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 as 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. Implicit in this calculation is the assumption that land will be afforested today and remain in forest thereafter.

We summarize the cost results by computing the average cost per ton of carbon in each county, using the land use shares as weights. Figures 5 and 6 show the cases without and with harvesting (maps showing the cost per ton of carbon separately for each use are presented in appendix figures 20 through 22). 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 forests, 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 figures 5 and 6 indicates that harvesting reduces per-ton costs in most counties.

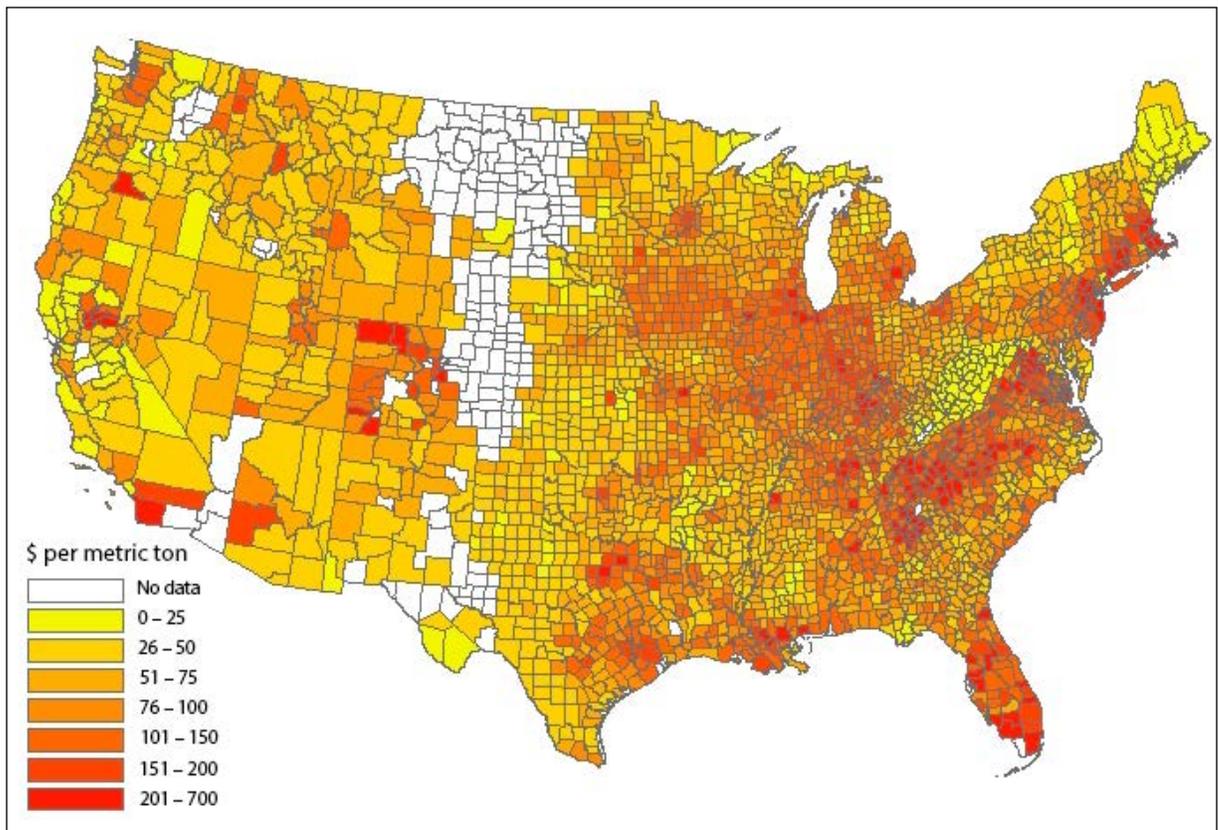


Figure 5—Average carbon sequestration costs without periodic harvesting (\$ per metric ton).

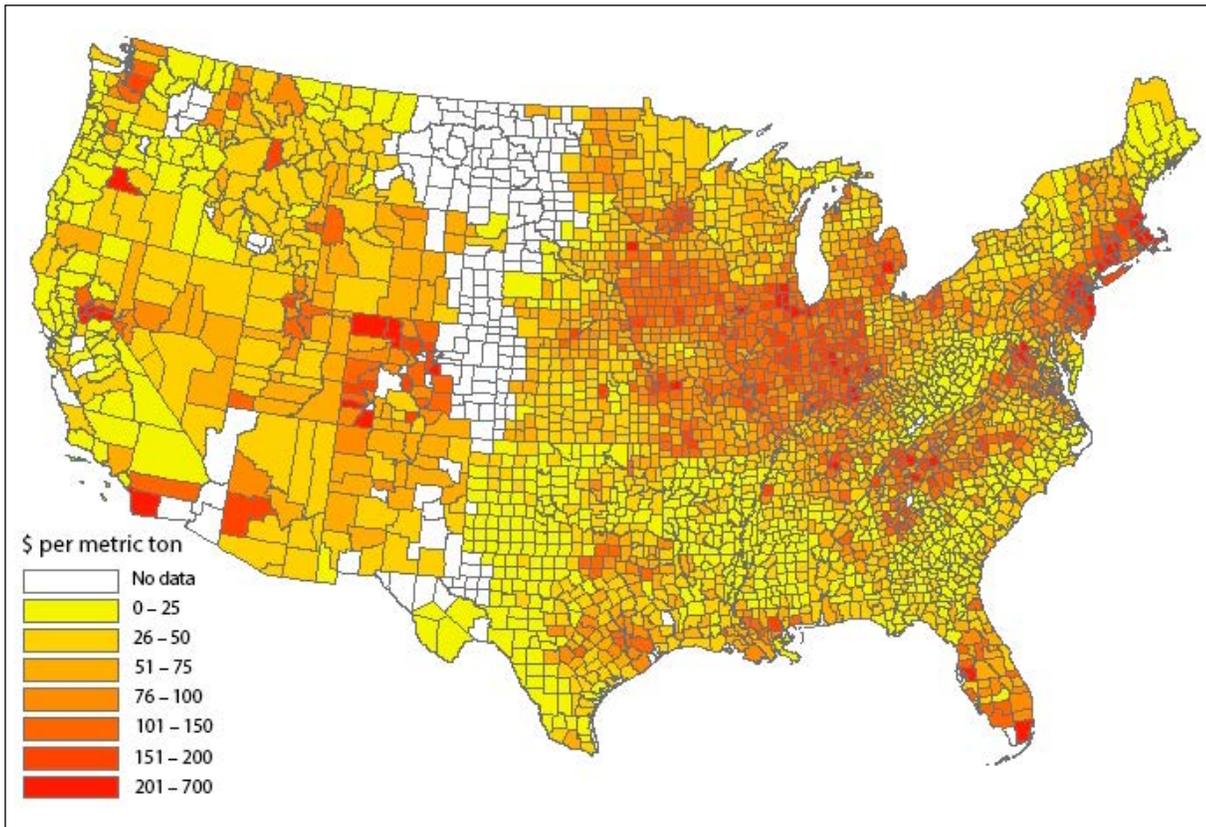


Figure 6—Average carbon sequestration costs with periodic harvesting (\$ per metric ton).

A national-level marginal cost curve for carbon sequestration can be constructed using these results. As in Lubowski et al. (2006), we order the cost-per-ton estimates and then plot them against the annualized cumulative carbon sequestered. The results indicate the total carbon uptake per year that would result for given per-ton carbon payments (fig. 7). With periodic harvesting, a carbon price of \$50 per ton generates 200 million tons of carbon annually, corresponding to approximately 13 percent of the annual emissions of the United States.<sup>10</sup> 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.

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**With periodic harvesting, a carbon price of \$50 per ton generates 200 million tons of carbon annually, corresponding to approximately 13 percent of the annual emissions of the United States.**

<sup>10</sup> The estimated U.S. net greenhouse gas emissions in 2009 were 1,532 million tons of carbon equivalent (U.S. Environmental Protection Agency 2011).

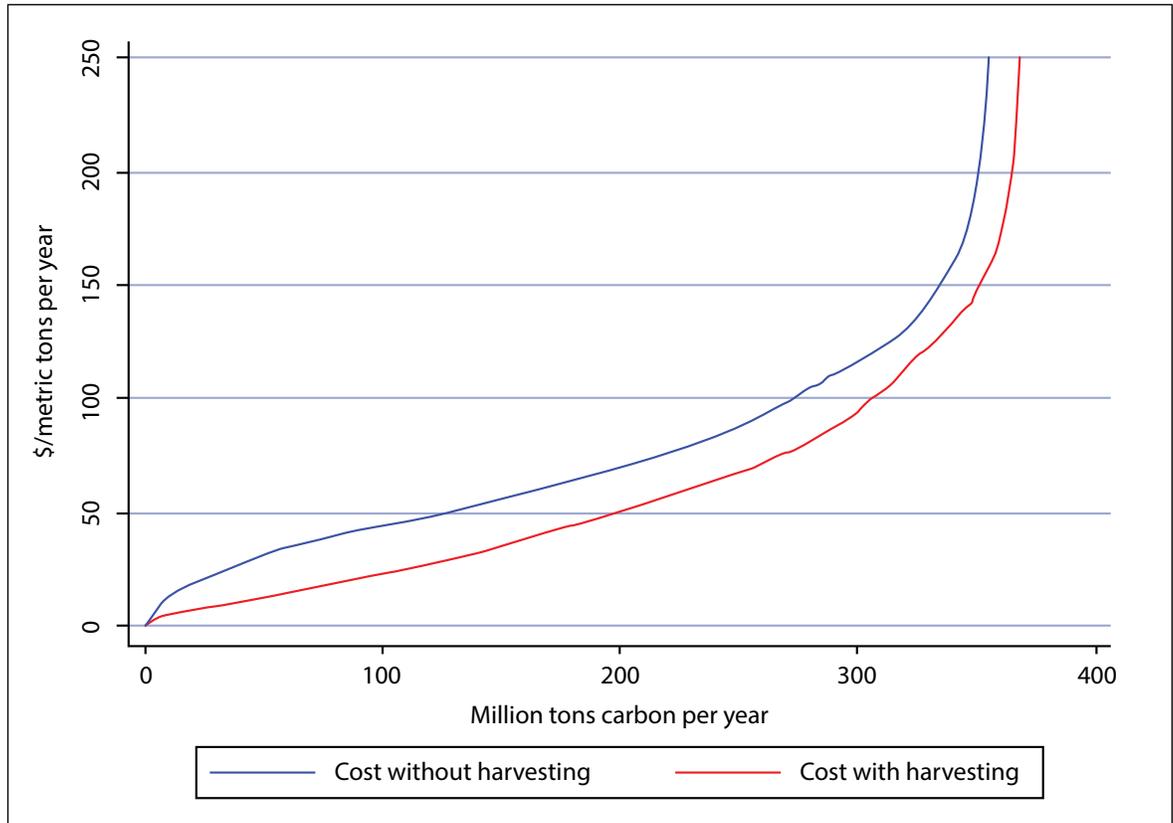


Figure 7—Marginal costs of carbon sequestration in forests in the United States (\$/metric ton/year).

For the rest of this section, we focus on results with periodic harvesting because this involves lower costs. Figure 8 presents marginal cost curves individually by land use. Rangeland provides the cheapest carbon sequestration, at least until the stock of available land is used up, followed by cropland and finally pasture. The higher marginal costs for pasture are related, in part, to the fact that there is less land nationwide in pasture, which means that the marginal cost curve for pasture turns up sooner than those for the other uses.

More details on these results are provided in table 2. 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 rangeland is largely exhausted, and cropland contributes about 40 percent 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

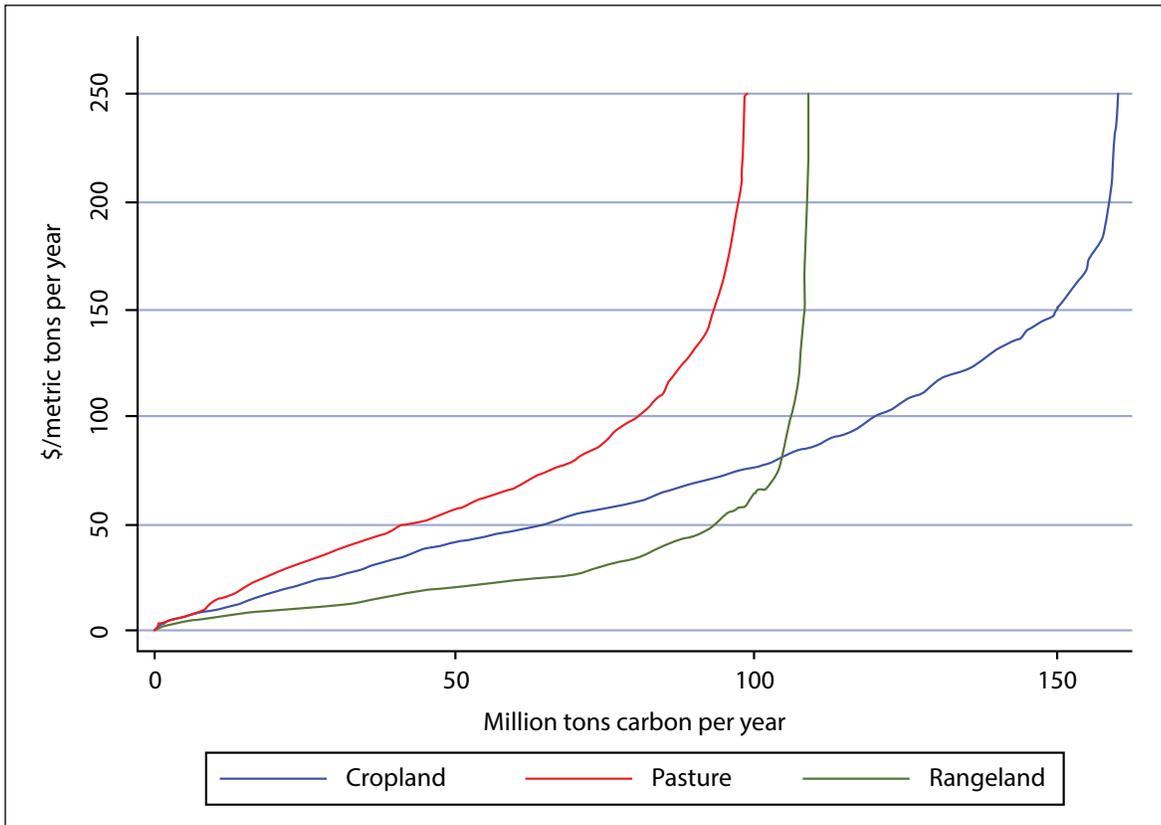


Figure 8—Marginal costs of carbon sequestration with periodic timber harvesting by initial use (\$/metric ton/year).

**Table 2—Summary of carbon sequestration cost results**

	Carbon prices (per ton)		
	\$50	\$100	\$150
Area afforested:	<i>Million acres</i>		
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:	<i>Million tons per year</i>		
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:	<i>Billion dollars per year</i>		
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

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**Incorporating the Holdridge forest zone constraints greatly affects cost estimates. Without the constraints, the amount of available land increases from 490 million acres to 805 million acres, causing the annual sequestration potential to increase 370 to 560 megatons (Mt) of carbon annually.**

cost is measured as the foregone rents plus establishment costs (or, equivalently, the area under the marginal cost curves in fig. 8). At \$50 per ton, a large share of the total costs is associated with rangeland conversion. At higher carbon prices, the opportunity costs arise mostly from the afforestation of cropland.

Figure 9 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 United States just east of the 100<sup>th</sup> meridian and, in particular, the Corn Belt region. Carbon sequestration costs are relatively high in this area (fig. 6), but much agricultural land is available for afforestation 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.

Incorporating the Holdridge forest zone constraints greatly affects cost estimates. Without the constraints, the amount of available land increases from 490 million acres to 805 million acres, causing the annual sequestration potential to increase 370 to 560 megatons (Mt) of carbon annually. The increase in land availability lowers the marginal cost of carbon sequestration (fig. 10). At a \$50-per-ton carbon price, for instance, the sequestration supply increases from 200 to 336 Mt annually.

## Comparison to Other Studies

We compare our results to those in Moulton and Richards 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. (2006) (125 million tons compared to 113 million tons). Those in Moulton and Richards 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 Moulton and Richards estimate diverges considerably from those in the other studies. Although there are many factors involved, two important ones are that Moulton and Richards assume a large stock of land available for afforestation and relatively low opportunity costs. In particular, the Moulton and Richards estimates do not account for foregone rents from future development. The results from this study closely match those in Lubowski et al. (2006) 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. (2006) 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.

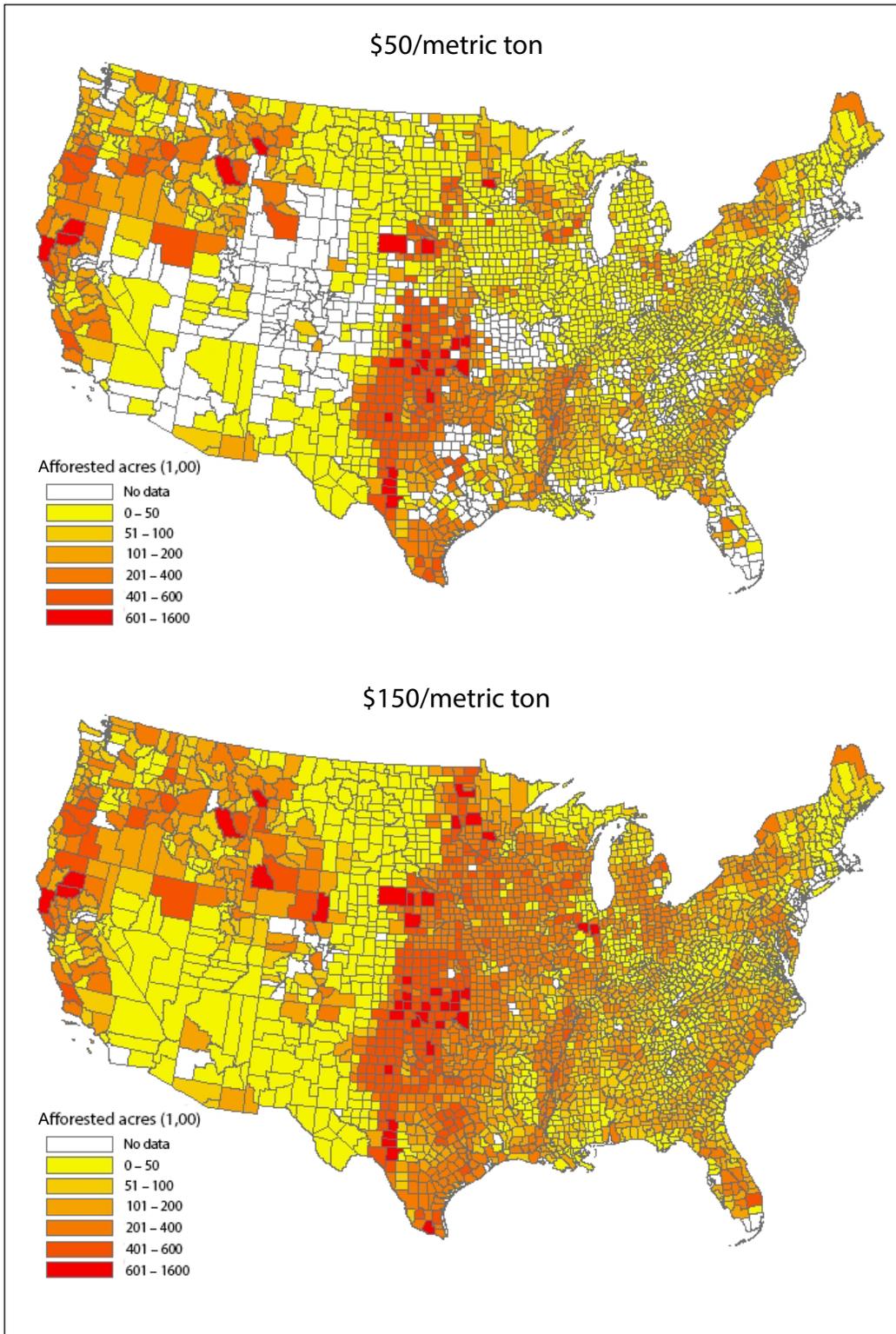


Figure 9—Distribution of afforested acres at carbon prices of \$50 and \$150 per metric ton.

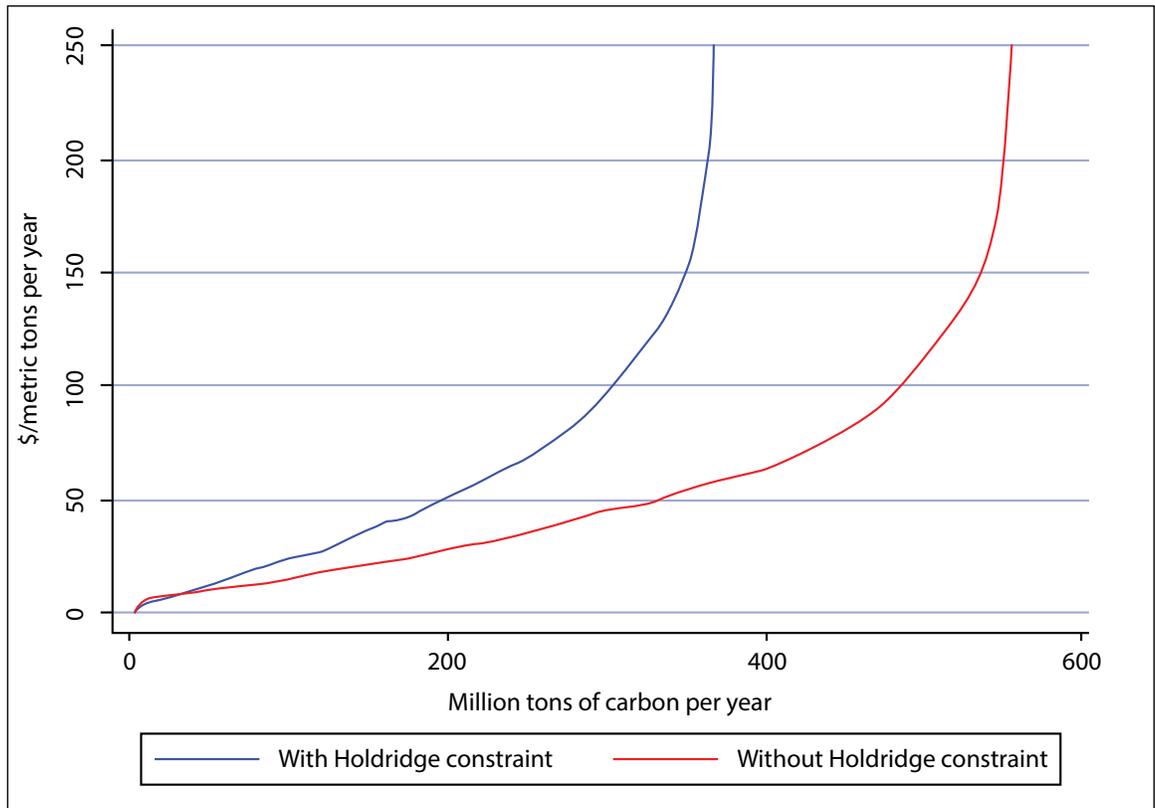


Figure 10—Effect of Holdridge Forest Zone constraints on marginal cost estimates.

**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 <sup>a</sup>	225.0	800.0				
Lubowski et al.	113.0	200.0	323.0	575.0	800.0	1050.0

<sup>a</sup> Moulton and Richards (1990) costs adjusted to 1997 values using the Consumer Price Index.

(2006) 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. (2006), 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. (2006) also include avoided deforestation. Finally, it is important to note that the Lubowski et al. (2006) 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.

## Limitations of This Study

As noted in the “Introduction,” to keep this analysis simple and transparent, 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 Moulton and Richards, 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 to 60 percent higher than in Moulton and Richards. Lubowski et al. (2006) account for endogenous prices and employ an econometric approach that can account for unobservable factors. At 500 million tons, their estimate of marginal cost is approximately 100 percent higher than the estimate in Moulton and Richards (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 (fig. 10), 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 FIA data that are developed from surveys of current forests, providing national coverage. 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, and technological trends (e.g., increased use of genetic stock improvement and other biotechnology advances) are likely to result in significant increases in yields per acre.

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**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.**

## Conclusions

We provide a new set of estimates of the costs to private landowners of sequestering carbon by converting nonforest (rural) land to forests in the United States in order to enhance policy analyses of climate change mitigation options involving afforestation opportunities. The new data set includes coverage of afforestation opportunities on rangeland, new estimates of opportunity costs of nonforest land uses (using information on annual net returns adjusted for information derived from land value data and constraints on forest establishment potential), estimates of forest establishment (conversion) costs, and estimates of the foregone option to future urban development. The data set is county level, differentiated by land use category, and considers the role of possible timber harvests in reducing the net costs.

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.

Future investigations of long-term carbon sequestration programs must grapple with the possibility of climate change, even if avoiding climate change is the intention of the policy. Many 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 International Panel on Climate Change scenarios of climate change. In a related study, Haim et al. (2010) explored how changes in forest and agricultural yields and agricultural commodity prices would affect future patterns of land use in the United States. Improved afforestation data by region would be beneficial. In our analysis, we implicitly treat counties as homogenous units where variables for each county (soil productivity, land values, etc.) are defined at the mean. This accounts for heterogeneity much more than in many earlier studies, though more could be done as part of further work (e.g., afforestation yields across soil types, other land conditions, and forest management intensities by region).

Other future research and sensitivity analyses could investigate policy design issues and effects on costs of sequestration. Our estimates of the marginal costs of carbon sequestration in forest are based on the private opportunity costs of the land, and impacts on costs of afforestation policies by ownership type from government actions warrant further research, e.g., government subsidy programs for agriculture. 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) found significant efficiency gains from the use of a contracting scheme that limits government payments for carbon sequestration. 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) examined policies that can address additionality in a domestic policy setting.

Finally, future research can include broadening consideration of costs and benefits. Although 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, and 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 United States. 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.

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**Establishing new forests on agricultural lands can provide wildlife habitat, and improve water quality by preventing erosion and reducing use of agricultural chemicals, among other benefits.**

## References

- Adams, D.M.; Alig, R.J.; Callaway, J.M.; McCarl, B.A.; Winnett, S.M. 1996.** The forest and agricultural sector model (FASOM): model structure and policy applications. Res. Pap. PNW-RP-495. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 60 p.
- Adams, D.M.; Alig, R.J.; McCarl, B.A.; Callaway, J.M.; Winnett, S.M. 1999.** Minimum cost strategies for sequestering carbon in forests. *Land Economics*. 75(3): 360–374.
- Adams, R.M.; Adams, D.M.; Callaway, J.M.; Chang, C.C.; McCarl, B.A. 1993.** Sequestering carbon on agricultural land; social cost and impacts on timber markets. *Contemporary Policy Issues*. 11(1): 76–87.
- Alig, R.; Adams, D.; McCarl, B.; Callaway, J.M.; Winnett, S. 1997.** Assessing effects of mitigation strategies for global climate change with an intertemporal model of the U.S. forest and agriculture sectors. *Environmental and Resource Economics*. 9: 259–274.
- Busch, J.; Lubowski, R.N.; Godoy, F.; Steininger, M.; Yusuf, A.A.; Austin, K.; Hewson, J.; Juhn, D.; Farid, M.; Boltz, F. 2012.** Structuring economic incentives to reduce emissions from deforestation within Indonesia. *Proceedings of the National Academies of Sciences*. 9(4): 1062–1067.
- Conservation Biology Institute. 2010.** PAD-US 1.1. CBI ed. Corvallis, OR: May.
- Dempsey, J.; Plantinga, A.J.; Alig, R.J. 2010.** What explains differences in the costs of carbon sequestration in forests? A review of alternative cost estimation methodologies. In: Alig, R.J., tech. coord. *Economic modeling of effects of climate change on the forest sector and mitigation options: a compendium of briefing papers*. Gen. Tech. Rep. PNW-GTR-833. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 169 p.
- Dudek, D.; LeBlanc, A. 1990.** Offsetting new CO<sub>2</sub> emissions: a rational first greenhouse policy step. *Contemporary Policy Issues*. 8: 29–42.
- Haim, D.; Alig, R.J.; Plantinga, A.J.; Sohngen, B. 2011.** Climate change and future land use in the United States: an economic approach. *Climate Change Economics*. 2(1): 27–51.

- Holdridge, L.R. 1967.** Life zone ecology. San Jose, Costa Rica. Tropical Science Center. 124 p.
- Horowitz, J.; Just, R. 2013.** Economics of additionality for environmental services from agriculture. *Journal of Environmental Economics and Management*. 66: 105–122.
- Latta, G.; Adams, D.M.; Alig, R.J.; White, E. 2011.** Simulated effects of mandatory versus voluntary participation in private forest carbon offset markets in the United States. *Journal of Forest Economics*. 17: 127–141.
- Lubowski, R.N. 2002.** Determinants of land-use transitions in the United States: econometric analysis of changes among the major land-use categories. Cambridge, MA: Harvard University. Ph.D. dissertation.
- Lubowski, N.R.; Plantinga, A.J.; Stavins, R.N. 2006.** Land-use change and carbon sinks: econometric estimation of the carbon sequestration supply function. *Journal of Environmental Economic and Management*. 51: 135–152.
- Lugo, A.E.; Brown, S.L.; Dodson, R.; Smith, T.S.; Shugart, H.H. 1999.** The Holdridge Life Zones of the conterminous United States in relation to ecosystem mapping. *Journal of Biogeography*. 26: 1025–1038.
- Marland, G. 1988.** The prospect of solving the CO<sub>2</sub> problem through global reforestation. DOE Report DOE/NBB-0082. Washington, DC: U.S. Department of Energy, Office of Energy Research.
- Mason, C.F.; Plantinga, A.J. 2013.** The additionality problem with offsets: optimal contracts for carbon sequestration in forests. *Journal of Environmental Economics and Management*. 66: 1–14.
- Matthews, S.; O'Connor, R.; Plantinga, A.J. 2002.** Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. *Ecological Economics*. 40(1): 71–87.
- Moulton, R.J.; Richards, K.R. 1990.** Costs of sequestering carbon through tree planting and forest management in the United States. Gen. Tech. Rep. WO-58. Washington, DC: U.S. Department of Agriculture, Forest Service. 47 p.
- Plantinga, A.L.; Lubowski, R.N.; Stavins, R.N. 2002.** The effects of potential land development on agricultural land prices. *Journal of Urban Economics*. 52: 561–581.

- Plantinga, A.J.; Mauldin, T.; Miller, D. 1999.** An econometric analysis of the costs of sequestering carbon in forests. *American Journal of Agricultural Economics*. 81: 812–824.
- Plantinga, A.J.; Richards, K.R. 2010.** International forest carbon sequestration in a post-Kyoto Agreement. Discussion Paper 08-11. In: Aldy, J.E.; Stavins, R.N., eds. *Post-Kyoto International Climate Policy*. New York, NY: Cambridge University Press.
- Plantinga, A.J.; Wu, J. 2003.** Co-benefits from carbon sequestration in forests: evaluating reductions in agricultural externalities from an afforestation policy in Wisconsin. *Land Economics*. 79(1): 74–85.
- Richards, K.R.; Andersson, K. 2001.** The leaky sink: persistent obstacles to a forest carbon sequestration program based on individual projects. *Climate Policy*. 1: 41–54.
- Richards, K.R.; Moulton, R.; Birdsey, R. 1993.** Costs of creating carbon sinks in the US. *Energy Conservation and Management*. 34(9-11): 905–912.
- Richards, K.R.; Stokes, C. 2004.** A review of forest carbon sequestration cost studies: a dozen years of research. *Climatic Change*. 63(1-2): 1–48.
- Schatzki, T. 2003.** Options, uncertainty, and sunk costs: an empirical analysis of land use change. *Journal of Environmental Economics and Management*. 46(1): 86–105.
- Sedjo, R. 1989.** Forests: A tool to moderate global warming? *Environment*. 31(1): 14–20.
- Smith, J.E.; Heath, L.; Skog, K.E.; Birdsey, R.A. 2006.** Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. Gen. Tech. Rep. GTR-NE-343. Newton Square, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station. 216 p.
- Stavins, R.N. 1999.** The costs of carbon sequestration: a revealed preference approach. *American Economic Review*. 89: 994–1009.
- Stavins, R.; Richards, K. 2005.** The cost of U.S. forest based carbon sequestration. Prepared for the Pew Center for Global Climate Change. [http://www.hks.harvard.edu/fs/rstavins/Monographs\\_&\\_Reports/Richards\\_&\\_Stavins\\_Final\\_Pew\\_Report.pdf](http://www.hks.harvard.edu/fs/rstavins/Monographs_&_Reports/Richards_&_Stavins_Final_Pew_Report.pdf). (May 14, 2013).

- U.S. Environmental Protection Agency. 2011.** Inventory of US greenhouse gas emissions and sinks: 1990–2009. EPA 430-R-11-005. <http://www.epa.gov/climatechange/ghgemissions/usinventoryreport/archive.html>. (April 2, 2013).
- Van Kooten, G.; Shaikh, S.L.; Suchanek, P. 2002.** Mitigating climate change by planting trees: the transaction costs trap. *Land Economics*. 78(4): 559–572.
- Withey, J.; Lawler, J.; Polasky, S.; Plantinga, A.J.; Nelson, E.; Wilsey, C.; Schloss, C.; Nogeire, T.; Ruesch, A.; Ramos, J.; Reid, W. 2012.** Maximizing return on conservation investment in the conterminous U.S. *Ecology Letters*.

## Appendix

To access county-level data on land prices, tree establishment costs, carbon uptake rates, and eligible land for conversion to forest, follow this link:  
[http://www.fs.fed.us/pnw/pubs/pnw\\_gtr888/county-level-data\\_nielsen2013.xlsx](http://www.fs.fed.us/pnw/pubs/pnw_gtr888/county-level-data_nielsen2013.xlsx)

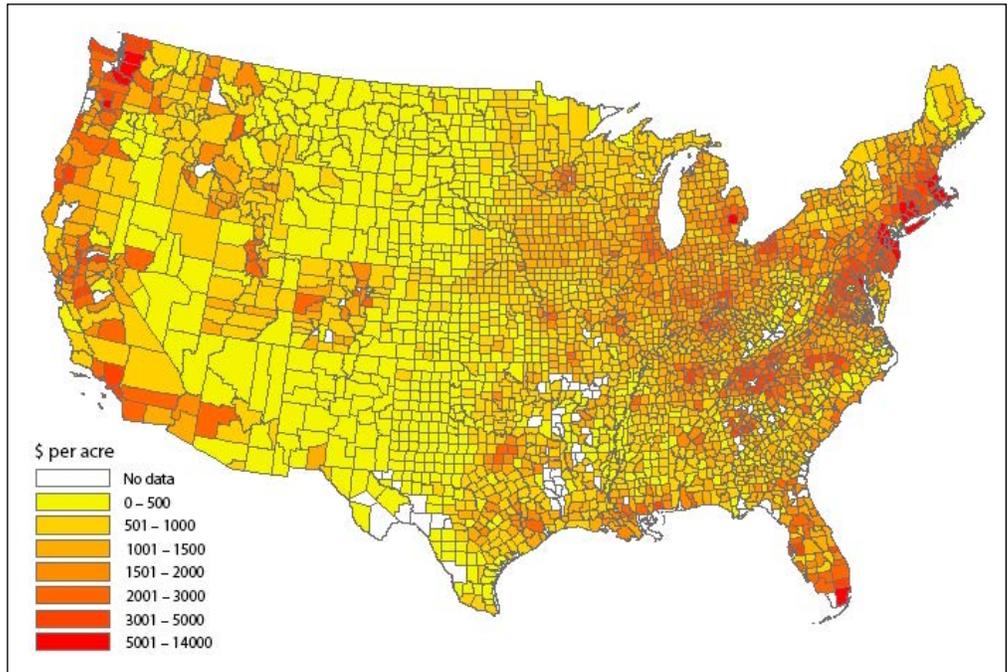


Figure 11—Average crop price per acre, by county. Note: Areas with zero acreage in crops, according to the 1997 Natural Resources Inventory, are shown in white.

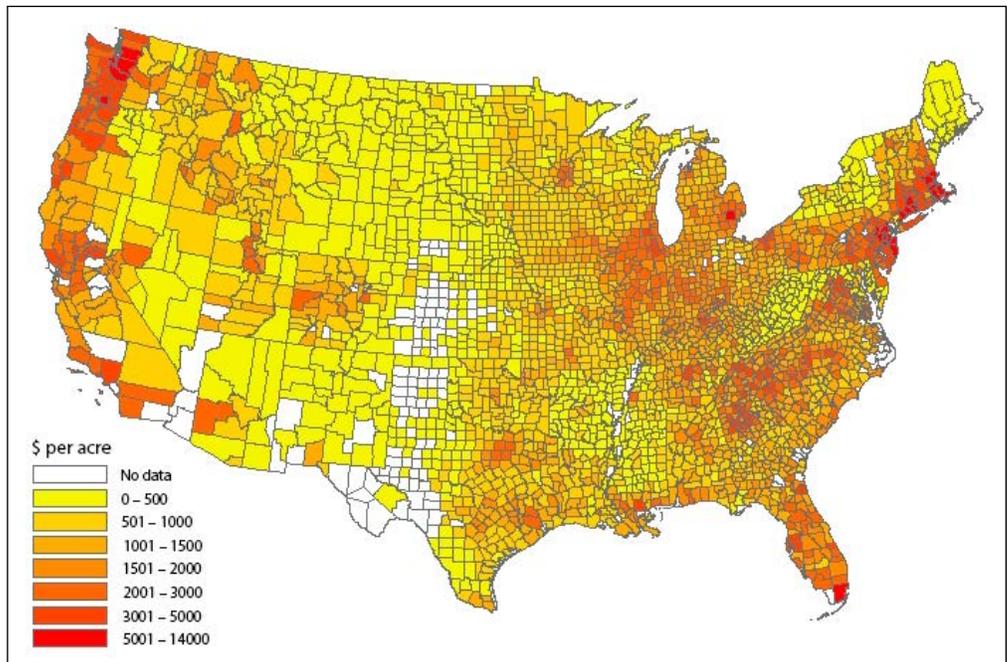


Figure 12—Average pasture price per acre, by county. Note: Areas with zero acreage in pasture, according to the 1997 Natural Resources Inventory, are shown in white.

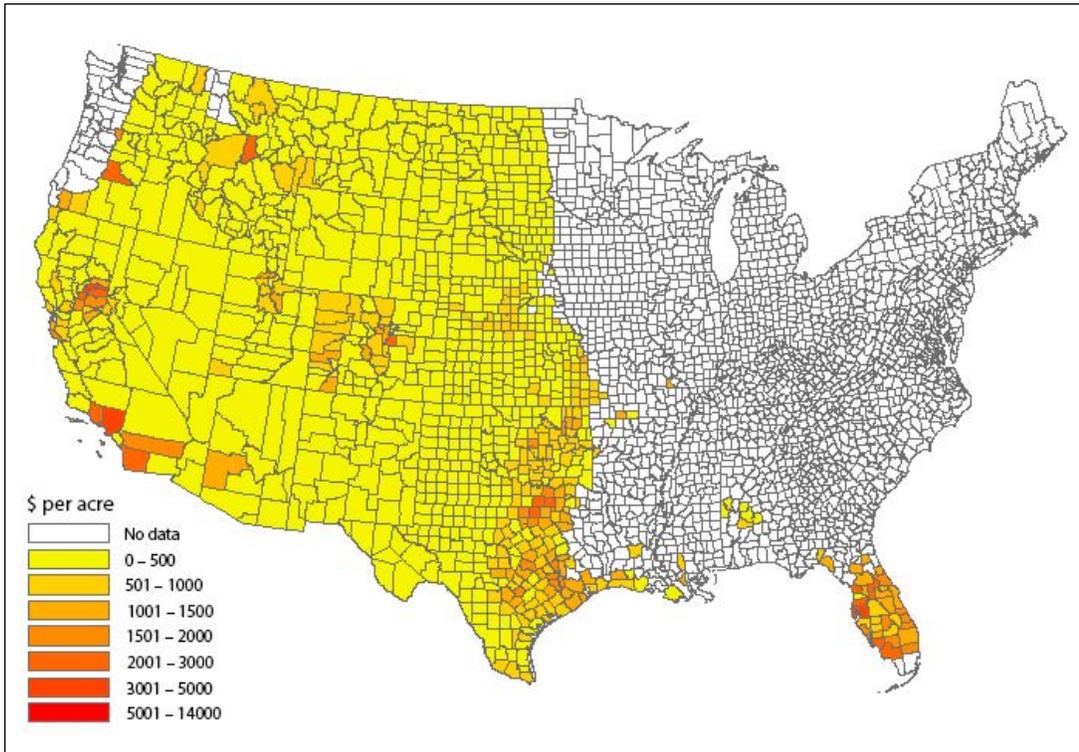


Figure 13—Average range price per acre, by county. Note: Areas with zero acreage in range, according to the 1997 Natural Resources Inventory, are shown in white.

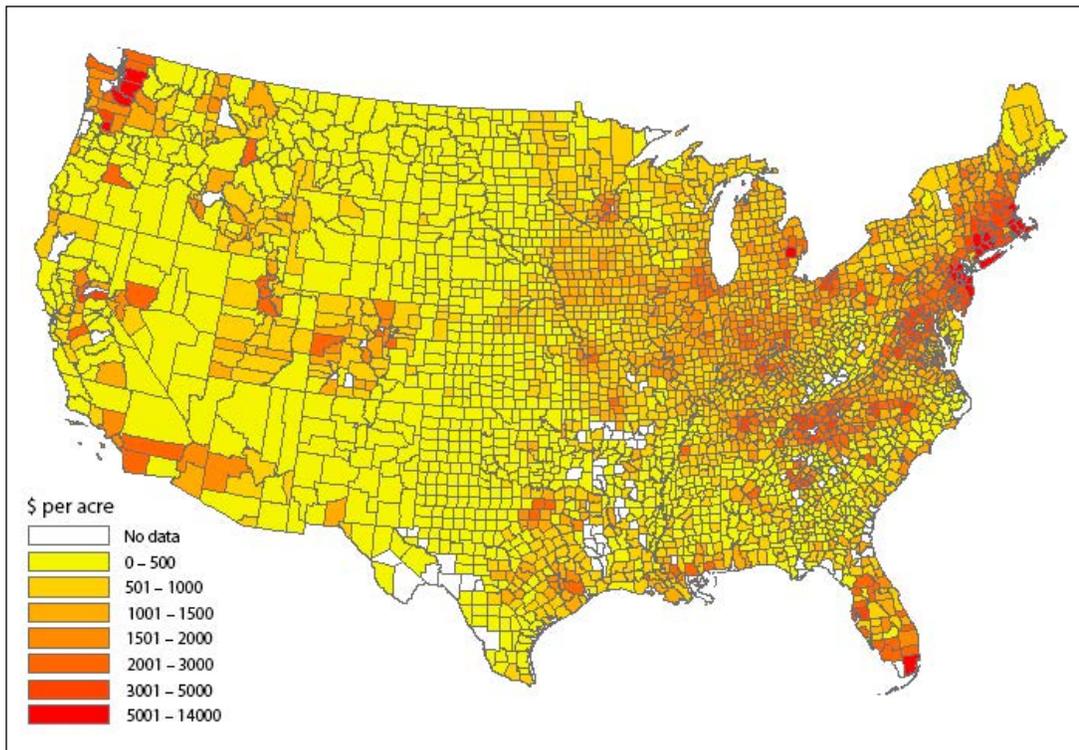


Figure 14—Average crop price per acre net of harvesting revenues, by county. Note: Areas with zero acreage in crops, according to the 1997 Natural Resources Inventory, are shown in white.

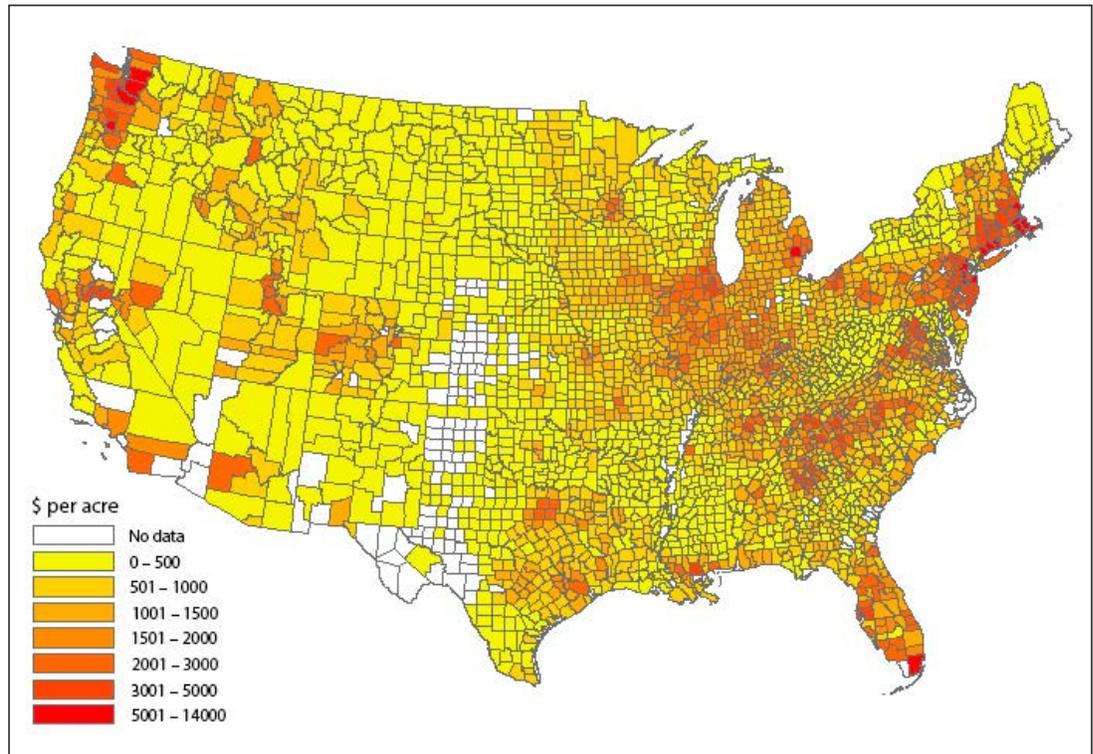


Figure 15—Average pasture price per acre net of harvesting revenues, by county. Note: Areas with zero acreage in pasture, according to the 1997 Natural Resources Inventory, are shown in white.

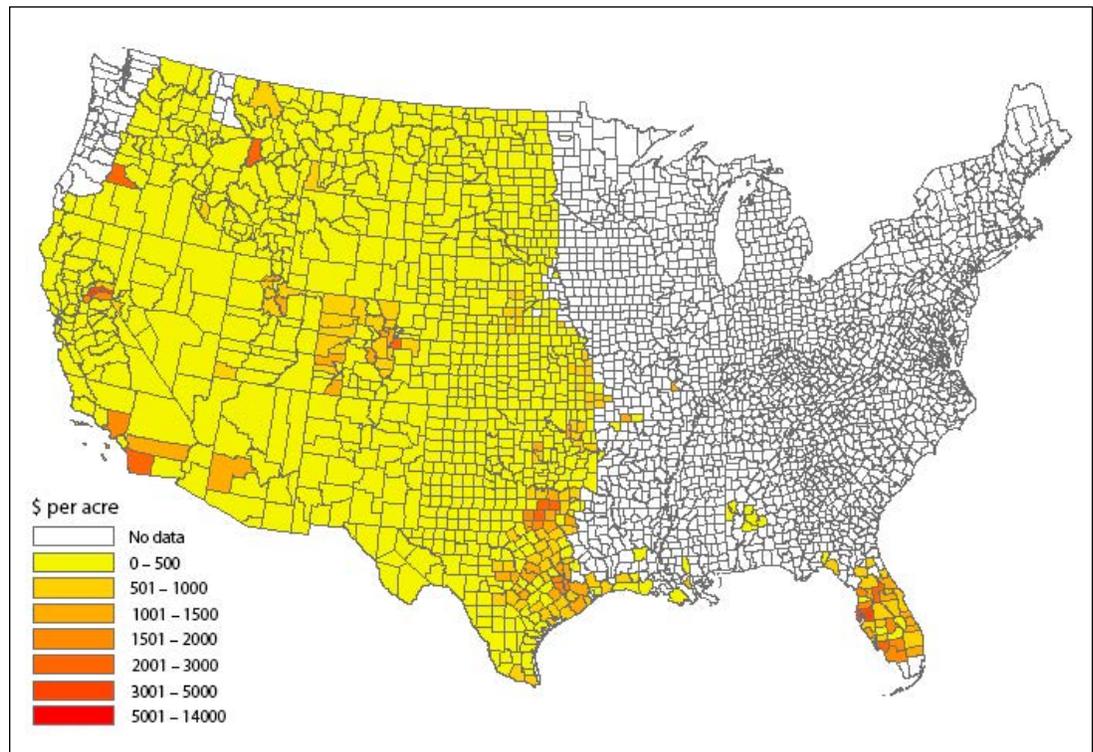


Figure 16—Average range price per acre net of harvesting revenues, by county. Note: Areas with zero acreage in range, according to the 1997 Natural Resources Inventory, are shown in white.

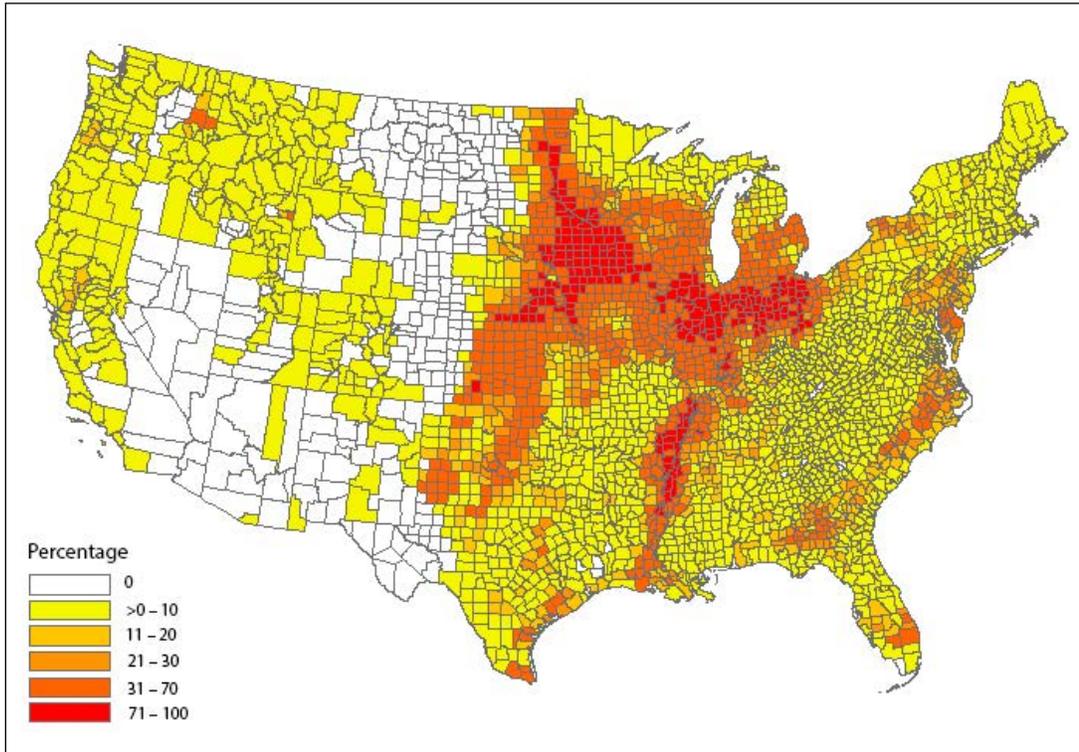


Figure 17—The share of each county in crops and a Holdridge forest zone. Note: The definition of cropland is based on the 2001 National Land Cover Database.

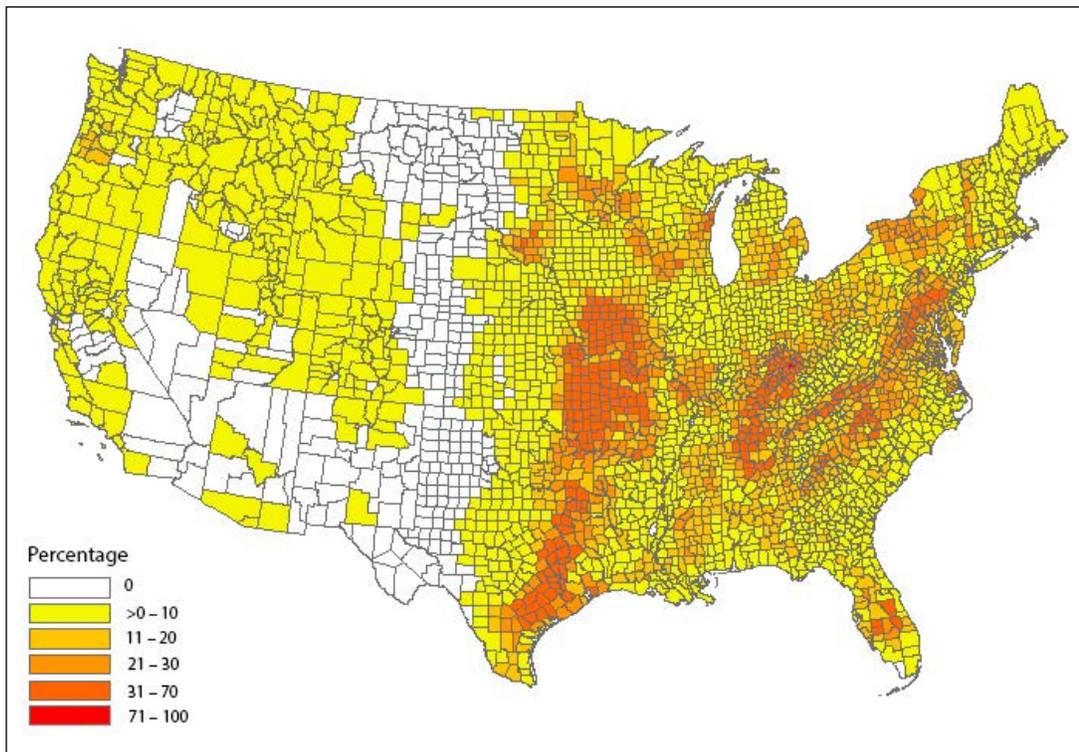


Figure 18—The share of each county in pasture and a Holdridge forest zone. Note: The definition of pasture is based on the 2001 National Land Cover Database.

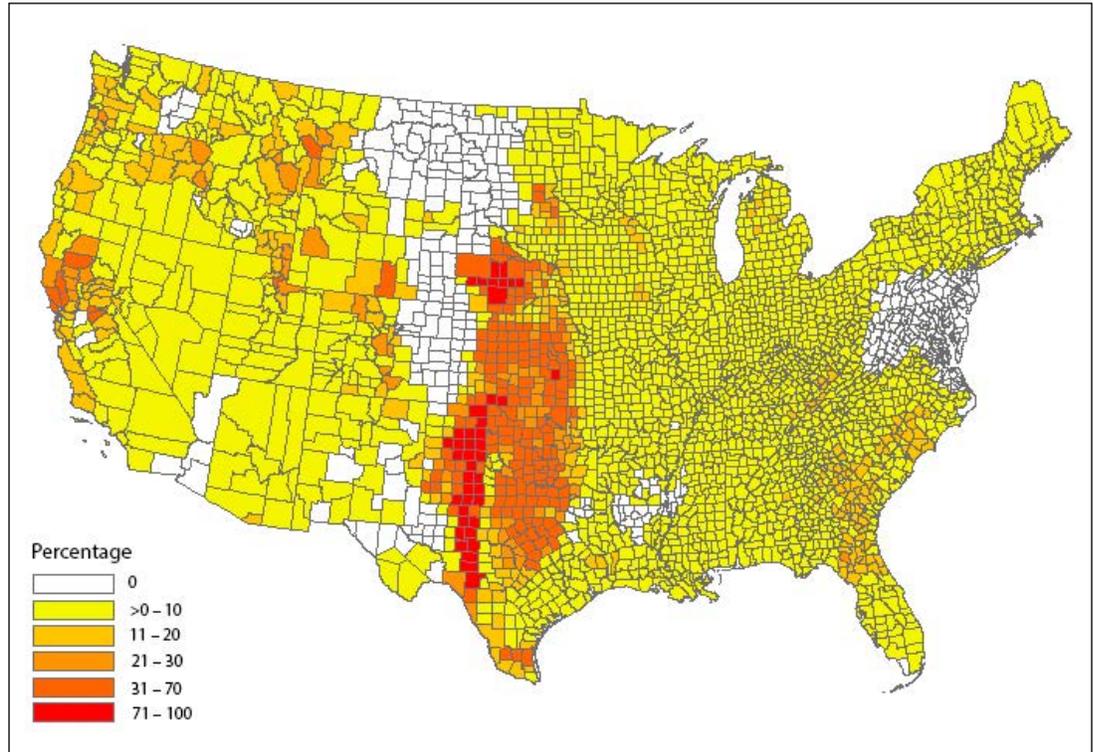


Figure 19—The share of each county in range and a Holdridge forest zone. Note: The definition of range land is based on the 2001 National Land Cover Database categories. West of the 100<sup>th</sup> meridian, we define range by categories 71 (grassland/herbaceous) and 52 (shrub/scrub) and, east of 100<sup>th</sup> meridian, only by category 71. Unlike in figures 13 and 16, this definition implies positive acres of range east of the 100<sup>th</sup> meridian.

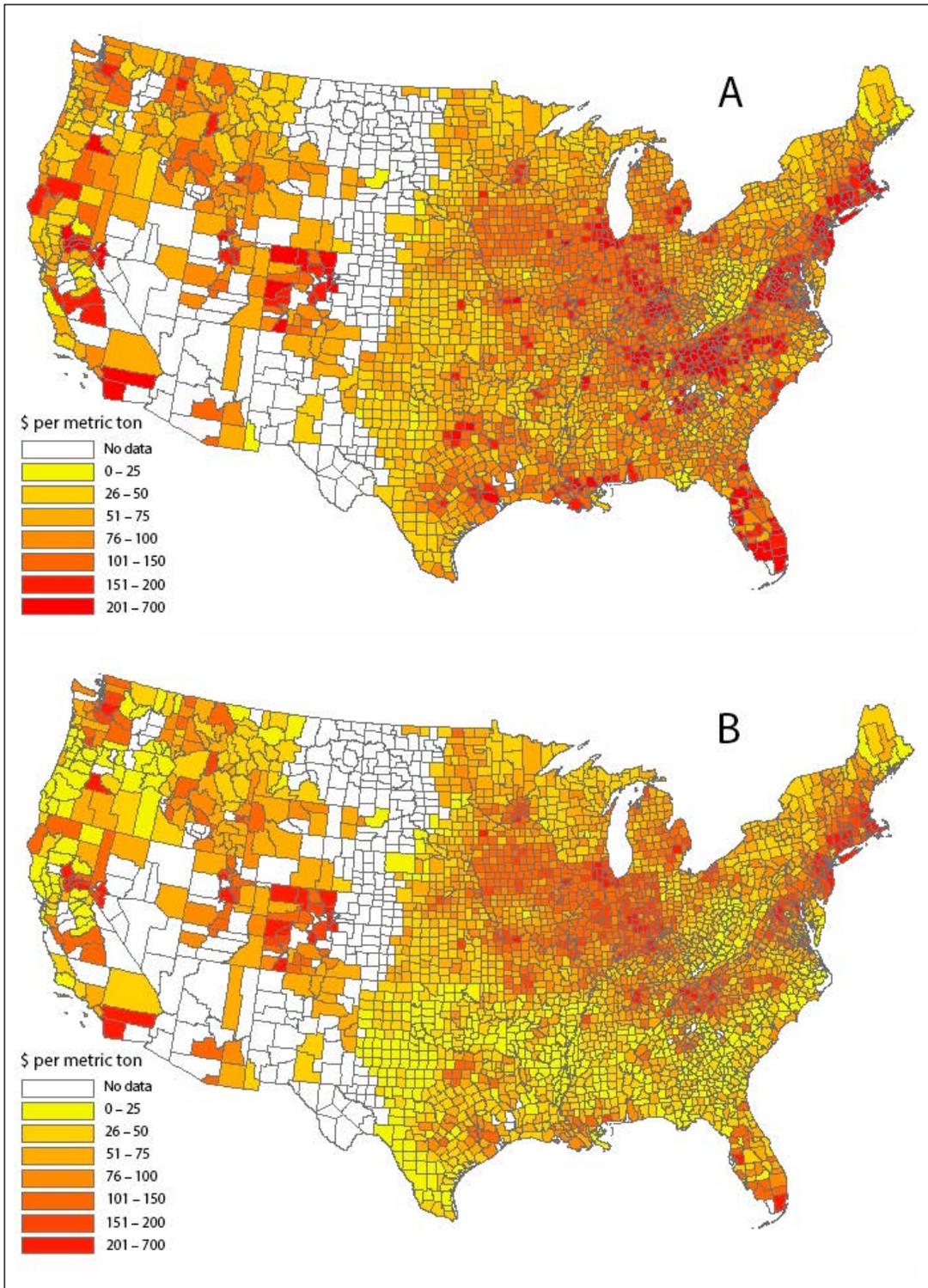


Figure 20—Average carbon sequestration costs on cropland (\$/metric ton): (A) without harvesting, (B) with harvesting.

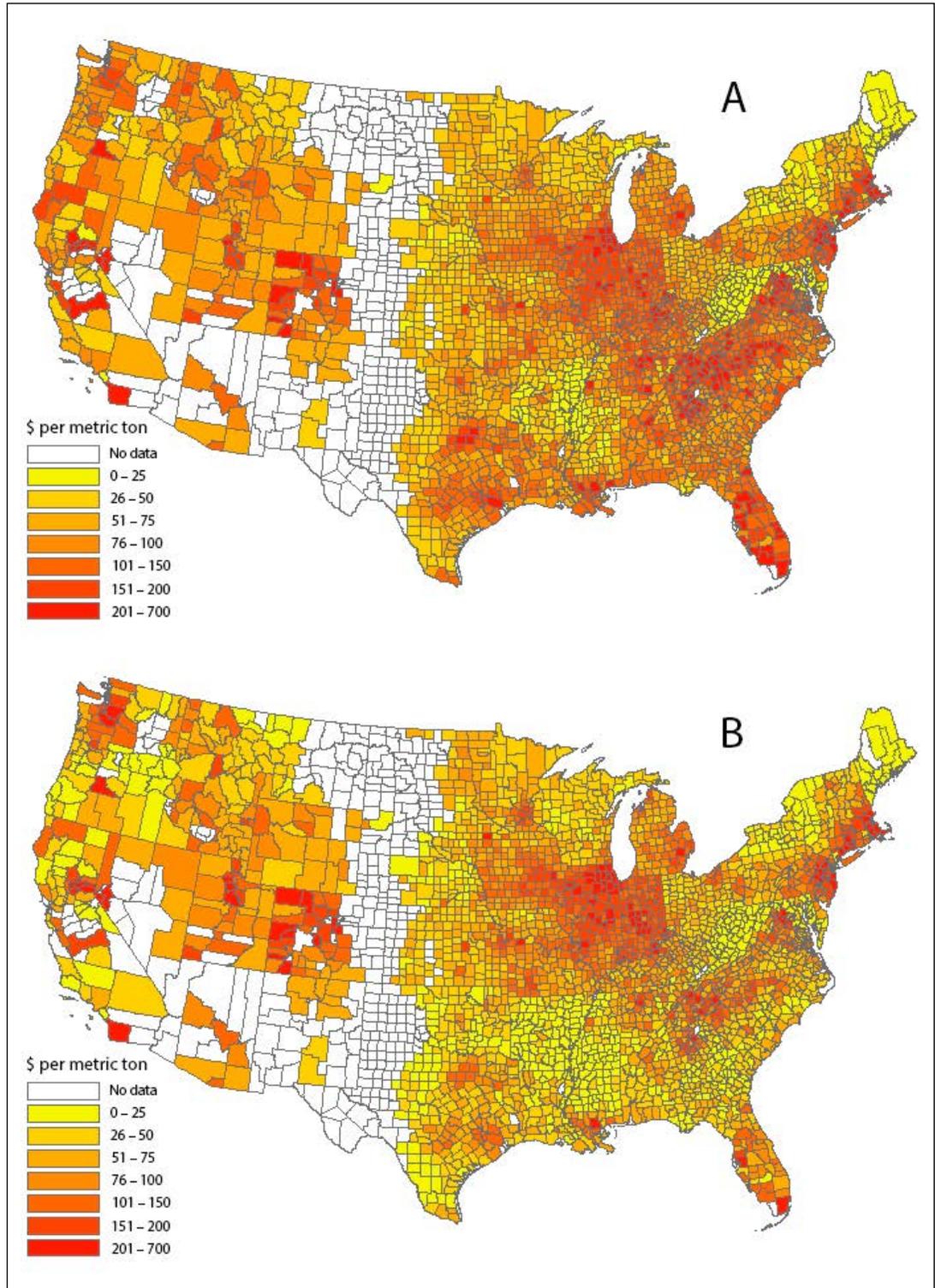


Figure 21—Average carbon sequestration costs on pasture land (\$/metric ton): (A) without harvesting, (B) with harvesting.

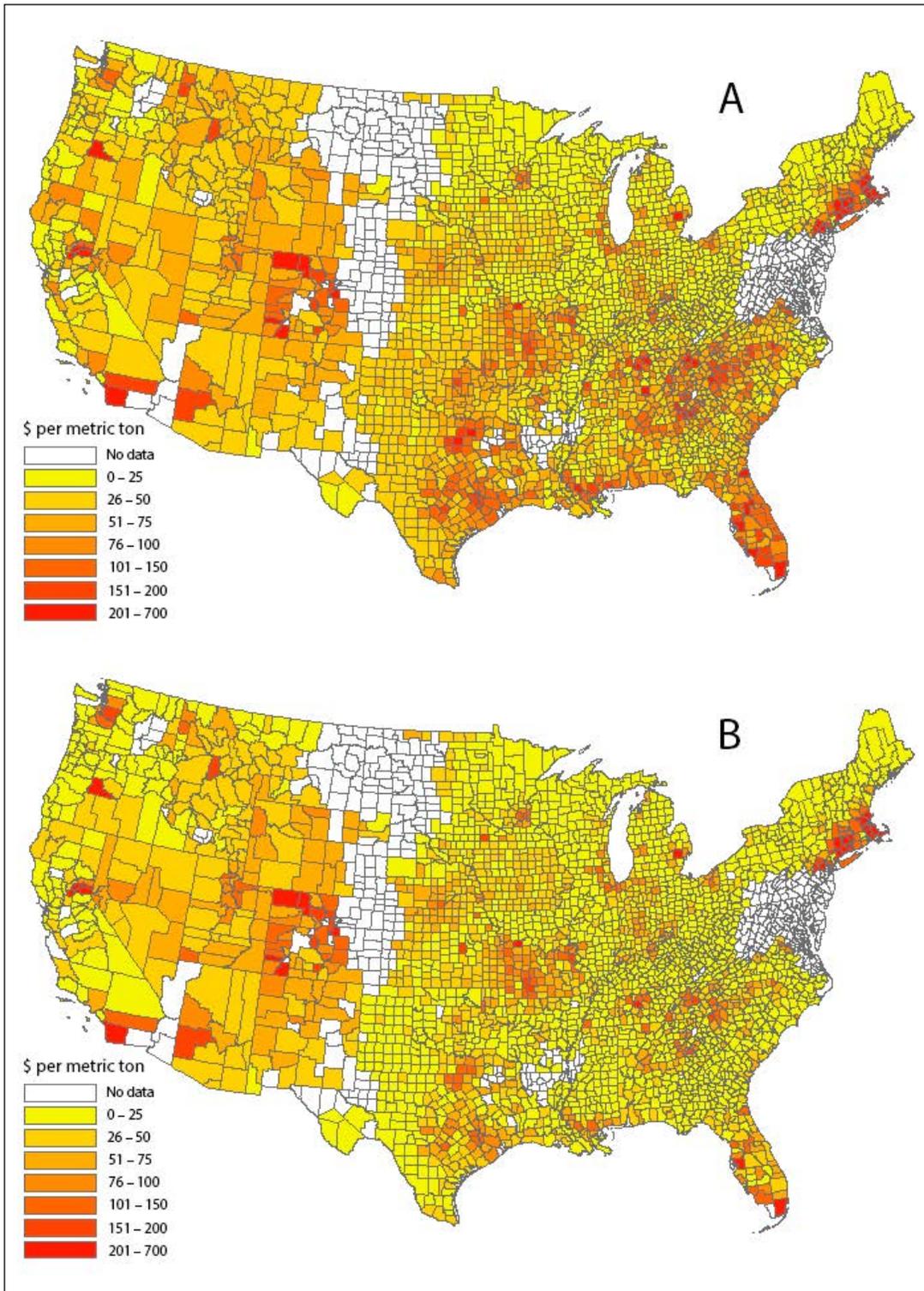


Figure 22—Average carbon sequestration costs on rangeland (\$/metric ton): (A) without harvesting, (B) with harvesting. Note: Rangeland is defined using 2001 National Land Cover Database categories. See note to figure 19 for more details.



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