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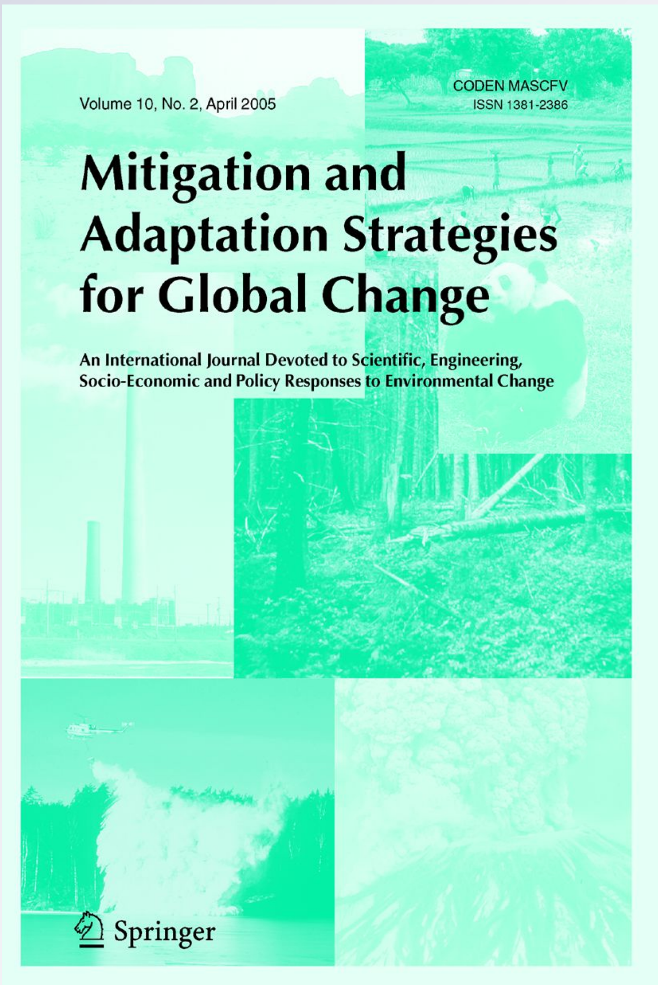

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ORIGINAL ARTICLE

Estimating carbon supply curves from afforestation of agricultural land in the Northeastern U.S.

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Abstract The Regional Greenhouse Gas Initiative for the northeastern states of the U.S. allows for terrestrial carbon (C) sequestration offsets generated by afforestation activities only. This paper estimates the maximum potential quantity and associated costs of increasing the storage of carbon by afforestation of existing agricultural land in the 11 states of the Northeast United States. The focus of the work was to describe location, the quantity, and at what cost it would be economically attractive to shift agricultural production to afforestation to increase carbon storage in the region. Widely available data sets were used to (1) identify spatially-explicit areas for lower costs carbon offsets and (2) estimate carbon supply curves related to afforestation of agricultural land over three time periods (10, 20, and 40 years). Carbon accumulation and total carbon offset project costs were estimated at a county scale and combined to identify expected costs per ton of carbon dioxide equivalents (CO_2e). Large variation in estimated costs per ton of CO_2e are driven by varying carbon accumulation potentials and opportunity costs of taking land out of agricultural production, as well as the duration of the project activity. Results show that the lowest cost carbon offset projects will be in certain counties of Maine, Vermont, and New York. Pasture land, with lower opportunity costs, generally presents the opportunity for lower cost carbon offset projects relative to cropland. This analysis estimates that afforestation of pasture land in the northeast will not become economically attractive until the price rises above $10 per metric tonne (MT) CO_2e and that up to 583 million MT could be economically sequestered if the price were to rise to $50 per MT CO_2e, based on a 40-year project life. With regard to cropland in the northeast, afforestation does not become economically advantageous for land owners until the price rises above $40 per MT CO_2e. It is estimated that up to 487,000 MT could be sequestered from cropland if the price were to rise to $50 per MT CO_2e, based on a 40-year project life.

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1 Introduction

The Regional Greenhouse Gas Initiative (RGGI) is the first mandatory, market-based effort in the United States to reduce greenhouse gas emissions. Ten Northeastern and Mid-Atlantic states—Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont have agreed to cap and reduce carbon dioxide (CO_2) emissions from the power sector by 10% by the year 2018.

One of the approaches the participating RGGI states can take to reduce emissions is to employ offsets (greenhouse gas emissions reduction or sequestration projects outside the electricity sector) to help companies meet their compliance obligations. A relatively promising offset strategy is afforestation, which is the planting of forest on land that has not been in forest recently, for example, agricultural land. The objective of this study was to provide estimates of the costs and potential supply of carbon credits that could be produced through afforestation of agricultural land in the RGGI states, using a consistent and spatially explicit approach. By providing estimates of the potential carbon sequestration that could result from various offset prices, this paper can help potential purchasers seek out the states, counties, and land types that are likely to produce the least costly offsets.

Several earlier studies have analyzed the carbon sequestration potential and costs resulting from changes in the use and management of agricultural land in individual states (Stavins 1999; Plantinga et al. 1999) or across the whole USA (Lewandrowski et al. 2004; Lubowski et al. 2005). The marginal costs reported in each study varied widely, ranging from about \$10 to \$120 per ton CO_2, primarily due to differences in the carbon sequestration potential and the opportunity costs of the agricultural lands. The results from these studies are difficult to compare because the land use practices for carbon sequestration differed among the studies (e.g. conservation tillage, afforestation of cropland and/or rangeland, converting cropland to pasture), the costs included in the analysis were not the same for each study, the analyses were done at different scales, and results were simulated over different and non-consistent time periods.

However, despite these differences in approach, they all found that different activities become economically attractive at different prices. For example, at low prices (e.g. \$10 per ton CO_2) farmers would likely adopt conservation tillage because it has low opportunity cost, but if prices rose to \$25 per ton CO_2 or greater, more farmers may adopt afforestation of agricultural land. All the studies concluded that use of agricultural lands for carbon sequestration activities should be considered in the development of a cost-effective portfolio of domestic U.S. climate change policies.

Stavins and Richards (2005) compared results from 11 studies that estimated marginal costs of forest-based carbon sequestration. To aid the comparison, they standardized several variables across the studies, such as discount rate, constant-year dollars, geographic scope, and reporting units. They found that programs in the USA could sequester an additional 270 million metric tons of carbon annually over a 100 year period at marginal costs that ranged from \$25 to \$75 per ton. The range of marginal costs increased to \$30 to \$90 per ton for programs that could sequester 50 million metric tons annually. While it is possible that a national program could sequester more carbon, the marginal costs rise rapidly as more prime agricultural lands with high opportunity costs was converted.

Many of the land use practices that enhance carbon sequestration achieve other environmental benefits such as increasing soil organic matter and fertility, reducing soil erosion, providing wildlife habitat, and increasing yield of timber (Richards et al. 2006). These other benefits are more difficult to quantify but clearly would provide benefits to society as a whole.

The overall goal of this regional study was to investigate the economic potential of increasing terrestrial carbon storage as a climate mitigation strategy on lands in the 11 RGGI states of the Northeast USA.

The overall goal of this regional study was to investigate the economic potential of increasing terrestrial carbon storage as a climate mitigation strategy on lands in 11 states of the Northeast USA. The states included in this analysis are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont. We used a consistent and spatially-explicit analysis in our research that allows for the identification of areas with relatively greater economic potential for carbon storage. Such information allows companies and other interested entities to identify the specific areas within the region that are likely to produce the least expensive carbon offset credits.

The study generates estimates of the potential supply of carbon credits associated with afforestation of agricultural land, as well as the cost per ton of carbon dioxide equivalents (CO_2e; in this paper we use the term CO_2e in describing our results) at the county scale over 10, 20, and 40 year time periods. The use of different time frames can help companies prepare for an uncertain regulatory future by providing estimates of the quantity of carbon credits that would potentially be available at different price points for different classes of C offset projects over different time frames and can help them prepare a portfolio of potential responses for a range of future climate scenarios.

2 Approach and methods

This analysis was performed using widely available and consistent datasets so that (1) the analysis could be easily updated as new information becomes available and (2) this approach could be replicated in other regions of the U.S. The analysis employed both spatial data such as land cover maps and tabular data, reported at county scales, such as USFS Forest Inventory and Analysis (FIA) databases and USDA National Resources Inventory (NRI) and National Agricultural Statistics Service (NASS) databases. A complete list of the sources of spatial and other data used in this analysis can be found in Appendix A. The analysis incorporated information about current land use, potential changes in land use and the incremental carbon resulting from the change, opportunity costs, costs for site preparation and planting, annual maintenance costs, and measurement and verification costs. The analysis was performed in a geographic information system (GIS), allowing for a spatial representation of the results. All analyses were done at the county-level scale of resolution. The carbon supply for each carbon mitigation strategy was estimated for three time durations—10 years, 20 years and 40 years. Further details of the analysis are given in Walker et al. (2007).

A series of steps were performed to assess the quantity of potential carbon sequestration (all reported in metric tonnes of CO_2e per hectare) and the associated costs from afforestation of agricultural lands as briefly described below.

2.1 Classification of lands within the region

The most recent land cover maps and associated data were obtained from the web sites of the relevant state agencies. The complete list of these agencies and data sources can be found in Walker et al. (2007). The land cover classification schemes were reclassified into four classes: forest, pasture land, cropland, and other. The cropland and pasture land categories are the focus of this analysis. The cropland category was created by aggregating the categories of small grains, row crops, and fallow lands. The pasture land category included pasture, hay, and other grasses.

2.2 Estimate available land areas in each category

The Northeast region is dominated by forest lands, which comprises more than 67% of total land area (Table 1). Croplands and pasture lands make up only 6 and 13%, respectively, of the total land area in the region. Delaware and Maryland have a greater percentage of cropland, with 38 and 28% of the total land area, respectively. Pasture land in Pennsylvania and New York are above the regional average at 22 and 19%, respectively. New Jersey does not provide a land cover dataset with pasture as a distinct category. The land use/land cover datasets provided by New Jersey combine cropland and pastureland into a single category. While it was possible to parse cropland out of the dataset using other categories in the dataset such as fallow fields and agricultural wetlands, it was not possible for pastureland (Table 1). Therefore, that category was excluded from analysis in New Jersey.

2.3 Estimate the quantity of potential carbon sequestration

The 1997 USDA NRI database was used to determine which forest type was most likely to exist in each county if land were afforested. Changes in afforestation from 1982 to 1997 were examined to determine the dominant species for new establishments in each county. Carbon sequestration potential was estimated by developing potential growth curves using the compiled USDA Forest Service FIA database (Smith et al. 2003, updated 2005). This information was then combined with the spatial database of available lands to estimate the potential amount of CO_2e sequestered per county. This analysis estimated the increase in live tree carbon stocks in above and below ground biomass resulting from afforestation. Afforestation of cropland would most likely lead to an increase in soil carbon levels; however this carbon pool was not included in the analysis. Also not incorporated in this analysis were the emission reductions associated with reducing agricultural equipment usage or the additional emissions resulting from land preparation and monitoring the land over time.

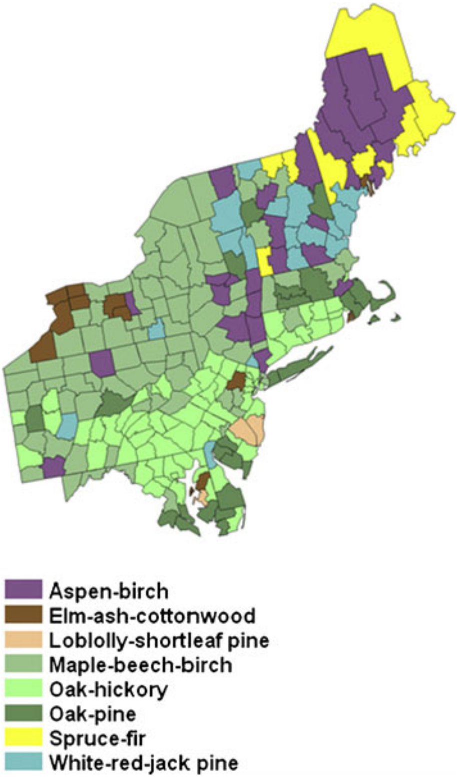
From the NRI database, sample points that moved from non-forest to a forest type between the 1987 and 1997 database years (and associated expansion factors) were extracted and summed for each county. This resulted in an estimated area of land per county that moved from non-forest to a particular forest type. The forest type with the greatest increase in area in each county was then assigned to that county (Fig. 1). Most of the region's newly developed forests were deciduous forest types. Coniferous forests were only assigned to counties in the most northerly states in the region.

Using FIA data, volume yields were estimated for eight forest types and four site productivity classes (high, medium high, medium-low, and low) for the 11 states in the region. From these data, functions were developed to estimate potential growing stock volume per hectare of forest land. Volume to biomass expansion equations were then used to expand growing stock volume estimates to biomass carbon (Smith et al. 2003, updated 2005). By using these equations, both above ground and below ground live tree biomass were estimated (Fig. 2).

Table 1 Area of major land classes in each state of the region

	Total area	Pastureland		Cropland		Forest		Other	
	(ha)	(ha)	(%)	(ha)	(%)	(ha)	(%)	(ha)	(%)
Connecticut	1,288,912	109,585	8.5%	44,892	3.5%	822,934	63.8%	309,737	24.0%
Delaware	532,130	1,483	0.3%	203,565	38.3%	77,715	14.6%	250,865	47.1%
Maine	8,329,748	403,914	4.8%	86,479	1.0%	7,250,693	87.0%	571,569	6.9%
Maryland	2,522,615	88,978	3.5%	716,437	28.4%	1,043,347	41.4%	645,043	25.6%
Massachusetts	2,116,664	37,015	1.7%	90,060	4.3%	1,200,327	56.7%	793,203	37.5%
New Hampshire	2,398,169	89,382	3.7%	6,213	0.3%	1,891,001	78.9%	412,017	17.2%
New Jersey	1,944,424	–	–	33,827	1.7%	908,265	46.7%	1,022,799	52.6%
New York	12,577,284	2,437,036	19.4%	707,382	5.6%	8,247,897	65.6%	1,201,247	9.6%
Pennsylvania	11,748,134	2,641,700	22.5%	582,283	5.0%	7,774,332	66.2%	737,681	6.3%
Rhode Island	270,621	6,074	2.2%	10,236	3.8%	126,555	46.8%	127,462	47.1%
Vermont	2,487,200	124,683	5.0%	231,682	9.3%	1,788,201	71.9%	287,903	11.6%
Region	46,215,901	5,939,850	12.9%	2,713,056	5.9%	31,131,271	67.4%	6,359,531	13.8%

Fig. 1 Forest type assigned to afforestation activity of crop and pasture lands for each county



The FIA data were also used to determine which site class to assign to a given county. The number of FIA plots of each site class in each county was extracted from the FIA database and a mean site class per county was determined. Under this method, all counties were assigned to either the low or medium-low productivity classes, as no mean county site classes were shown to be in higher classes.

On average, there is the potential to sequester approximately 145 t CO_2e/ha through afforestation over 20 years (Table 2). The amount of potential carbon that could be sequestered through afforestation of croplands using existing forest types in any given county will be dependent on the amount of land available in the county, the site quality, and the growth rate of the dominant tree types. Counties with higher site quality and assigned a forest type with higher productivity will be able to sequester greater amounts of carbon within a specific time period.

2.4 Estimate the total economic costs associated with land use conversion

The economic analysis employs four categories of costs related to establishing carbon projects on agricultural land. These include opportunity, conversion, maintenance, and measuring and monitoring costs. Each cost category is briefly described below. In the economic analysis, we are interested in ascertaining the "price" a farmer would need to receive to take a parcel of land out of agriculture and put it in some carbon sequestering use (i.e. afforestation). That "price" must be equal to or greater than the return the farmer is currently receiving from the agricultural use of that land plus the associated costs incurred

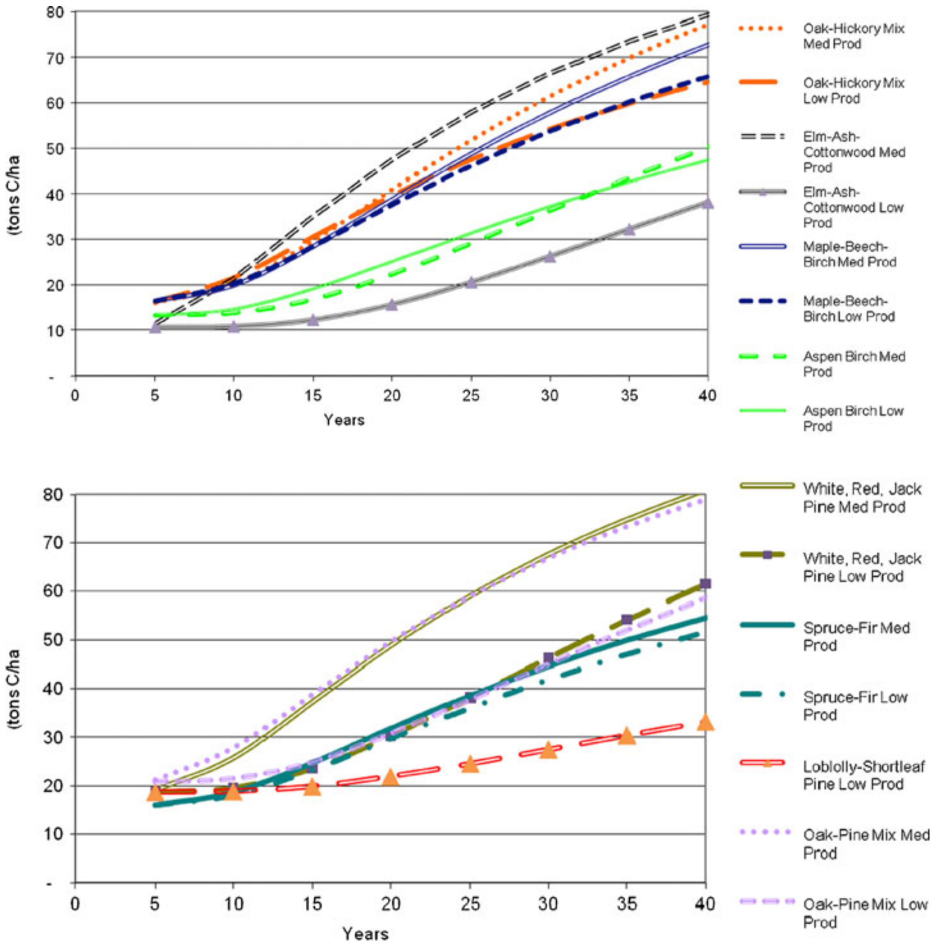


Fig. 2 Estimated carbon sequestration potential over time for medium and low productivity site classes

in producing certified carbon offset credits. Therefore, the "price" will have to be equal to or greater than the marginal return to the farmer from the parcel of land under consideration. The marginal return is the estimated revenue less the variable (i.e. input) costs for the agricultural enterprise in question. The marginal return to the farmer is equal to the opportunity cost, as this is the amount of profit (or loss) that the farmer would forego if the land was not in agricultural production. To the opportunity cost needs to be added the conversion, maintenance, and measuring & monitoring costs to estimate the total costs of the afforestation activity.

For interpreting this analysis, it is important to understand the difference between variable and fixed costs. Fixed costs (FC), also known as overhead costs, are those expenses that would continue to be incurred in the short-run, even if crops were not planted and/or production was zero. Examples of FC include property taxes and machinery ownership costs. By contrast, variable costs (VC) are those expenses that are a direct result of the production process. Examples of VC include fertilizer, herbicides, labor, and fuel. Fixed costs are not considered in this analysis for two important reasons. First, farmers

Table 2 County-area-weighted mean estimated potential CO_2e sequestration per area (t CO_2e/ha) through afforestation in each state

	10 years	20 years	40 years
Connecticut	76	152	277
Delaware	94	175	297
Maine	69	117	206
Maryland	76	132	226
Massachusetts	91	165	284
New Hampshire	84	147	264
New Jersey	79	135	234
New York	74	142	259
Pennsylvania	79	152	277
Rhode Island	69	132	254
Vermont	76	135	241
Region	79	145	254

would continue to incur land ownership and other fixed costs. Second, it is unlikely that a farmer would enroll all land in a carbon sequestration project, and instead would likely enroll only some fields or parcels. Fixed costs for the farm, therefore, would remain the same.

The most significant cost category in this analysis is the opportunity costs. The ultimate cost of producing carbon on agriculture land is going to differ from field to field and county to county, primarily based on the quality of the soil and growing conditions, which directly influences both agricultural yields (i.e. opportunity costs) and carbon yields (i.e. afforestation). Marginal returns per area of land can be calculated with the expression,

$$\mathrm{MR} = \mathrm{PY} - \mathrm{CY} + \mathrm{G} \tag{1}$$

where P is the price per unit for each commodity received by the farmer, Y is the expected yield of that crop, C is the variable cost of production per unit, and G is the amount of money received as government payments or subsidies for producing that crop.

For farmgate prices for corn, soybeans, and hay, estimates developed by the Food and Agriculture Policy Research Institute (FAPRI) were used (FAPRI 2005). The estimates are created for each commodity for each year through 2015. A mean of the estimates from 2006 to 2015 was used. These estimates are developed as national averages for the U.S. for all leading agricultural commodities. To tailor these estimates for each of the 11 states in the region, a historical price differential between the average U.S. price and the average state price from 1980 to 2005 was calculated and applied. The time-series data on average state farmgate prices was obtained from the USDA National Agricultural Statistics Service (NASS). The differential for each crop for each year was calculated and averaged across the 25 years. This average differential was used to adjust the national average price projections to be used for each state (Table 3).

The economic analysis methodology used here for estimating the opportunity costs of afforestation projects is based on widely available data on prices, costs, and yields of the major crops produced in each state in the region. This methodology was intentionally designed to be easily replicable across states. In doing so, some degree of local specificity regarding costs and prices of crop production were foregone, but the simplicity and replicability of this approach outweighs the small margins of error caused by using regional cost and price data.

Table 3 Estimated average national and state crop prices in U.S. dollars (2006–2015)

	Corn ($/bushel)	Soybeans ($/bushel)	Hay ($/ton)
National average	2.23	5.28	92.22
Connecticut	2.56	5.28	130.34
Delaware	2.54	5.33	123.47
Massachusetts	2.56	5.28	100.95
Maryland	2.55	5.32	122.22
Maine	2.56	5.28	128.74
New Hampshire	2.56	5.28	125.28
New Jersey	2.48	5.21	120.53
New York	2.56	4.94	98.80
Pennsylvania	2.64	5.24	116.05
Rhode Island	2.56	5.28	134.76
Vermont	2.56	5.28	107.82

Historical crop yield data are available at the county level from USDA-NASS. For the states where annual yield data were available (all excluding New England states), an average of yields from 2000 to 2004 was used. For the New England states, yields from the 2002 Census of Agriculture were used. The average yields for corn, soybeans, and hay are shown by state in Table 4. The variation in average yields at the county level created a significant amount of the variation in opportunity and total C costs within the states and across the region.

The VC of production for corn and soybeans are taken from estimates created by the USDA Economic Research Service (ERS) for the "Northern Crescent" region (USDA Economic Research Service, 2006). This region corresponds fairly well with the Northeastern states. Because ERS does not produce cost of production estimates for hay, this analysis has used estimates produced by Penn State University (Penn State University, 2005). The estimates of the variable cost of production are based on specific yield level per acre. To increase the accuracy of these estimates across the range of yields in this analysis, the VC estimates for each county were adjusted to reflect the average yield for each county.

Table 4 Average yields by major crop for each state

	Corn (bushels/ha)	Soybeans (bushels/ha)	Hay (tons/ha)
Connecticut	262.97	n/app	4.98
Delaware	328.98	85.22	5.97
Massachusetts	242.39	n/app	4.17
Maryland	315.82	89.31	6.43
Maine	263.60	n/app	4.98
New Hampshire	276.28	n/app	4.50
New Jersey	279.02	80.75	5.41
New York	282.09	83.03	5.49
Pennsylvania	279.83	97.10	5.87
Rhode Island	237.85	n/app	5.05
Vermont	235.99	n/app	4.88

It is important to note that not all VC fluctuate with yields (e.g. fuel usage is not generally related to yield). However, fertilizer is one of the larger segments of VC and fertilization rates are usually based on an expected yield for a given field or area. Therefore, for yields that are at least 10% different from the average, the VC was adjusted in the same direction by 5%. For yields that are more than 20% different, VC were adjusted by 10%.

Government subsidy payments to farms can, and often do, represent a sizeable portion of farm revenue, depending on the year. There are three primary payment mechanisms: direct, counter-cyclical, and loan deficiency payments. Each payment type has its own calculation formula. For each commodity there are specific price targets, payment levels, and caps. Using a series of calculations, each of these three payment mechanisms was factored into the marginal revenue estimates. More detail on these calculations can be found in Walker et al. (2007).

Using Eq. 1, the opportunity costs per unit area were calculated for the production of each commodity on representative cropland in each county of the 11 states of the region. The opportunity cost of producing corn will differ from the opportunity cost of producing soybeans. In practice, these crops will be grown on the same land in a rotation that often includes some years of alfalfa or other forage crop. The relative area in corn versus soybeans in any given county varies across counties and states. Soybeans are generally not produced in the New England states. Therefore, to calculate county-level and more accurate estimates of opportunity costs, this analysis employed a weighting of the opportunity costs for corn and soybeans within each county. This weighting was based on the average percentage of cropland in each county that was planted with corn relative to the percentage that was planted with soybeans. These percentage weights for each county were calculated as an average over 2000 through 2004 with data from USDA. However, as described above, annual data were not available for the New England states and data from the 2002 Census of Agriculture for each state were used in its place.

The opportunity costs of afforestation vary across the states and their counties. The average net present value of the opportunity cost on cropland in the region for a 10-year carbon offset project was $3,211 per hectare. This represents the foregone income over variable costs of production in each of 10 years, discounted into current dollars. For pasture land, the regional average for a 10-year project was $1,704 per hectare. The opportunity costs for pasture lands in Maine were much lower than the other states in the region, averaging less than $494 per hectare for a 10-year project. This reflects the low hay yields in Maine as reported in the NASS data base.

Conversion and maintenance costs are those associated with land preparation, planting, maintenance, and herbivory protection where needed. To estimate these 'conversion costs', a simple survey of tree planting costs was prepared and sent to regional foresters by state or other foresters and related specialists in the US Forest Service, universities, or forest companies in the 11 Northeast states. The largest variable in the conversion costs are herbivory protection and mechanical site preparation. The conversion and maintenance costs range from $1,080 to $3,366 per hectare. These costs are an initial one-time cost and therefore will be independent of the length of the project period.

Monitoring costs vary according to numerous factors. These include the size of the area being monitored, whether the total area is one large block or disaggregated into smaller parcels, the expected variation in the carbon stocks, the pools being monitored, and the frequency of monitoring. For this analysis, it was assumed a typical "project" would be 400 ha, in disaggregated parcels, with an expected coefficient of variation of the carbon stocks of 30%, monitoring only above and below biomass of the trees, and a monitoring event of every 5 years. Expert opinion, based on Winrock's experience of work on several afforestation projects, was used to estimate the monitoring costs. The net present value of the monitoring activities (assuming a net discount rate of 4%) was as follows: $50.90/ha for a 10-year project, $71.70/ha for a 20-year project, and $95.60/ha for a 40-year project.

Each of the cost categories described above have been incorporated into a total net present value analysis for afforestation of agricultural land across the region. The weighted annual opportunity cost for cropland and pastureland in each county was discounted over the life of the carbon project (10, 20, and 40 years). A real (i.e. adjusted for inflation) discount rate of 4% was used in the analysis. This present value opportunity cost represents the stream of annual marginal returns to the farmer, in current dollars, from crop or pasture production over the life of the carbon project. Discounting is used to account for the time-value of money as well as the uncertainty of future events related to agricultural production.

This estimated net present value cost could be viewed as the minimum price necessary to induce landowners to afforest agricultural land. However, the reduced risk associated with a carbon contract relative to the various risks inherent in agricultural production could make this cost estimate greater than the minimum amount necessary for more risk adverse land owners to pursue carbon projects. The area-weighted average total cost for a carbon offset project on pasture land is $3,903 per hectare for a 10-year project and $6,009 per hectare for a 40-year project. On cropland, these costs are $5,634 per hectare for a 10-year project and $10,218 per hectare for a 40-year project (Table 5). However, this varies across the region with costs generally lower in the northern states.

2.5 Estimating marginal cost curves

The final stage in the analysis was to combine the total costs associated with converting agricultural land to forests with the projected sequestered carbon from this land use

Table 5 Area weighted average total costs associated with conversion from cropland or pasture to forest land for each state

	Cropland - total costs			Pasture land - total costs		
	$/ha			$/ha		
	10 years	20 years	40 years	10 years	20 years	40 years
Connecticut	4,983	7,376	10,086	3,197	4,383	5,726
Delaware	4,551	6,684	9,099	3,612	5,109	6,804
Maine	4,486	6,653	9,106	1,557	1,711	1,878
Maryland	6,492	8,583	10,950	5,886	7,569	9,475
Massachusetts	5,219	7,772	10,662	3,386	4,701	6,189
New Hampshire	5,057	7,595	10,469	2,755	3,726	4,825
New Jersey	5,676	7,253	9,038	NA	NA	NA
New York	4,871	7,018	9,449	2,702	3,384	4,157
Pennsylvania	6,669	8,882	11,386	5,437	6,817	8,379
Rhode Island	4,456	6,492	8,798	3,743	5,298	7,059
Vermont	4,442	6,510	8,851	2,656	3,087	3,868
All States	5,634	7,784	10,218	3,903	4,888	6,009
Maximum	7,317	9,968	12,968	7,170	9,721	12,610
Minimum	2,520	3,374	4,341	393	420	879

action, resulting in \$ per ton of CO_2e. The supply curves are generated by plotting the quantity of CO_2e sequestered at different prices. The resulting marginal cost per ton CO_2e for afforestation of agricultural land can then be easily compared with other mitigation options.

3 Results

Costs per ton of CO_2e will vary depending on both the total project costs and the potential carbon sequestration capacity. Costs ranged from a minimum of \$39/ton CO_2e to a maximum of \$230/ton CO_2e for a 10-year project on cropland and range from \$15 to \$237/ ton CO_2e for pasture land (Table 6, Figs. 3 and 4). Areas with low cost per ton CO_2e are areas with both low total costs of land use change and rapid carbon sequestration rates. Due to higher opportunity and conversion costs, the southerly states in this northeast region tend to have higher costs per ton of CO_2e. For all counties, pasture land has lower costs per ton CO_2e because of the lower opportunity costs relative to cropland.

Afforestation of agricultural land in the region would not be economically attractive until the price exceeded \$10 per ton CO_2e, and even at this price it would only make sense to afforest pasture land (Fig. 5). The minimum price point that would induce land owners to undertake afforestation projects on cropland is \$36 per ton CO_2e. The steepness of the carbon supply curves for cropland (Fig. 5) indicates that large amounts of carbon sequestered through afforestation of agricultural land will not be likely until price points above \$75 per ton CO_2e are reached. This is especially true for 10- and 20-year projects. For longer time periods, the total maximum amount of CO_2e sequestered increases at all

Table 6 Area-weighted mean marginal cost in \$/ton CO_2e for each state for afforestation of cropland and pasture land. Minimum and maximum county values for the region are also shown

	Cropland			Pasture land		
	\$/ton CO_2e			\$/ton CO_2e		
	10 years	20 years	40 years	10 years	20 years	40 years
Connecticut	90	87	94	58	52	53
Delaware	69	68	75	54	51	56
Maine	93	100	110	35	27	24
Maryland	122	118	122	104	93	95
Massachusetts	84	85	94	54	51	54
New Hampshire	90	96	104	52	50	50
New Jersey	101	97	100			
New York	97	95	99	53	45	42
Pennsylvania	121	105	106	99	81	79
Rhode Island	98	100	102	80	78	79
Vermont	85	89	96	48	40	40
All States	105	101	105	73	61	58
Minimum	39	36	38	15	12	10
Maximum	230	248	227	237	257	236

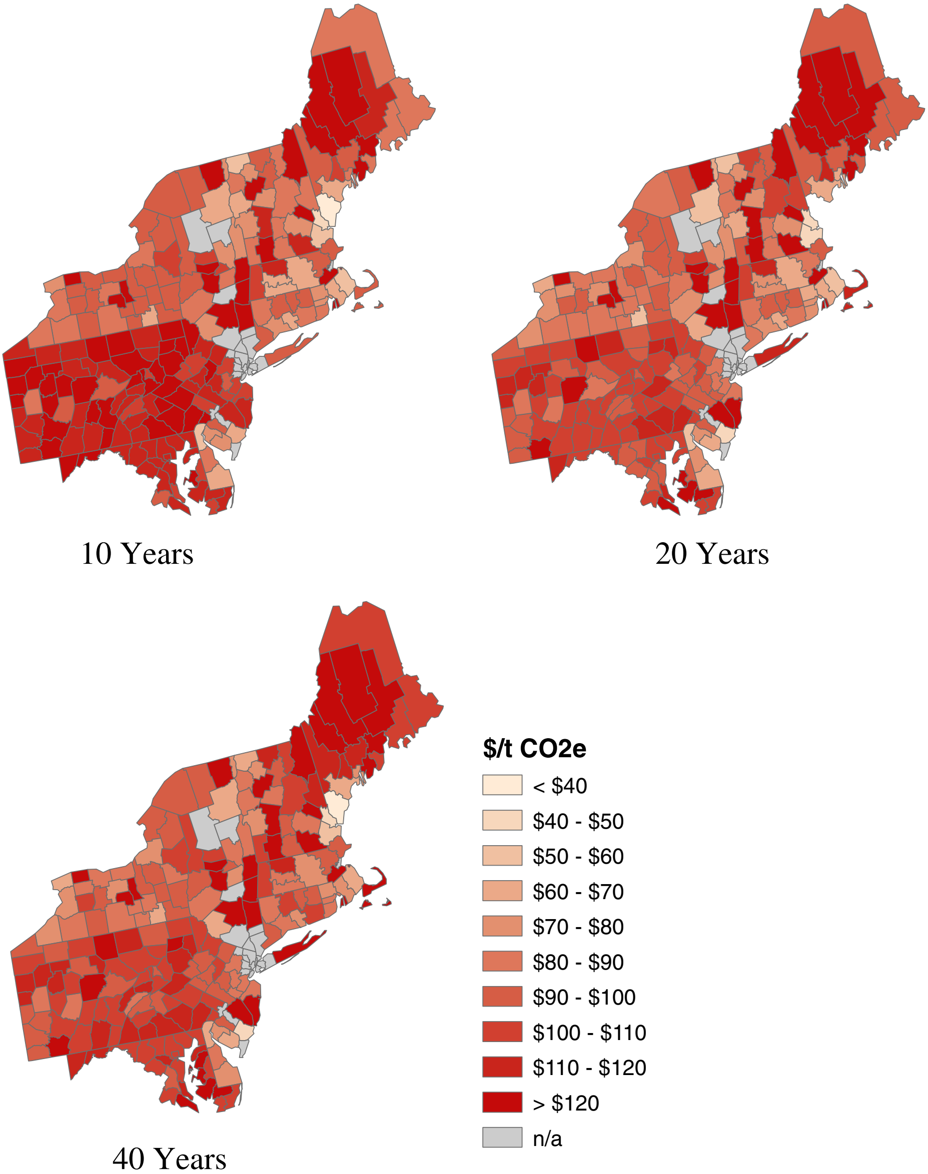


Fig. 3 Marginal costs of potential carbon supply on crop land areas for 10-, 20-, and 40-year projects

price points as trees accumulate carbon through time. Based on the lower opportunity costs of pasture land, the supply curves show much more carbon sequestration from afforestation projects at price points below $75 per ton CO_2e.

At prices below $50 per ton of CO_2e, very little cropland is available for afforestation-based sequestration (Table 7). At that same price point, up to 583 million tons of CO_2e could be sequestered on pasture land. If carbon prices were to reach even $7 per ton of CO_2e, it is estimated that up to 13.8 million tons of CO_2e could be sequestered on pasture lands in the region using 40-year projects. The amount of sequestration

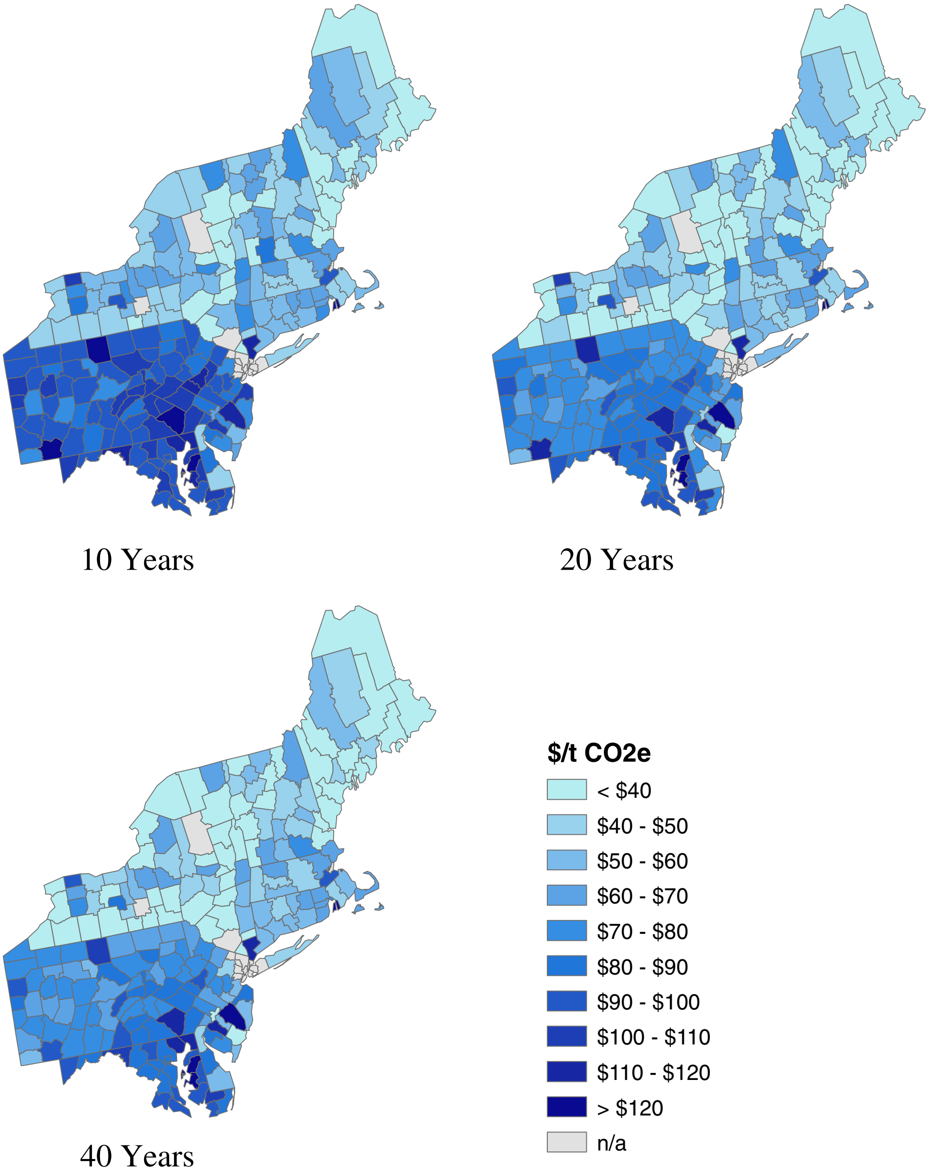


Fig. 4 Marginal costs of potential carbon supply for pasture land areas

resulting from 20-year projects could be up to 8 million tons. However, for 10-year projects this drops dramatically to only 141,000 t.

Counties in Maine, Vermont, and New York offer the best opportunities, with low marginal costs and large areas of pastureland available for afforestation (Fig. 4). The potentially best value for carbon credits from afforestation of agricultural land seems to be on pasture land in far northeastern Maine, where the marginal costs are estimated to be as low as $10 per ton of CO_2e.

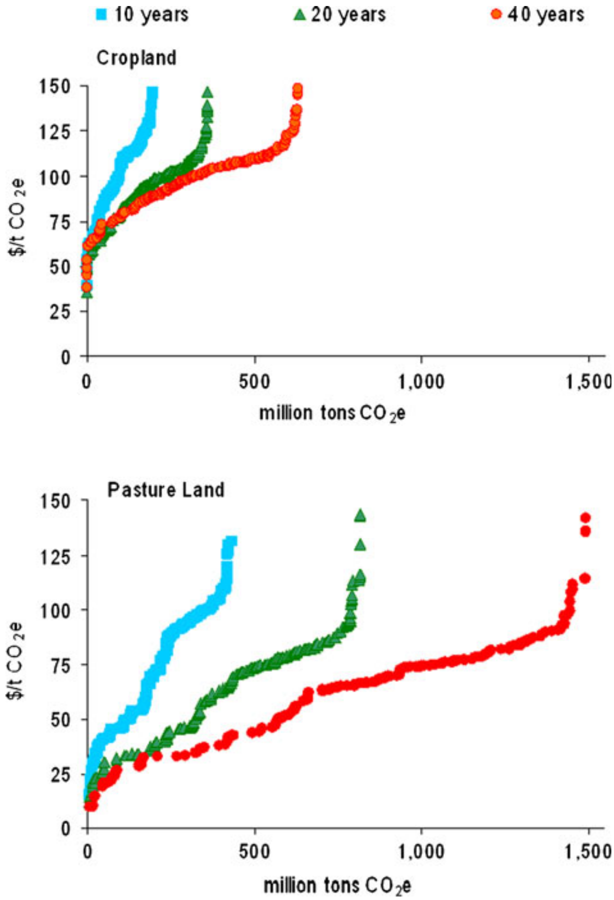


Fig. 5 Estimated carbon supply at various prices per ton of CO_2e for cropland and pasture land

The range of results found in this study is generally consistent with results from previous studies, which were generally in the range of $25-125 per ton CO_2e. Our study estimated the area-weighted marginal costs for each state in the region to be in the range of $30-100 per ton CO_2e. However, much greater variability is seen at the county level, where the range is from $10-237. By using county-specific soil and yield data, this paper provides estimates at a much finer geographic scale than has been done previously. As such, these

Table 7 Estimated total amount of CO_2e that could be sequestered by afforestation at various price points (in millions of tons CO_2e)

Price Point	Cropland			Pasture land		
	10 years	20 years	40 years	10 years	20 years	40 years
$7/t CO_2e	0	0	0	0.14	8.0	13.8
$10/t CO_2e	0	0	0	4.7	8.0	28.3
$20/t CO_2e	0	0	0	7.5	18.9	59
$40/t CO_2e	0.061	0.116	0.192	36.8	214	430
$50/t CO_2e	0.103	0.344	0.487	124	324	583

results could be used by entities interested in purchasing terrestrial carbon credits from the Northeast U.S. as a guide to help minimize costs.

4 Summary and conclusions

Widely available public datasets have been used to estimate spatially-explicit potential carbon sequestration and associated total costs related to afforestation projects on agricultural land in 11 states of the northeastern U.S. The combination of carbon sequestration potential and agricultural productivity of individual parcels are the primary drivers of the varying economic attractiveness of this type of project at lower carbon price points.

This type of analysis plays an important role in the process that potential purchasers of carbon credits will need to undertake. By scientifically identifying the specific areas where afforestation projects are likely to be more affordable and attractive, this analysis can help to steer purchasers toward the most likely suppliers of carbon credits from the agricultural community.

Pasture land is a more likely source of carbon credits from afforestation than is cropland in the Northeastern U.S. Marginal costs as low as \$10 per ton of CO_2e are estimated to be available from Northeastern Maine. This is due to the lower agricultural opportunity costs yet still good forest productivity with the appropriate species. The northern tier of the region, including Maine, New Hampshire, Vermont, and New York, has greater potential to produce these types of carbon credits than does the southern part of the region.

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Appendix A. Sources of spatial and other data used in this analysis

Sources of spatial data:

- Connecticut Department of Environmental Protection—*Land Use and Land Cover Mapping for the Connecticut and New York Portions of the Long Island Sound Watershed*. This is based on LANDSAT Thematic Mapper Satellite Imagery and SPOT Panchromatic Satellite Imagery for 1994 and 1995. The resolution is 30 m. The minimum mapping unit is 1 ha. There are 28 land use categories.
- Delaware Office of State Planning—*2002 Land Use and Land Cover Data.* Based on the 1997 land-use data of the State and 2002 false color infrared digital orthophotography at a scale of 1:2400.
- Maryland Department of Planning—*2002 Land Use/Land Cover for Maryland.* Developed using high altitude aerial photography and satellite imagery, land cover types were updated using 2002 aerial photography for Central Maryland. Urban land use categories were refined using parcel information.
- Massachusetts Executive Office of Environmental Affairs—*MassGIS Land Use 2002.* The dataset has 37 land use classifications interpreted from 1:25,000 aerial photography.

Coverage is complete statewide for 1971, 1985, and 1999. Additionally, more than half the state was interpreted from aerial photography flown during 1990, 1991, 1992, 1995 or 1997.

- Maine Office of Geographic Information System—*Land Cover and Wetlands of the Gulf of Maine*. Land cover from five interpretations of Landsat data, and wetland cover from photo-interpretations were combined to yield a 31-class raster coverage, for the Gulf of Maine watershed. The resolution is 30 m.
- University of New Hampshire, EOS-WEBSTER Earth Science Information Partner—*New Hampshire Land Cover Assessment—2001*. The New Hampshire Land Cover Assessment categorizes land cover and land use into 23 classes, based largely on the classification of Landsat imagery. The resolution is 30 m.
- New Jersey Department of Environmental Protection—*1995/97 Landuse/Landcover by Watershed Management Area*. Created by comparing the 1986 LU/LC layers from the NJDEP GIS database to the 1995/97 color infrared digital imagery, and delineating areas of change.
- Rhode Island Department of Administration—Statewide Planning Program—*1995 Land Use edition 2c*. Updated using 1995 USGS DOQs from a similar RIGIS Land Use data set generated in 1988 as the update vector base source.
- Vermont Center for Geographic Information—*LandLandcov_LCLU2002*. This dataset was derived by classifying independently three 2002 Landsat-7 ETM+ scenes, supplemented by ancillary data sources. The resolution is 30 m.
- USGS Seamless Data Distribution System, Earth Resources Observation and Science—*USGS National Land Cover Data (NLCD)*. NLCD 92 is a 21-category land cover classification scheme that has been applied consistently over the conterminous U.S. It is based primarily on Landsat 1992 imagery. Ancillary data sources included topography, census, agricultural statistics, soil characteristics, other land cover maps, and wetlands data. The resolution is 30 m.
- ESRI county and state datasets—Administrative polygons of state and county boundaries, originally created for the Digital Chart of the World. The Digital Chart of the World (DCW) is an Environmental Systems Research Institute, Inc. (ESRI) product originally developed for the US Defense Mapping Agency (DMA) using DMA data. We used the DCW 1993 version at 1:1,000,000 scale.

Sources of non-spatial data:

- US Forest Service Forest Inventory and Analysis (FIA) data
- Natural Resources Inventory (NRI)
- Volume to biomass equations from USDA Forest Service
- Harvested crop acres and yields by county for each state from USDA National Agricultural Statistics Service (NASS)
- Estimated future crop prices for 2006–2015 from the Food and Agriculture Policy Research Institute (FAPRI)
- Historical crop price data by state from USDA-NASS
- Cost of production data from USDA Economic Research Service (ERS)

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