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Effects of land use change on soil carbon cycling in the conterminous United States from 1900 to 2050

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[1] We developed matrices representing historical area transitions between forest and other land uses. We projected future transitions on the basis of historical transitions and econometric model results. These matrices were used to drive a model of changes in soil and forest floor carbon stocks. Our model predicted net carbon emission from 1900 until 1982, then sequestration until 2030, with little subsequent change. However, the northeast region showed substantial carbon sequestration from 1900 to the present. From 1990 to 2004, afforestation caused sequestration averaging 17 Tg C yr^{-1}: 6 Tg C yr^{-1} in soil and 11 Tg C yr^{-1} in forest floor. Deforestation caused emission averaging 12 Tg C yr^{-1}: 3 Tg C yr^{-1} from soil and 9 Tg C yr^{-1} from forest floor. However, these effects were only 5% of the total change in carbon stocks in all forestland.

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1. Introduction

[2] Increases in temperature and CO_2 in the atmosphere during recent decades have prompted widespread concern about how climate change may damage ecosystems, economies, and human health. Because of these concerns, many countries have joined international agreements to document and reduce emissions of CO_2 and other greenhouse gases. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was drafted, and eventually ratified by 150 countries including the USA. To comply with treaty commitments, many nations annually prepare an official inventory of greenhouse gas emissions and sinks. The 1990–2002 inventory of forest carbon estimates of the USA [*U.S. Environmental Protection Agency*, 2004] does not include past effects on the soil carbon pools, and only net changes from land use change are included in other pools. Other international agreements and discussions also have led to the need for explicit national estimates of carbon emissions and sinks for forest-related land use change, particularly afforestation and deforestation (changes from other land use into forest are termed "afforestation" and changes from forest to other land use are termed "deforestation").

[3] Land use change effects are important historically in the USA [*Caspersen et al.*, 2000; *Houghton and Hackler*, 2000; *Houghton et al.*, 2000; *Hurtt et al.*, 2002; *Pielke et al.*, 2002], although carbon changes in soil are substantially less than those in biomass [*Houghton and Hackler*, 2000]. We improve on these previous analyses in several ways. First, we use newly developed historical estimates of gross (two-way) changes in land use (historical refers to any time prior to the present). Use of gross rather than net land use transition data is important because afforestation causes a gradual gain in carbon stocks for many decades, while deforestation causes a much more rapid loss in carbon stocks. During any time period, some land is moving from one land use to another, for example from forest to plowed agriculture, although little land moves out of developed. At the same time, other lands are moving from plowed agriculture to forest. If only the net change in land use is used to model the effects of land use on carbon cycling, the different dynamics of afforestation and deforestation are not captured adequately. Secondly, we develop estimates that can be integrated with existing estimates of carbon cycling in the forest sector. Thirdly, we model effects of afforestation and deforestation on the forest floor including fine woody debris. These "pools" of carbon may not have been adequately addressed in previous analyses. Fourthly, we develop improved equations representing the effects of changes in land use on soil carbon mass based on data from the literature. Fifthly, we develop estimates of changes in forest floor carbon mass based on a recent model of forest floor carbon dynamics in the USA [*Smith and Heath*, 2002]. Sixthly, we develop estimates of future projected changes in carbon dynamics in the soil and forest floor from the present through the year 2050 based on our analyses and on existing econometric models of the forest sector. Such estimates could contribute to planning mitigation strategies based on projected future effects of land use change. Finally, we develop estimates of carbon emission and sequestration for the period from 1990 to the present. Such estimates could be used to improve greenhouse gas inventories produced to

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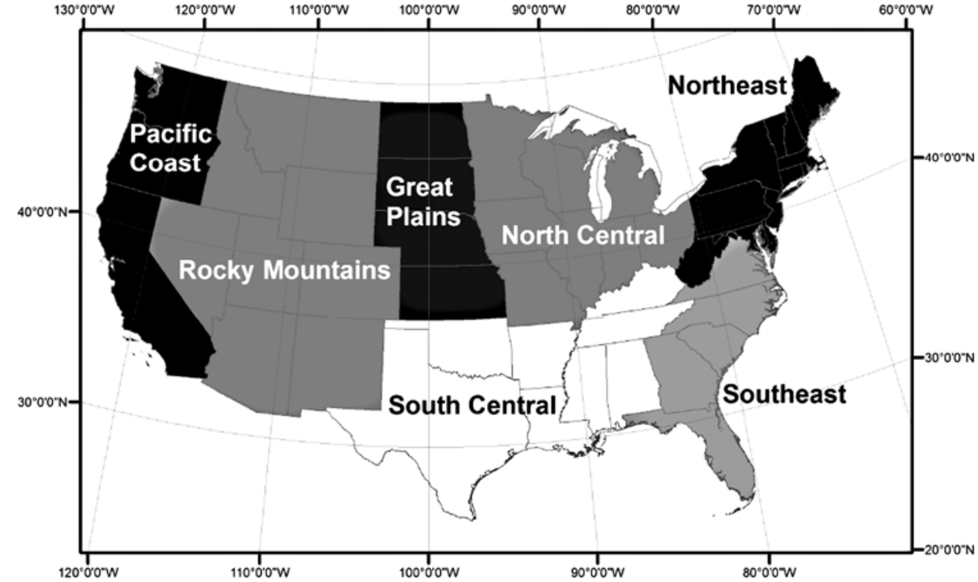

Figure 1. The seven regions used by the land use change model.

meet reporting requirements under the United Nations Framework Convention on Climate Change.

[4] The convention for the sign of carbon changes differs by discipline. We use the convention that emission of carbon to the atmosphere has a positive sign and carbon sequestration has a negative sign.

2. Methods

[5] Two types of information are required to develop estimates of how past and current land use changes alter soil and forest floor carbon pools: (1) historical data on the rates of transitions of land area among land uses such as undisturbed forest, highly managed forest, plowed agricultural land, and permanent grassland, and (2) estimates of the effects of specific land use transitions on carbon stocks. For historical land use transitions, data have recently been extracted and summarized from USDA Forest Service publications, USA Department of Commerce publications, USDA Natural Resources Conservation Service National Resources Inventory (NRI) reports and other sources [*Birdsey and Lewis*, 2003]. Historical data on the area of forestland in the USA have been summarized by *Smith et al.* [2001]. To model how such effects may continue into the future, projections of future land use transition rates are also required.

[6] For our model, the conterminous USA is broken into 7 regions as shown in Figure 1. Results for the Southern and Southeastern regions were presented previously [*Woodbury et al.*, 2006]. Herein, we present new estimates of land use changes throughout the entire conterminous USA and use them to estimate effects of land use change on soil and forest floor carbon pools from 1900 through 2050.

[7] The model estimates gross carbon changes in the forest floor and soil carbon pools in different forest types for each of 7 regions comprising the conterminous U.S (Figure 1). Estimates of other carbon pools, including live trees, understory, and down dead wood are already available, for example from the FORCARB model [*Heath et al.*, 2003].

[8] The types of land use change addressed by the model are illustrated with black arrows in Figure 2. For example, forestland can become deforested during the conversion to plowed cropland, while at the same time other plowed cropland can become afforested and become forest. Land use changes shown in dashed arrows are not addressed by the model, for example changes in soil carbon stocks with a transition from pasture to urban land. Likewise, effects of changes from one forest type to another are outside the scope of this study. For similar reasons, effects of changes in management intensity within a forest type are not included in the model.

[9] In the model, a transition matrix represents the area of land undergoing each type of transition for each forest type for each time period. To model this system, changes in forest floor carbon stocks and soil carbon stocks must be estimated separately for each type of land use change for each date; that is, for each cell in the transition matrix. Because soil and forest floor carbon stock estimates depend on the length of time since a land use transition, each transition is treated as a separate ‘‘cohort’’ and its carbon stock is tracked separately from other cohorts. Because the model predicts that some effects of land use transitions continue for decades, all such transition cohorts are tracked separately from the year of the land use transition until the end of the model run. Land use transitions are defined separately for each forest type group (see Table 7 in section 2.2 for a list of forest type groups). Land use transitions in each forest type are modeled as aggregate gross changes for the multistate regions shown in Figure 1. For both afforestation and deforestation, separate equations are used to predict changes in soil and forest floor carbon

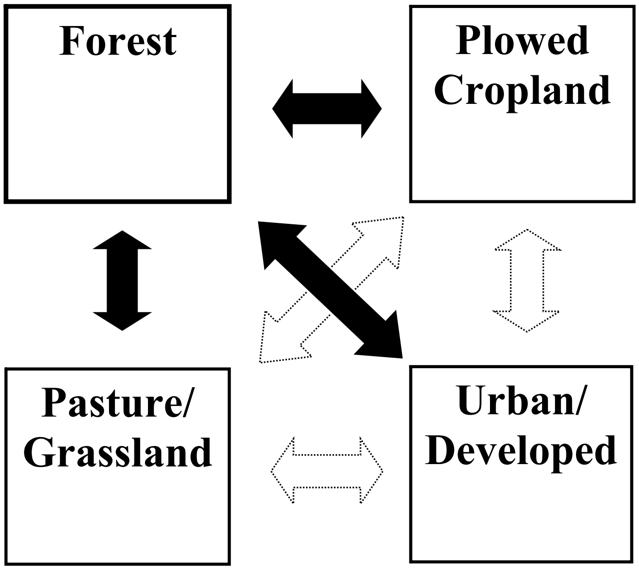

Figure 2. Transitions among different types of land use. Solid arrows show transitions included by the model. Other arrows show transitions not included in the model. The arrows have heads in both directions to indicate that transitions in each direction are included separately in the model.

stocks. Separate parameters for some of these equations are used for different forest types.

[10] The model is currently implemented as a series of worksheets and a macro written in Visual Basic for Applications within a Microsoft Excel workbook. The workbook contains all input data, all model parameters, and graphical and tabular summaries of model results. Land use transition data were developed to run the model between 1907 and 2050.

2.1. Historical and Future Changes in Forest Area

[11] For each region, the model uses two sets of inputs of areas undergoing transitions in land use, one for historical estimates and one for future estimates. The historical set covers the period from 1907 to 1997 and the future set covers 1997 to 2050. The "future" set includes years from 1998 onward because they must be estimated. Each set characterizes gross area change as a matrix of the area of land undergoing transitions between forests, cropland, pasture, and "other" land. There are separate estimates for transitions in each direction.

Table 1. Area of Forest Land by Region From 1907 to 1997: Conterminous USA[a]

	Period Ending in Year						
Region	1907	1938	1953	1963	1977	1987	1997
Southeast	37.24	35.27	37.62	38.34	36.60	35.84	35.88
South-Central	58.15	54.31	53.85	54.10	51.27	49.61	50.76
Northeast	24.12	29.22	30.92	33.02	33.67	34.51	34.60
North-Central	32.01	35.08	34.09	34.12	32.07	32.46	34.33
Great Plains	2.71	2.50	2.12	2.02	1.90	1.71	1.94
Rocky Mountains	57.43	56.22	55.18	54.86	52.63	54.80	56.03
Pacific Coast	42.49	41.39	39.12	38.98	37.69	37.40	36.49
Total	**254.2**	**254.0**	**252.9**	**255.4**	**245.8**	**246.3**	**250.0**

[a] Based on work of *Smith et al.* [2001]; area given in million hectares.

Table 2. Historical Area Afforested by Region From 1907 to 1997: Conterminous USA[a]

	Period Ending in Year						
Region	1907	1938	1953	1963	1977	1987	1997
Southeast		2.26	4.44	2.12	0.90	0.93	1.61
South-Central		1.51	3.19	3.27	2.23	1.44	2.47
Northeast		5.28	2.54	3.58	2.18	1.26	1.34
North-Central		3.27	0.84	1.00	0.89	1.10	2.39
Great Plains		0.44	0.36	0.35	0.12	0.05	0.27
Rocky Mountains		0.27	0.28	1.23	0.90	1.22	1.68
Pacific Coast		1.09	0.13	0.46	0.05	0.15	0.36
Total	**0.00**	**14.12**	**11.78**	**12.00**	**7.28**	**6.14**	**10.13**

[a] Derived from work of *Birdsey and Lewis* [2003] and *Smith et al.* [2001] as described in the text; area given in million hectares.

[12] The historical set contains estimates of deforestation and afforestation by forest type group for each time period ending in the following years: 1907, 1938, 1953, 1963, 1977, 1987, and 1997. These data are a modification of estimates developed by *Birdsey and Lewis* [2003]. Modifications were made such that the sum of afforestation and deforestation rates for each time period would match the total historical forest areas for the subsequent time period as reported by *Smith et al.* [2001]. The historical forest area, afforestation, deforestation, and estimates are presented in Tables 1, 2, and 3. In these tables, transitions are presented under the year at the end of a period. For example, transitions that occurred between 1987 and 1997 are listed under the heading "1997". In the model, however, it is assumed that transitions occurred at the midpoint of each period. It would be more realistic to spread the transitions among all of the years within a period. However, the model must keep track of the effects of land use for each forest type for each land use for each transition that occurs for all subsequent years until the end of the model run. Therefore the number of separate "cohorts" that must be tracked is reduced by more than an order of magnitude when the assumption is made that all land use changes occurred during a single year of the period.

Table 3. Historical Area Deforested by Region From 1907 to 1997: Conterminous USA[a]

	Period Ending in Year						
Region	1907	1938	1953	1963	1977	1987	1997
Southeast		4.25	2.07	1.40	2.63	1.70	1.57
South-Central		5.35	3.66	3.02	5.11	3.05	1.32
Northeast		0.17	0.78	1.54	1.11	0.85	1.26
North-Central		0.20	1.82	1.03	2.64	0.95	0.52
Great Plains		0.66	0.75	0.51	0.25	0.16	0.04
Rocky Mountains		1.40	1.39	1.55	1.69	0.50	0.45
Pacific Coast		1.82	2.76	0.59	1.34	1.15	0.58
Total	**0.00**	**13.85**	**13.23**	**9.64**	**14.76**	**8.37**	**5.74**

[a] Derived from work of *Birdsey and Lewis* [2003] and *Smith et al.* [2001] as described in the text; area given in million hectares.

Table 4. Area of Forest Land by Region From 2000 to 2050: Conterminous USA[a]

	Period Ending in Year					
Region	2000	2010	2020	2030	2040	2050
Southeast	35.80	35.42	35.09	34.65	34.34	33.97
South-Central	50.78	50.88	51.00	51.07	51.18	51.27
Northeast	34.77	34.83	34.76	34.35	33.76	33.37
North-Central	34.95	35.23	34.85	34.32	33.84	33.25
Great Plains	2.00	2.06	1.98	1.90	1.82	1.74
Rocky Mountains	55.97	56.15	56.14	56.05	55.91	55.70
Pacific Coast	36.61	36.26	35.80	35.24	34.79	34.34
TOTAL	**250.9**	**250.8**	**249.6**	**247.6**	**245.6**	**243.6**

[a] Area given in million hectares.

Table 6. Area Deforested by Region From 2000 to 2050: Conterminous USA[a]

	Period Ending in Year					
Region	2000	2010	2020	2030	2040	2050
Southeast	0.35	1.27	1.23	1.33	1.20	1.27
South-Central	0.39	1.29	1.29	1.29	1.29	1.29
Northeast	0.11	0.38	0.45	0.78	0.97	0.76
North-Central	0.12	0.41	0.78	0.93	0.89	1.00
Great Plains	0.01	0.02	0.10	0.10	0.10	0.10
Rocky Mountains	0.20	0.45	0.45	0.54	0.59	0.65
Pacific Coast	0.08	0.62	0.73	0.83	0.72	0.72
Total	**1.25**	**4.44**	**5.04**	**5.81**	**5.77**	**5.80**

[a] Area given in million hectares.

[13] The current and future input set contains estimates of area change for each time period ending in the following years: 1997, 2000, 2010, 2020, 2030, 2040, and 2050. We developed this set on the basis of extrapolation of transition rates from 1987 to 1997 into the future, along with projections of forest area by type from the ATLAS model [*Mills and Zhou*, 2003], based on the econometric net area change models developed by *Alig et al.* [2003]. To develop estimates of future gross rates of afforestation and deforestation within each region after 1997, first a "base" or minimum rate for both afforestation and deforestation was set equal to the minimum of either the afforestation or deforestation rate for each forest type from 1987 to 1997 from the historical set described above (Tables 2 and 3). Then an additional amount of either afforestation or deforestation was added depending on whether the total area of a forest type was predicted to increase or decrease for that time period, on the basis of estimates developed for the ATLAS model [*Mills and Zhou*, 2003; *Alig et al.*, 2003]. This additional amount was added to afforestation if the total area of a forest type increased or to deforestation if the total forest area decreased.

[14] Because the ATLAS model uses forest types that are more aggregated than those of our model, the types were disaggregated for all years on the basis of the areas of each forest type in 1997. The ATLAS model covers only privately owned timberland (productive accessible forest available for harvesting). Area of public forest and forest areas not defined as timberland for 1997 were added to the set based upon the area of such land reported by *Smith et al.* [2001]. These areas were assumed to remain constant from 1997 to 2050 [*Mills and Zhou*, 2003]. The current and future estimates of forest area, afforestation, and deforestation for each region are presented in Tables 4, 5, and 6.

Table 5. Area Afforested by Region From 2000 to 2050: Conterminous USA[a]

	Period Ending in Year					
Region	2000	2010	2020	2030	2040	2050
Southeast	0.27	0.89	0.89	0.89	0.89	0.89
South-Central	0.41	1.39	1.41	1.37	1.40	1.39
Northeast	0.29	0.44	0.38	0.38	0.38	0.38
North-Central	0.73	0.69	0.41	0.41	0.41	0.41
Great Plains	0.07	0.08	0.02	0.02	0.02	0.02
Rocky Mountains	0.13	0.63	0.45	0.45	0.45	0.45
Pacific Coast	0.20	0.27	0.27	0.27	0.27	0.27
Total	**2.10**	**4.39**	**3.83**	**3.79**	**3.82**	**3.80**

[a] Area given in million hectares.

[15] It should be noted that in addition to afforestation and deforestation, forests of one type can change into forests of another type. Such "type change" does not change the total forest area, but does change the area of individual forest types. Because of such type change, the cumulative sum of afforestation and deforestation rates is not usually equal to the area in each forest type. Instead, this difference represents the net changes among forest types that occurred for each forest type. Thus we are not accounting for gross area changes among forest types. Harvesting of land that remains in forest may also alter forest floor and possibly soil carbon stocks. However, because we expect such changes to be transient and minor in comparison to effects of deforestation, we have not included them in our model.

[16] The following are key model assumptions.

[17] 1. The model estimates the average change for each broad forest type group within a large region (Figure 1). For example, all land in the loblolly pine/shortleaf pine type group within the Southeast region that is deforested to cropland is estimated to lose the same amount of soil and forest floor carbon, respectively, over time.

[18] 2. Prior to deforestation, the soil and forest floor have the maximum possible soil carbon density for a given forest type.

[19] 3. Prior to afforestation, the soil and forest floor have lost the maximum possible amount of carbon.

[20] 4. When land is afforested, it is assumed that the same forest type was present prior to deforestation.

[21] 5. There is no change in soil and forest floor carbon due to transitions between plantations and naturally regenerated stands of the same forest type.

[22] 6. Carbon lost from both forest soil and forest floor is emitted to the atmosphere. For example, no carbon is assumed to be stored in sediments.

[23] 7. There is no change in soil carbon due to transition from forest to pasture or developed land, but there is loss of forest floor carbon.

Table 7. Soil and Forest Floor Carbon Parameter Values for Each Forest Type Group

Forest Type Group	Regions	Soil Maximum C Mass to 1 m Depth[a]	Forest Floor Parameters[b]			
			A	B	C	D
White-red-jack pine	SE, SC	196	20.4	27.1	12.2	3.8
	GP, NC, NE	196	19.1	25.6	13.8	8.4
Eastern spruce-fir	SE, SC	193	20.4	27.1	12.2	3.8
	GP, NC, NE	193	62.9	57.8	33.7	8.4
Longleaf-slash pine (planted)	SE, SC	136	20.4	27.1	12.2	3.8
	GP, NC, NE	136	19.1	25.6	13.8	8.4
Longleaf-slash pine (natural)	SE, SC	136	20.4	27.1	12.2	3.8
	GP, NC, NE	136	19.1	25.6	13.8	8.4
Loblolly-shortleaf pine (planted)	SE, SC	92	20.4	27.1	12.2	3.8
	GP, NC, NE	92	19.1	25.6	13.8	8.4
Loblolly-shortleaf pine (natural)	SE, SC	92	20.4	27.1	12.2	3.8
	GP, NC, NE	92	19.1	25.6	13.8	8.4
Oak-pine	SE, SC	82	15.4	20.1	10.3	3.8
	GP, NC, NE	82	65	79.5	29.7	8.4
Oak-hickory	SE, SC	85	15.3	61.8	6.0	3.2
	GP, NC, NE	85	24.9	134.2	8.2	9.2
Oak-gum-cypress	SE, SC	152	15.3	61.8	6.0	3.2
	GP, NC, NE	152	24.9	134.2	8.2	9.2
Elm-ash-cottonwood	SE, SC	118	15.3	61.8	6.0	3.2
	GP, NC, NE	118	24.9	134.2	8.2	9.2
Maple-beech-birch	SE, SC	140	15.3	61.8	6.0	3.2
	GP, NC, NE	140	50.4	54.7	27.7	9.2
Aspen-birch	SE, SC	237	15.3	61.8	6.0	3.2
	GP, NC, NE	237	18.4	53.7	10.2	9.2
Eastern other forest types	SE, SC	100	15.3	61.8	6.0	3.2
	GP, NC, NE	100	65	79.5	29.7	8.4
Eastern non-stocked	SE, SC	100	2.7	36.3	1.4	3.6
	GP, NC, NE	100	4.8	75.98	2.4	8.88
Douglas fir	PC, RM	90	53.6	47.0	37.2	24.1
Ponderosa pine	PC, RM	70	43.9	87.3	24.1	24.1
Western white pine	PC, RM	68	43.9	87.3	24.1	24.1
Western fir-spruce	PC, RM	138	53.6	47.0	37.2	24.1
Hemlock-sitka Spruce	PC, RM	157	53.6	47.0	37.2	24.1
Larch	PC, RM	66	53.6	47.0	37.2	24.1
Lodgepole pine	PC, RM	63	43.9	87.3	24.1	24.1
Redwood	PC, RM	86	92.6	52.1	62.2	24.1
Other hardwoods	PC, RM	80	50.1	62.0	31.7	19.8
Pinyon-juniper	PC, RM	56	43.9	87.3	21.1	24.1
Chaparral	PC, RM	59	17.3	67.1	8.7	23.2
Western other forest types	PC, RM	90	53.6	47.0	37.2	24.1
Western nonstocked	PC, RM	100	17.3	67.1	8.7	23.2

[a] Based on work of *Johnson and Kern* [2003]; given in $t\ ha^{-1}$.
[b] Based on work of *Smith and Heath* [2002].

[24] 8. There is no change in soil or forest floor carbon due to transitions between forest types.

[25] 9. Disturbances such as fire are not included in the model except as they are captured by differences in average soil and forest floor carbon mass between land use types.

[26] 10. Changes in soil bulk density are not explicitly accounted for, but the parameter selected for the total change in soil carbon with deforestation implicitly accounts for higher bulk density in agricultural soils.

[27] 11. A change in land use between plowed agricultural land and forest will cause a change in soil and forest floor carbon.

2.2. Forest Floor Carbon Equations

[28] The forest floor is defined broadly as the organic layer above the mineral soil including woody debris smaller than 7.5 cm in diameter. We used equations from the FORCARB model to predict forest floor carbon mass changes in response to land use transitions. There are two equations – one for afforestation (equation (1)), and one for deforestation (equation (2)). There are separate parameters for these equations for different forest types (Table 7). The derivation of these equations and their parameters is given by *Smith and Heath* [2002]. The equation for afforestation was altered from that presented by *Smith and Heath* [2002] such that carbon does not accumulate above a maximum value for each forest type, set as the beginning value following harvest.

[29] Change in forest floor carbon mass due to afforestation (Mg ha^{-1}), FF_a, is given as

$$\mathrm{FF_a} = \frac{-1 \times A \times t}{B + t} \text{ up to a limit of}: C, \tag{1}$$

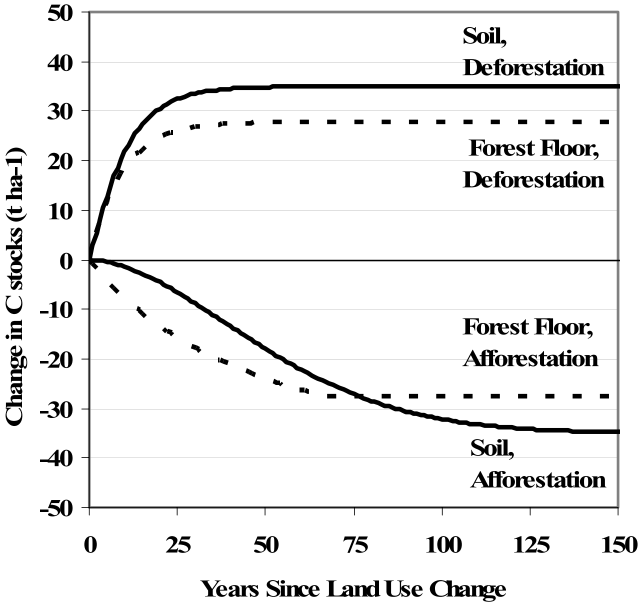

Figure 3. Example of afforestation and deforestation effects on carbon in the soil and forest floor of the maple-beech-birch forest type in the Northeast region. The equations for forest floor are based on those of *Smith and Heath* [2002], modified not to exceed average forest floor C accumulation.

where A = parameter (for values of parameters for each forest type, see Table 7), B = second afforestation parameter, and C = parameter representing the maximum carbon emission (Mg ha^{-1}).

[30] Change in forest floor carbon mass due to deforestation (Mg ha^{-1}), FF$_d$, is given as

$$\mathrm{FF_d} = C - C \times \mathrm{e}^{-\frac{t}{D}}, \qquad (2)$$

where C = parameter representing the maximum carbon emission (Mg ha^{-1}), D = parameter representing the rate of carbon emission over time, and t = time since land use change (years).

[31] Note that for deforestation, nearly all of the change in carbon occurs within the first 20 years, but for afforestation, changes in carbon occur for approximately 60 years.

2.3. Soil Carbon

[32] We chose a negative exponential equation to describe soil carbon after deforestation, the same type of equation used to describe deforestation effects on forest floor carbon. Parameters were set on the basis of data from the literature. For the proportion of soil carbon lost after deforestation from temperate forests to cropland we chose a parameter value of 25% loss to 1 m depth. This value is (1) close to the mean calculated for USA and Canadian data (weighted by study) derived from data summarized by *Murty et al.* [2002], (2) close to the global value accounting for bulk density by *Murty et al.* [2002], (3) is the midpoint from *Post* [2003] based on *Post and Kwon* [2000], and (4) is essentially the same as that used by *Houghton and Hackler* [2000, 2001] (but note that they use a higher average soil carbon value so that their predicted change is greater).

[33] The forest floor deforestation equation (equation (2)) includes a parameter representing the average carbon emission rate for each forest type throughout its range (Table 7). Because the same factors affect carbon emission from soil, the same parameter for each forest type was used for the rate of carbon loss from soil as a proportion of the maximum carbon loss due to deforestation. However, because data from the literature suggest that soil carbon decomposes more slowly than forest floor carbon [*Woodbury et al.*, 2006], an adjustment factor was applied to represent this difference. This adjustment factor was defined as an additional negative exponential equation shown in equation (3). Adjustment factor to represent slower emission of soil carbon compared to forest floor carbon after deforestation, AF, is given as

$$\mathrm{AF} = n + s \times \left(1 - \mathrm{e}^{-\frac{t}{r}}\right), \qquad (3)$$

where n = minimum adjustment factor = 0.74, s = maximum additional adjustment factor (with n summing to 1) = 0.26, r = shape parameter = 7, and t = Time since land use change (years).

[34] Equations (1) and (3) are combined to calculate the emission of carbon after deforestation as shown in equation (4). Change in soil carbon mass after deforestation (Mg ha^{-1}), SC$_d$, is given as

$$\mathrm{SC_d} = \left(1 - e^{\frac{-t}{D}}\right) \times \left[n + s \times \left(1 - e^{\frac{-t}{r}}\right)\right] \times E \times F/100, \qquad (4)$$

where D = parameter representing the rate of carbon emission over time, E = maximum soil carbon density (Mg ha^{-1}; see Table 7), and F = decrease in soil C mass due to cultivation (%), set to 25%.

2.4. Soil Carbon After Afforestation

[35] The change in soil carbon mass after afforestation is represented by a Weibull equation as shown in equation (5). This equation provides a better fit to these data (40% smaller sum of squared errors) than do the equations of *Houghton and Hackler* [2000, 2001] and *West et al.* [2004] [*Woodbury et al.*, 2006]. For equation (5), we also show an additional step: multiplying by the area afforested (for example, Table 2) to produce a total change in carbon mass for a region in units of teragrams (Tg). This same step also must be applied to equations (1), (2), and (4) to make regional estimates.

[36] Change in soil C mass after afforestation (Tg), SC$_a$, is given as

$$\mathrm{SC_a} = G \times -1 \times E \times \frac{F}{100} \times \left(1 - \mathrm{e}^{-\left(\frac{t}{H}\right)^{1.8}}\right), \qquad (5)$$

where G = area afforested (1,000 ha), H = time required to regain 2/3 of maximum soil carbon density (60 yr), and other parameters are as shown in previous equations. An

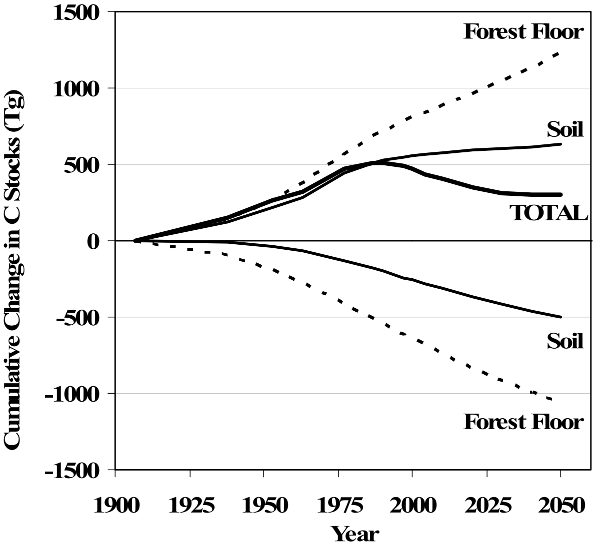

Figure 4a. Cumulative effect of land use change on forest floor and soil carbon from 1900 to 2050 for the conterminous USA, by type of transition and carbon pool (positive values are emission to the atmosphere, negative values are sequestration).

example of the above equations for the maple-beech-birch forest type in the Northeast region is shown in Figure 3.

3. Results

3.1. Cumulative Effects of Land Use Change

[37] Figure 4a shows the cumulative effects of afforestation and deforestation on soil and forest floor carbon pools from 1900 to 2050 for the conterminous USA. Figure 4b shows the same results on an annual basis for the years during which land use changes were modeled. Note that the changes in carbon pools begin at zero in 1907 because we are not including effects of land use change prior to 1907.

[38] Land use change caused net carbon emission from the soil and forest floor each year until the late 20th century, followed by net sequestration until the present. In the future, the model projects continued net sequestration early in the 21st century, followed by no net C flux after 2040. These modest net effects are the result of much larger gross effects of afforestation and deforestation.

[39] Over the entire period from 1900 to 2050, effects of land use change on forest floor carbon mass due to both afforestation and deforestation are greater than those on soil carbon mass. For afforestation, such effects are much greater at all times, but for deforestation, effects on the forest floor are only slightly greater in the first half of the 20th century, but increasingly greater from the latter half of the 20th century onward. Although changes in forest floor carbon mass are greater than changes in soil carbon mass, the change from net annual emission to net annual sequestration is due to the reduced rate of emission from soil after 1980, because changes in emission and sequestration of carbon from the forest floor change only very gradually during the latter half of the 20th century.

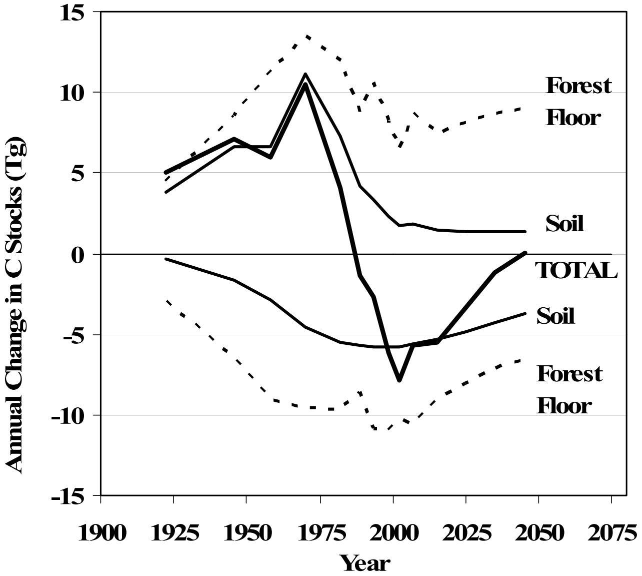

Figure 4b. Annual effect of land use change on forest floor and soil carbon from 1900 to 2050 for the conterminous USA, by type of transition and carbon pool (positive values are emission to the atmosphere, negative values are sequestration).

3.2. Cumulative Effects by Region

[40] Figure 5 shows the cumulative net effects of land use change on soil and forest floor carbon mass from 1900 to

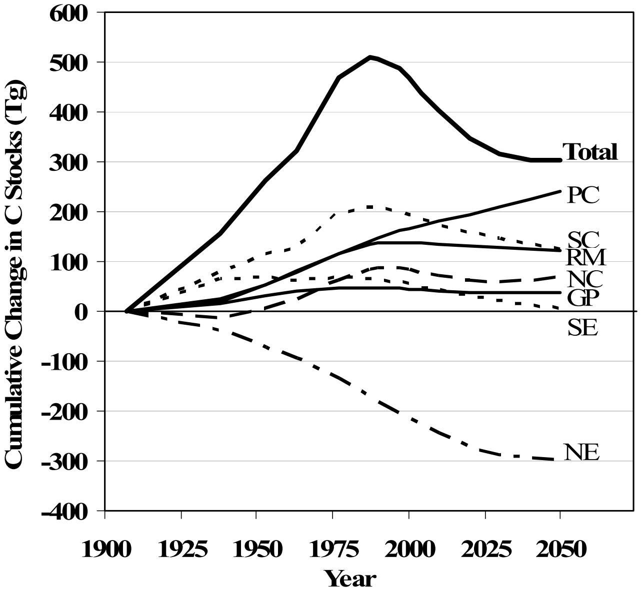

Figure 5. Cumulative effect of land use change on forest floor and soil carbon from 1900 to 2050 by region for the conterminous US (positive values are emission to the atmosphere, negative values are sequestration). Region abbreviations: PC, Pacific Coast; SC, South Central; RM, Rocky Mountain; NC, North Central; GP, Great Plains; SE, Southeast; NE, Northeast. See Figure 1 for region boundaries.

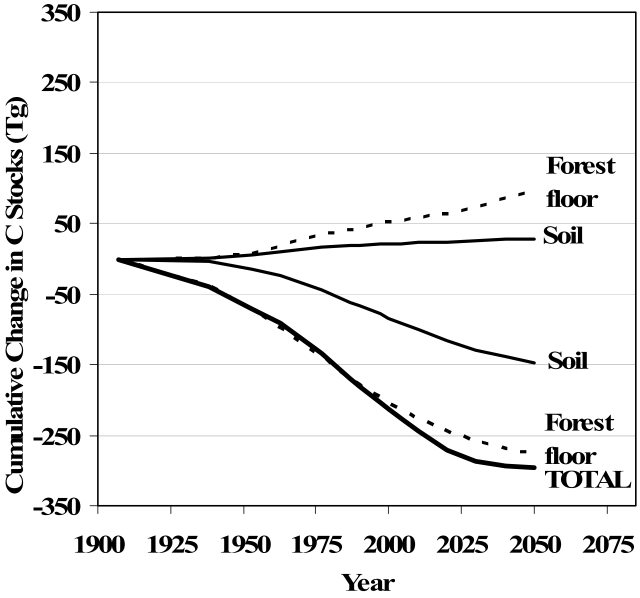

Figure 6. Cumulative effect of land use change on forest carbon from 1900 to 2050 for the Northeast region, by carbon pool (positive values are emission to the atmosphere; negative values are sequestration).

2050 for each of the 7 regions of the conterminous USA. The darkest line show the same total net change for all regions as shown in Figure 4a, although the vertical scale is different. With two exceptions (Northeast, Pacific Coast), the regions have generally similar patterns of net carbon change over time, with net loss of carbon prior to the 1980s and sequestration of carbon after that time. However, the rate of sequestration is predicted to decrease in the future.

[41] The pattern in the Northeast region is very different from all other regions, with a large, steady rate of carbon sequestration from 1900 to the present, and predicted continued sequestration through the 2030s. The cumulative effect of land use change in the Northeast is greater than for any other region. This effect occurs because there is carbon sequestration in the Northeast throughout the entire modeled period rather than the pattern observed in most other regions of net carbon loss for many decades followed by carbon sequestration. These results reflect the predominant afforestation of marginal agricultural land that took place during the 20th century (Tables 2 and 3). Afforestation rates were very high early in the 20th century, and decreased somewhat by the end of the century. Conversely, deforestation rates were very low early in the century, but increased so that by the 1990s they nearly matching the afforestation rate, resulting in little net change in forest area during the 1990s (Tables 2 and 3). Total forest area increased by 44% from 1900 to 2005 (Tables 1 and 4). For both afforestation and deforestation, effects of land use change on forest floor carbon mass were roughly double those on soil carbon mass. Because forest floor dynamics occur more quickly than those in the soil after a land use transition, cumulative effects on the forest floor also occur sooner for the region (Figure 6).

[42] The Pacific Coast has the opposite pattern as the Northeast: a steady loss of carbon from 1900 to 2050. Unlike most other regions, there was no net sequestration in the Pacific Coast during any period. This pattern is due to moderate rates of deforestation for most time periods along with very low rates of afforestation (Tables 2 and 3). Total forest area decreased by 14% from 1900 to 2005, a net loss of 6.1 million hectares (Tables 1 and 4).

[43] In the South-Central region, forest area decreased by 13% from 1900 to 2005 (Tables 1 and 4). Afforestation rates were lower than in the Southeast, Northeast and North-Central regions in the first half of the 20th century, but were similar to these other regions in the latter half of the century (Table 2). However, deforestation rates were higher in the South-Central region than in any other region throughout all of the 20th century except that they were slightly lower than those in the Southeast for the period ending in 1997 (Table 3). The North-Central region had net carbon sequestration prior to 1940 (Figure 4a). After 1940, the pattern of cumulative carbon flux from the soil and forest floor in the North-Central region is similar to that in the South-Central region, although the magnitude is smaller (Figure 4a). In the Southeast region net emission of C was lower than that in South-Central region from the 1930s to the 1980s, but subsequently was similar to that in the South-Central region.

[44] For the Rocky Mountain region, it is striking that there is virtually no sequestration in the soil due to afforestation, but there is substantial sequestration in the forest floor (Figure 7). This pattern occurs because afforestation is almost all from pastureland (data not shown). With the transition from pastureland to forest land, the model predicts no change in soil carbon mass, but a substantial increase in forest floor carbon mass. With deforestation, there is substantial loss of carbon from the soil, because more of the land transitions to cropland than to pasture (data not

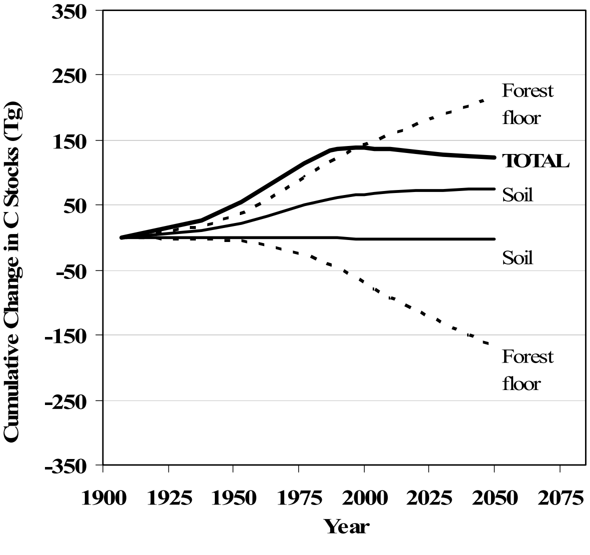

Figure 7. Cumulative effect of land use change on forest carbon from 1900 to 2050 for the Rocky Mountain region, by carbon pool (positive values are emission to the atmosphere; negative values are sequestration).

Table 8. Effects of Land Use Change by Region and Type Of Transition: 1990 to 2004[a]

Region	Soil, Afforestation	Soil, Deforestation	Forest Floor, Afforestation	Forest Floor, Deforestation	Total Net Change
Southeast	−25	7	−17	21	**−14**
South-Central	−22	6	−24	15	**−25**
Northeast	−25	3	−35	13	**−44**
North-Central	−4	10	−27	14	**−7**
Great Plains	−3	2	−5	2	**−4**
Rocky Mountains	−1	7	−32	26	**0**
Pacific Coast	−2	3	−10	34	**26**

[a] Given in Tg C.

shown). However, as for other regions, even for deforestation, the loss of carbon is greater from the forest floor than from the soil.

3.3. UNFCCC Reporting Period

[45] Many countries prepare annual inventories of greenhouse gas emissions and sequestration to meet commitments under the UNFCCC. Such inventories begin from a base year of 1990 and report annual changes until the present. The effects of land use change on soil and forest floor carbon stocks presented in this paper, along with similar estimates for other regions of the United States, could be used to improve estimates used in the USA greenhouse gas inventory [e.g., *U.S. Environmental Protection Agency*, 2004].

[46] From 1990 to 2004, afforestation caused sequestration averaging 17 Tg C yr^{-1}, of which 6 Tg C yr^{-1} was in the soil and 11 Tg C yr^{-1} was in the forest floor. During this same period, deforestation caused emission to the atmosphere of 12 Tg C, yr^{-1} of which 3 Tg C yr^{-1} was from the soil and 9 Tg C yr^{-1} was from the forest floor. Results for each region are shown in Table 8.

[47] However, the net effect of land use change on carbon mass in soil and forest floor from 1990 to 2004 was only 5% (4.9 Tg C, yr^{-1}) of the net change in all carbon stocks on all forestlands, including soil and forest floor, trees (87 Tg C, yr^{-1}) and coarse woody debris (14 Tg C, yr^{-1}). [*U.S. Environmental Protection Agency*, 2003, 2004]. Afforested area is 25% of current forest area (Tables 1 and 2); thus changes in tree carbon stocks and coarse woody debris also dominate carbon stock changes on afforested land. Thus change in the overall forest carbon budget during this period is dominated by changes in tree carbon stocks.

[48] Figure 8 shows the contribution of each historical land use transition period on carbon flux from soil and forest floor during 2004. As observed for the cumulative trends over time in Figure 4a, the magnitude of change in the forest floor is generally greater than that in the soil. Particularly in the soil, the relative influence of recent time periods is much greater for deforestation than for afforestation, because carbon is lost rapidly after deforestation, but is gained very slowly in the soil after deforestation (equations (4) and (5)). Because Figure 8 shows the actual effect of each prior land use transition, it represents a combination of the dynamics in equations (1)–(5) along with the effects of different amounts of land use transition in different periods in Tables 1–6. Figure 8 demonstrates that even the earliest time period from 1907 to 1938 does influence the prediction of carbon flux in 2004, highlighting the importance of including such early periods to make accurate predictions of current carbon fluxes, particularly for afforestation.

4. Discussion

4.1. Estimates of Area Change

[49] Land use change as a component of global change has received increasing attention in the United States during the past decade in relation to carbon cycling and other topics [*Sisk*, 1998], and a number of models of land use change have been developed [*Agarwal et al.*, 2002]. Effects of land use change on carbon cycling in the United States have been estimated previously using historical data on land use transitions along with either models of forest growth [*Houghton et al.*, 1999; *Houghton*, 2003; *Hurtt et al.*, 2002] or forest inventory data [*Heath et al.*, 2002].

[50] Our model improves upon earlier analyses by using new estimates of gross afforestation and deforestation rates from 1907 to 1997 based primarily on those developed by *Birdsey and Lewis* [2003]. These estimates incorporate information from many sources, particularly USDA Forest

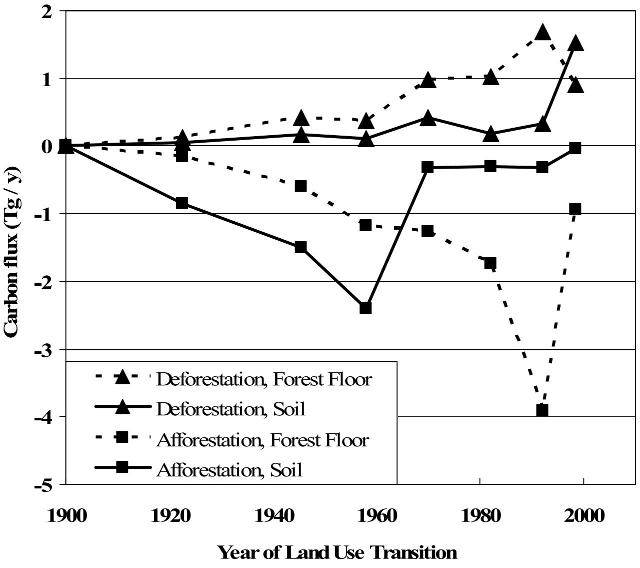

Figure 8. Contribution of each historical land use transition period on carbon flux from soil and forest floor during 2004.

Service databases and reports, the NRI database, and the Census of Agriculture. The USDA Forest Service reports and databases are the best single source of information about the area of forest in the conterminous United States, but historically they have not focused on quantifying specific land use transitions, such as from pasture to forest, or forest to plowed agricultural land. The NRI database does focus on these transitions, but it only began in 1982 and does not include Federally owned lands. Bringing together these and other data represents progress toward a more complete accounting of land use changes in the United States during the 20th century.

[51] It is challenging to harmonize different sources of historical information to develop comprehensive estimates of land use transitions, because different data sets are derived from different samples and use different definitions of land use. We adjusted the rates of afforestation and deforestation estimated by *Birdsey and Lewis* [2003] to match the total historical forest areas for each region reported by *Smith et al.* [2001]. These adjustments were made because we judged the report by *Smith et al.* [2001] to be the most comprehensive source of published information about forest areas throughout the 20th century. Although USDA Forest Service data are the best available for estimating historical forest areas, there is some uncertainty in the forest area estimates. Within the conterminous United States, the USDA Forest Service mandates that forest area data are accurate within 3% at the 67% confidence level (one standard error) per 405,000 ha of forestland [*Miles et al.*, 2001]. However, for larger areas, the uncertainty in area is concomitantly smaller, and the timberland areas in most regions of the conterminous USA are much larger (Table 1). It is difficult to quantify uncertainty for forest area estimates for the first half of the 20th century and uncertainties are likely larger than suggested by these more recent guidelines. Additionally, for all time periods, there is much more relative uncertainty in the estimated rate of area change than in the estimated total area because the change occurs on such a small proportion of the total forest area.

[52] Although there are uncertainties in the input data for the model, currently these data represent the best available compilation of gross land use changes for the conterminous United States. Other published land use transition estimates such as the report by *Alig et al.* [2003] present net changes in forest area rather than gross changes. Because the lag times in the response of forest soil and forest floor carbon are much faster for deforestation than for afforestation, carbon stocks change more rapidly following deforestation than following afforestation (equations (1)–(5)). Using only the net area change will not account for these dynamics and so will not provide as accurate estimates of land use change effects on soil and forest floor carbon stocks as will using gross area changes.

[53] As discussed in section 2, future rates of deforestation and afforestation were based on projections of historical rates and the net area change models developed by *Alig et al.* [2003]. These projections are based on a blend of historical forest inventory data and surveys of forestland managers to determine likely trajectories of land management trends and land use change in the future [*Alig and Butler*, 2004; *Alig et al.*, 2003; *Zhou et al.*, 2003].

[54] Because the rates of carbon gain in soils and the forest floor with afforestation are so much slower than the rates of carbon loss after deforestation, the gross data on transitions among land uses in our model makes a substantial difference in predictions of the effects of land use change on carbon flux in forests. For example, for the conterminous USA we project that from 2000 to 2010 there will be a net loss of 100,000 hectares of forestland (Table 4). However, we project that there will be net carbon sequestration of 12 Tg C in forest floor and soil during this same period (Figure 5). A projection based only on the net change in forest area during this period would project net emission of carbon rather than net sequestration. Such effects also can be seen in the influence of prior decades on current carbon fluxes as shown in Figure 8.

4.2. Scaling Soil Carbon Losses Due to Cultivation

[55] We assumed that all soil carbon lost owing to deforestation is emitted to the atmosphere. However, some soil carbon may move by mass flow during erosion events, and subsequently be buried in nearby low-lying areas or carried further downstream. Some of this soil carbon may be deposited in farm ponds, lakes and reservoirs, where it may be sequestered for many years or decades. Estimates of the proportion of soil carbon emitted to the atmosphere versus sequestered in sediments due to deforestation range from 0 to 100%, as reviewed by *Lal* [2003]. On a global basis, *Lal* [2003] assumes that 20% of eroded carbon may be emitted to the atmosphere. If we assume that 50% of the soil C lost owing to conversion of forestland to plowed agricultural land is due to erosion, and only 20% of this eroded carbon is emitted to the atmosphere, then the average loss of soil carbon with deforestation might be 15% instead of 25%. Therefore the predicted carbon emission and sequestration rates from our model due to afforestation and deforestation may be upper bound estimates due to uncertainty in soil carbon density values and the proportion of carbon emitted from eroded soils.

4.3. Comparison With Previous Estimates of Land Use Change Effects

[56] Land use change affects carbon stocks not only in the soil and forest floor, but also in trees and wood products. To develop a more complete accounting of land use change on USA carbon stocks, we have estimated land use change effects on carbon stocks in trees and understory vegetation, coarse woody debris, and wood products. For this purpose, we assume that at the national scale, net changes in tree carbon stocks are primarily due to effects of current and prior land use change including forest harvesting. We used forest inventory data from between 146,302 (1987) and 174,401 (2002) individual forest plots throughout the USA. Carbon stocks were estimated at the plot level, and then scaled up to individual states on the basis of the area represented by each plot. Data on the production of wood products and experimental data on carbon emission during decomposition were used to estimate carbon stocks and sequestration rates in wood products and landfills. The

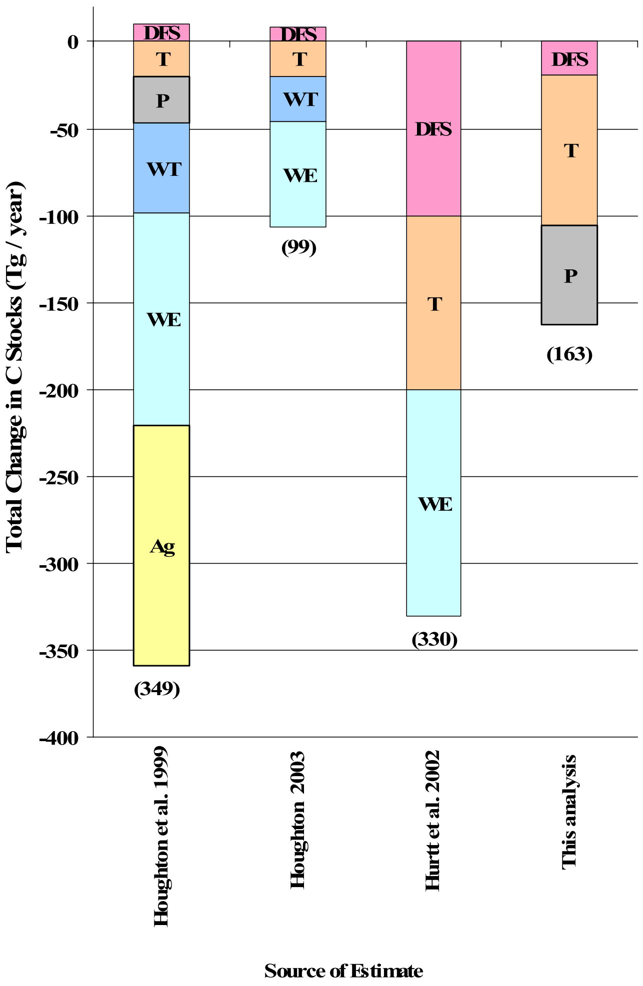

Figure 9. Comparison of our model with other published estimates of net effects of land use change on annual USA carbon flux during recent decades. Symbols are as follows: DFS (Coarse and fine woody debris, forest floor, and soil), P (Wood products), T (Tree and understory), WT (Woodland thickening), WE (Woody encroachment), Ag (Agricultural soil management). The total sum of all pools is displayed above the bars. Note that the Hurtt et al. 2001 analysis does not include wood products, and we have labeled their ''nonforest and pasture'' flux ''woody encroachment'' because they refer to woody encroachment as a major component of that flux.

methodology used to develop these estimates has been described previously [*U.S. Environmental Protection Agency*, 2003].

[57] Figure 9 compares our results to previously published estimates for the USA. To facilitate comparison with published studies only net effects are shown, and some pools such as soil, forest floor and coarse woody debris are combined. We estimate the net effect of land use change in the USA during the period from 1990 to the present to be sequestration of 163 Tg yr^{-1}, which is lower than two of 3 previously published estimates (Figure 9). Both the lowest and highest estimates shown are from Houghton and colleagues [*Houghton et al.*, 1999; *Houghton*, 2003]. The estimate with the most similar total effect to ours is the more recent estimate of *Houghton* [2003]. However, this similarity is unrelated, because most of their total estimate is due to woodland thickening and woody encroachment, while most of our total estimate is due to forest trees and wood products. Furthermore, our estimate of the net effect of land use change on soil, forest floor, and coarse woody debris is larger and opposite in sign to both estimates of *Houghton et al.* [1999] and *Houghton* [2003]. Our estimate of changes in tree carbon stocks is 87 Tg yr^{-1} compared to their estimate of only 20 Tg yr^{-1}. Our estimate of changes in tree carbon stocks is based on analysis of more than 146,000 plots measured as part of a statistically designed survey [*Smith et al.*, 2001] while those of Houghton and colleagues [*Houghton et al.*, 1999; *Houghton*, 2003] are based on applying a growth model to estimated net changes in forest area.

[58] The overall estimate of *Hurtt et al.* [2002] is 330 Tg yr^{-1}, which is more than double our estimate of 163 Tg yr^{-1}. On the basis of a growth model, they estimate changes in tree carbon stocks similar to our estimate, but they estimate even larger changes of 100 Tg yr^{-1} due to woody encroachment on nonforest land. Furthermore, their estimate of net change in soil, forest floor and woody debris is fivefold greater than ours. They do not include estimates of changes in wood products, nor changes due to agricultural soil management.

[59] A recent quantitative uncertainty analysis of changes in soil carbon stocks due to agricultural soil management estimated a range from 3 Tg yr^{-1} (emission) to -9 Tg yr^{-1} (sequestration), with a central estimate of -1.3 Tg yr^{-1} (sequestration [*Ogle et al.*, 2003]), which is much smaller than changes in most other carbon pools. On the basis of our results, effects of land use change during recent decades are dominated by changes in tree carbon stocks and storage of wood in wood products rather than soil, forest floor, or coarse woody debris. This result is important since changes in tree carbon stocks in the conterminous USA are measured with statistically based surveys, and thus should have greater certainty than estimates of changes in other carbon pools. The wide range of estimates for changes in carbon stocks due to woody encroachment indicate a need for more reliable data on this potentially important land use transition.

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