Land Use Change Effects on Forest Carbon Cycling Throughout the Southern United States

Peter B. Woodbury,* Linda S. Heath, and James E. Smith

ABSTRACT

We modeled the effects of afforestation and deforestation on carbon cycling in forest floor and soil from 1900 to 2050 throughout 13 states in the southern United States. The model uses historical data on gross (two-way) transitions between forest, pasture, plowed agriculture, and urban lands along with equations describing changes in carbon over many decades for each type of land use change. 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. In the South-Central region (Texas to Kentucky) land use changes caused a net emission of carbon before the 1980s, followed by a net sequestration of carbon subsequently. In the Southeast region (Florida to Virginia), there was net emission of carbon until the 1940s, again followed by net sequestration of carbon. These results could improve greenhouse gas inventories produced to meet reporting requirements under the United Nations Framework Convention on Climate Change. Specifically, from 1990 to 2004 for the entire 13-state study area, afforestation caused sequestration of 88 Tg C, and deforestation caused emission of 49 Tg C. However, the net effect of land use change on carbon stocks in soil and forest floor from 1990 to 2004 was about sixfold smaller than the net change in carbon stocks in trees on all forestland. Thus land use change effects and forest carbon cycling during this period are dominated by changes in tree carbon stocks.

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 United States. To comply with treaty commitments, many nations annually prepare an official inventory of greenhouse gas emissions and sinks. The current inventory of forest carbon estimates of the United States (USEPA, 2004) does not include past effects on the soil carbon pools, and only net changes in land use change are included. 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").

Land use change effects are important historically in the United States (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 (the term historical herein refers to any time before 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. 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 may not be captured adequately. Second, we develop estimates that can be integrated with existing estimates of carbon cycling in the forest sector. Third, we model effects of afforestation and deforestation on the forest floor and on small woody debris. These "pools" of carbon may not have been adequately addressed in previous analyses. Fourth, we develop improved equations representing the effects of changes in land use on soil and forest floor carbon mass based on data from the literature and a recent model of forest floor carbon dynamics in the United States (Smith and Heath, 2002). Fifth, 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 models of the forest sector. Such estimates are useful for planning purposes. 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 meet reporting requirements under the United Nations Framework Convention on Climate Change.

Two types of information are required to develop estimates of how past and current land use changes affect the soil and forest floor carbon pools: (i) 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 (ii) 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

USDA Forest Service-NE, P.O. Box 640, Durham, NH 03824. P.B. Woodbury, current address: Department of Crop and Soil Sciences, Cornell University, Ithaca, NY 14853. Received 26 Apr. 2006. *Corresponding author (pbw1@cornell.edu).

Published in J. Environ. Qual. 35:1348–1363 (2006).
Special Submissions
doi:10.2134/jeq2005.0148

677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: NRI, National Resources Inventory; UNFCCC, United Nations Framework Convention on Climate Change.

Forest Service publications, U.S. 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 United States 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.

In this paper, we present new estimates of gross land use changes and use them to estimate effects of land use change on soil and forest floor carbon pools for 13 states in the southern United States from 1900 through 2050. We describe the model, including the development of historical data sets, future estimates of land use change, and equations representing effects of specific land use transitions on soil and forest floor carbon stocks. For model development, we chose to focus on the 13-state southern region because it includes 29% of the total forest area and 40% of the timberland area of the conterminous United States and in 1996 provided 59% of U.S. timber harvest (Haynes, 2003). These percentages are expected to continue to 2050, despite a small decrease in forest and timberland area in the region (Alig et al., 2003). This area of the country has also undergone substantial land use change during the past century, and more changes are projected in coming decades. The analysis area is broken into two regions: South-Central and Southeast, as shown in Fig. 1. The model is applicable to other regions of the United States, and the methodology and equations are applicable to some other nations as well. Due to the lack of systematic databases of forest soil carbon densities and the concomitant variation in soil carbon estimates, a sensitivity analysis was conducted to determine how uncertainty in soil carbon estimates affects predictions of land use change effects on carbon cycling.

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.

MATERIALS AND METHODS

The model estimates gross carbon changes in the forest floor and soil carbon pools in different forest types for large regions of the United States (see Fig. 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).

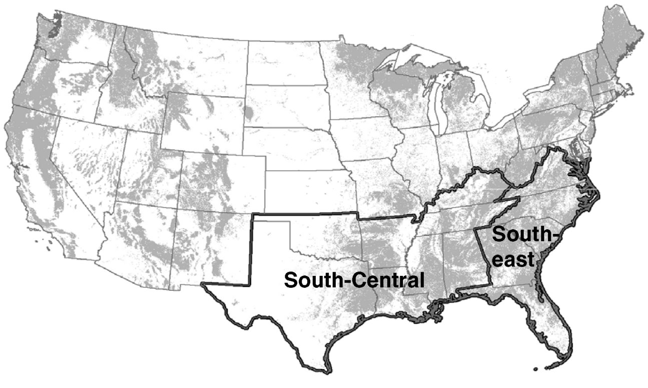

Fig. 1. The study region includes the eight-state South-Central and five-state Southeast regions of the United States. Gray shading shows forested areas (Smith et al., 2001).

In the model, we assume that specific land use changes cause characteristic changes in forest floor and soil carbon stocks, and each such change is represented by an equation. The model uses data describing land use transitions for each region for each of a number of time periods. The effects of each land use transition for each time period are modeled as a separate "cohort." For each cohort, the model equations predict how the carbon stocks in the soil and forest floor change over time after the transition. Model predictions for any time period of interest are calculated by summing all of the effects of each previous land use transition.

The types of land use change addressed by the model are illustrated with black arrows in Fig. 2. For example, forestland can become deforested 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. Additionally, effects of changes from one forest type to another are not currently included in the model because of the paucity of data documenting such changes and because we judged afforestation and deforestation to have much larger and better documented effects. For similar reasons, effects of changes in management intensity within a forest type are not included in the model.

Model Structure

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

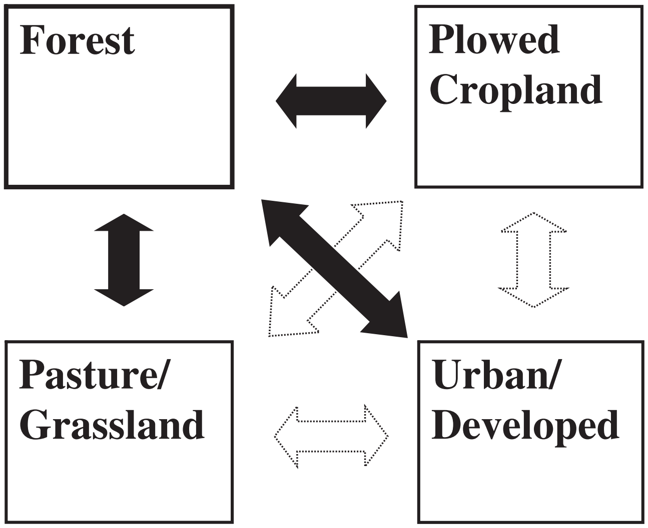

Fig. 2. Transitions among different types of land use. Black arrows show transitions included by the model. Dashed arrows show transitions not included in the model. The arrows have heads in both directions to indicate that transitions in each direction are included in the model.

Table 1. Area of forest land by forest type from 1907 to 1997 for the Southeast region of the United States.†

	Period ending in year						
Forest type	**1907**	**1938**	**1953**	**1963**	**1977**	**1987**	**1997**
	1000 ha						
White–red–jack pine	143	136	143	143	134	208	230
Spruce–fir	7	7	7	7	5	11	5
Longleaf–slash pine (planted)	0	0	157	734	1617	2472	2530
Longleaf–slash pine (natural)	6637	6285	6639	6062	3680	2338	1699
Loblolly–shortleaf pine (planted)	0	0	195	913	2134	2513	4313
Loblolly–shortleaf pine (natural)	8243	7806	8246	7529	6649	6210	4845
Oak–pine	3369	3191	3370	3371	4864	3881	4701
Oak–hickory	6757	6399	6760	8285	10326	10741	10782
Oak–gum–cypress	7236	6853	7247	7194	4590	5278	5479
Elm–ash–cottonwood	14	13	14	14	679	611	333
Maple–beech–birch	121	114	121	121	142	112	140
Aspen–birch	0	0	0	0	0	0	0
Other forest types	374	354	377	348	119	139	539
Non-stocked	4341	4111	4342	3619	1659	1321	286
Total	37242	35269	37620	38339	36598	35837	35882

† Source: Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003).

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. The forest type groups are shown in Table 1. Land use transitions in each forest type are modeled as aggregate gross changes for multi-state regions, as shown in Fig. 1. For both afforestation and deforestation, separate equations are used to predict changes in soil and forest floor carbon stocks. Separate parameters for some of these equations are used for different forest types.

Model Inputs

Historical and Future Changes in Forest Area

For each region, the model uses two input data sets of the area undergoing transitions in land use, one for historical estimates and one for future estimates. The historical data set covers the period from 1907 to 1997 and the future set covers 1997 to 2050. Each data 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, so estimates are gross changes rather than net changes. For example, during a given time period the area changing from a particular forest type into cropland is estimated separately from the area changing from cropland into that forest type.

The historical data set contains estimates of deforestation and afforestation by forest type group for each time period ending in the following years: 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 afforestation, deforestation, and area estimates for the Southeast region are presented in Tables 1, 2, and 3. The historical estimates for the South-Central region are presented in Tables 4, 5, and 6. 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 head-

Table 2. Historical area afforested by forest type from 1907 to 1997 for the Southeast region of the United States.†

	Period ending in year						
Forest type	**1907**	**1938**	**1953**	**1963**	**1977**	**1987**	**1997**
	1000 ha						
White–red–jack pine		0	0	0	0	0	0
Spruce–fir		0	0	0	0	0	0
Longleaf–slash pine (planted)		0	21	90	79	155	109
Longleaf–slash pine (natural)		397	632	163	108	32	51
Loblolly–shortleaf pine (planted)		0	97	129	94	174	543
Loblolly–shortleaf pine (natural)		1085	1576	605	218	167	303
Oak–pine		150	506	109	80	43	291
Oak–hickory		524	1436	949	281	298	203
Oak–gum–cypress		107	173	77	29	61	109
Elm–ash–cottonwood		0	0	0	9	0	0
Maple–beech–birch		0	0	0	0	0	0
Aspen–birch		0	0	0	0	0	0
Other forest types		0	0	0	0	0	0
Non-stocked		0	0	0	0	0	0
Total		2263	4441	2124	899	930	1610

† Source: based primarily on Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003) (see text for details).

Table 3. Historical area deforested by forest type from 1907 to 1997 for the Southeast region of the United States.†

	Period ending in year						
Forest type	**1907**	**1938**	**1953**	**1963**	**1977**	**1987**	**1997**
	1000 ha						
White–red–jack pine		8	0	0	10	0	0
Spruce–fir		0	0	0	0	0	0
Longleaf–slash pine (planted)		0	7	29	108	50	63
Longleaf–slash pine (natural)		802	209	208	466	232	203
Loblolly–shortleaf pine (planted)		0	49	24	40	42	57
Loblolly–shortleaf pine (natural)		1612	774	643	1224	807	824
Oak–pine		354	250	69	110	283	167
Oak–hickory		941	728	362	384	240	190
Oak–gum–cypress		536	56	68	288	49	63
Elm–ash–cottonwood		0	0	0	0	0	0
Maple–beech–birch		0	0	0	0	0	0
Aspen–birch		0	0	0	0	0	0
Other forest types		0	0	0	0	0	0
Non-stocked		0	0	0	0	0	0
Total		4252	2074	1405	2629	1703	1566

† Source: based primarily on Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003) (see text for details).

Table 4. Area of forest land by forest type from 1907 to 1997 for the South-Central region of the United States.†

Forest type	Period ending in year 1907	1938	1953	1963	1977	1987	1997
	1000 ha						
White–red–jack pine	64	60	59	60	50	46	46
Spruce–fir	5	5	5	5	7	8	0
Longleaf–slash pine (planted)	0	0	69	247	318	614	649
Longleaf–slash pine (natural)	2776	2592	2548	2370	1223	882	621
Loblolly–shortleaf pine (planted)	0	0	335	1197	2046	2115	4315
Loblolly–shortleaf pine (natural)	13410	12522	12311	11451	8456	8441	6886
Oak–pine	7015	6551	6440	6442	7883	7552	7522
Oak–hickory	22656	21158	20855	21734	23061	22373	20970
Oak–gum–cypress	8021	7490	7363	7364	6485	6494	6570
Elm–ash–cottonwood	1540	1438	1414	1414	854	646	629
Maple–beech–birch	443	414	407	408	289	276	329
Aspen–birch	0	0	0	0	0	0	0
Other forest types	0	0	0	0	0	0	2073
Non-stocked	2224	2076	2043	1410	598	165	151
Total	58153	54305	53849	54102	51268	49611	50761

† Source: Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003).

ing "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.

The current and future input data set contains estimates of area change for each time period ending in the following years: 2000, 2010, 2020, 2030, 2040, and 2050. We developed this data set based on extrapolation of transitions 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 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 data set described above (Tables 2, 3, 5, and 6). 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, based on estimates developed for the ATLAS model (Mills and Zhou, 2003; Alig et al., 2003). This additional rate was added to the afforestation rate if the total area of a forest type increased or to the deforestation rate if the total forest area decreased.

Because the ATLAS model uses forest types that are more aggregated than those of our model, the types were disaggregated for all years based on the areas of each forest type in 1997 (Tables 1 and 4). The ATLAS model covers only privately owned timberland (productive accessible forest). Area of public forests, and forest areas not defined as timberland for 1997 were added to the data set based on 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).

Table 5. Historical area afforested by forest type from 1907 to 1997 for the South-Central region of the United States.†

Forest type	Period ending in year 1907	1938	1953	1963	1977	1987	1997
	1000 ha						
White–red–jack pine		0	0	0	0	0	0
Spruce–fir		0	0	0	0	0	0
Longleaf–slash pine (planted)		0	1	10	7	8	43
Longleaf–slash pine (natural)		18	26	49	14	13	9
Loblolly–shortleaf pine (planted)		0	44	301	214	178	873
Loblolly–shortleaf pine (natural)		538	1113	234	421	381	260
Oak–pine		194	851	181	370	173	199
Oak–hickory		507	725	2213	968	452	693
Oak–gum–cypress		178	255	190	170	168	313
Elm–ash–cottonwood		52	149	32	49	46	35
Maple–beech–birch		1	2	5	1	1	6
Aspen–birch		0	0	0	0	0	0
Other forest types		0	0	0	0	0	0
Non-stocked		19	27	53	18	17	41
Total		1507	3193	3267	2234	1437	2473

† Source: based primarily on Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003) (see text for details).

Table 6. Historical area deforested by forest type from 1907 to 1997 for the South-Central region of the United States.†

Forest type	Period ending in year 1907	1938	1953	1963	1977	1987	1997
	1000 ha						
White–red–jack pine		4	1	0	13	4	0
Spruce–fir		0	0	0	0	0	0
Longleaf–slash pine (planted)		0	1	5	7	4	5
Longleaf–slash pine (natural)		119	74	83	121	70	21
Loblolly–shortleaf pine (planted)		0	18	161	211	121	36
Loblolly–shortleaf pine (natural)		1363	1175	501	1569	425	264
Oak–pine		686	838	191	365	523	122
Oak–hickory		2089	963	1545	955	1185	704
Oak–gum–cypress		739	364	202	932	171	107
Elm–ash–cottonwood		160	153	34	196	109	29
Maple–beech–birch		13	10	4	13	8	2
Aspen–birch		0	0	0	0	0	0
Other forest types		0	0	0	0	0	0
Non-stocked		173	62	290	724	435	30
Total		5346	3659	3017	5107	3053	1321

† Source: based primarily on Birdsey and Lewis (2003) and R. Birdsey, USDA Forest Service, Northern Global Change Program, Newtown Square, PA, personal communication (2003) (see text for details).

Table 7. Area of forest land by forest type from 2000 to 2050 for the Southeast region of the United States.

	Period ending in year					
Forest type	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
	1000 ha					
White–red–jack pine	11	11	11	9	10	9
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	2546	2798	2941	3056	3085	3059
Longleaf–slash pine (natural)	1661	1528	1452	1378	1336	1312
Loblolly–shortleaf pine (planted)	4338	4769	5013	5208	5257	5214
Loblolly–shortleaf pine (natural)	4736	4356	4140	3928	3809	3740
Oak–pine	4728	4817	4778	4683	4580	4509
Oak–hickory	10663	10315	10060	9969	9930	9901
Oak–gum–cypress	5338	5183	5033	4872	4778	4689
Elm–ash–cottonwood	313	304	294	286	280	275
Maple–beech–birch	142	137	134	133	132	132
Aspen–birch	0	0	0	0	0	0
Other forest types	331	260	263	266	265	265
Non-stocked	996	944	966	862	883	862
Total	35802	35421	35086	34651	34344	33967

The current and future estimates for all forestland for the Southeast region are presented in Tables 7, 8, and 9 and those for the South-Central region in Tables 10, 11, and 12.

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. For example, between 1900 and 1997, a substantial area of forestland was planted in the loblolly–shortleaf type, and much of this land was originally another forest type, such as the naturally regenerated loblolly–shortleaf type or the oak–pine type. 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 is assumed to represent the net changes among forest types that occurred for each forest type.

Forest Floor Carbon Equations

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 deforestation (Eq. [1]) and one for afforestation (Eq. [2]). There are separate parameters for these equations for different forest types (Table 13). The derivation of these equations and their parameters is given in 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.

Table 8. Area afforested by forest type from 2000 to 2050 for the Southeast region of the United States.

	Period ending in year					
Forest type	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
	1000 ha					
White–red–jack pine	0	0	0	0	0	0
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	19	63	63	63	63	63
Longleaf–slash pine (natural)	15	51	51	51	51	51
Loblolly–shortleaf pine (planted)	17	57	57	57	57	57
Loblolly–shortleaf pine (natural)	91	303	303	303	303	303
Oak–pine	50	167	167	167	167	167
Oak–hickory	57	190	190	190	190	190
Oak–gum–cypress	19	63	63	63	63	63
Elm–ash–cottonwood	0	0	0	0	0	0
Maple–beech–birch	0	0	0	0	0	0
Aspen–birch	0	0	0	0	0	0
Other forest types	0	0	0	0	0	0
Non-stocked	0	0	0	0	0	0
Total	268	894	894	894	894	894

Table 9. Area deforested by forest type from 2000 to 2050 for the Southeast region of the United States.

	Period ending in year					
Forest type	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
	1000 ha					
White–red–jack pine	1	0	0	0	0	0
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	25	90	89	99	90	97
Longleaf–slash pine (natural)	19	69	66	69	63	66
Loblolly–shortleaf pine (planted)	27	103	102	119	103	115
Loblolly–shortleaf pine (natural)	102	353	344	354	338	345
Oak–pine	61	217	213	226	208	217
Oak–hickory	81	303	288	315	278	299
Oak–gum–cypress	31	119	112	125	106	115
Elm–ash–cottonwood	1	3	3	4	3	3
Maple–beech–birch	0	2	1	2	1	1
Aspen–birch	0	0	0	0	0	0
Other forest types	1	4	2	3	2	3
Non-stocked	1	11	9	12	8	10
Total	348	1274	1229	1329	1200	1270

Equation [1] is for change in forest floor carbon mass due to deforestation:

$$\text{change} = C - C \times e^{-\frac{t}{D}} \qquad [1]$$

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

Equation [2] is for change in forest floor carbon mass due to afforestation:

$$\text{change} = \frac{-1 \times A \times t}{B + t} \text{ up to a limit of } C \qquad [2]$$

Table 10. Area of forest Land by forest type from 2000 to 2050 for the South-Central region of the United States.

	Period ending in year					
Forest type	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
	1000 ha					
White–red–jack pine	2	2	2	2	2	2
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	747	934	1063	1159	1199	1217
Longleaf–slash pine (natural)	589	588	603	611	603	585
Loblolly–shortleaf pine (planted)	4985	6230	7087	7729	7997	8111
Loblolly–shortleaf pine (natural)	6570	6561	6722	6814	6723	6521
Oak–pine	7707	7874	7779	7745	7731	7783
Oak–hickory	20445	18832	17815	17088	16966	17051
Oak–gum–cypress	6575	6682	6728	6720	6709	6706
Elm–ash–cottonwood	638	648	653	652	651	651
Maple–beech–birch	2201	2162	2146	2135	2153	2175
Aspen–birch	0	0	0	0	0	0
Other forest types	311	353	383	402	427	453
Non-stocked	11	14	16	17	19	21
Total	50781	50878	50995	51074	51181	51274

Table 11. Area afforested by forest type from 2000 to 2050 for the South-Central region of the United States.

	Period ending in year					
Forest type	2000	2010	2020	2030	2040	2050
	1000 ha					
White–red–jack pine	0	0	0	0	0	0
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	2	6	7	7	7	7
Longleaf–slash pine (natural)	3	10	10	10	10	10
Loblolly–shortleaf pine (planted)	12	45	50	47	52	50
Loblolly–shortleaf pine (natural)	81	273	275	271	274	272
Oak–pine	40	137	140	134	138	136
Oak–hickory	216	732	737	721	729	724
Oak–gum–cypress	35	119	122	117	121	119
Elm–ash–cottonwood	9	31	31	31	31	31
Maple–beech–birch	1	6	6	5	6	5
Aspen–birch	0	0	0	0	0	0
Other forest types	1	1	1	1	1	1
Non-stocked	9	30	30	30	30	30
Total	408	1391	1410	1372	1399	1387

where A is a parameter (for values of parameters for each forest type, see Table 13), B is a second afforestation parameter, and C is a parameter representing the maximum carbon emission (Mg ha^{-1}).

Figure 3 shows the predicted effects of afforestation and deforestation for a loblolly pine plantation. Note that for deforestation, nearly all of the change in carbon occurs within the first 10 yr, but for afforestation, changes in carbon occur for approximately 40 yr.

Soil Carbon

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 based on data from the literature. Data on the proportion of soil carbon lost after deforestation in temperate forests are summarized in Table 14. Based on these data, we chose a parameter value of 25% loss after deforestation in the model. This value is:

- close to the mean calculated for U.S. and Canadian data (weighted by study) derived from data summarized by Murty et al. (2002),
- close to the global value accounting for bulk density by Murty et al. (2002),
- midpoint from Post (2003) (based on Post and Kwon, 2000), and
- 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.

Table 12. Area deforested by forest type from 2000 to 2050 for the South-Central region of the United States.

	Period ending in year					
Forest type	2000	2010	2020	2030	2040	2050
	1000 ha					
White–red–jack pine	0	0	0	0	0	0
Spruce–fir	0	0	0	0	0	0
Longleaf–slash pine (planted)	1	5	5	5	5	5
Longleaf–slash pine (natural)	3	9	9	9	9	9
Loblolly–shortleaf pine (planted)	11	36	36	36	36	36
Loblolly–shortleaf pine (natural)	78	260	260	260	260	260
Oak–pine	37	122	122	122	122	122
Oak–hickory	208	693	693	693	693	693
Oak–gum–cypress	32	107	107	107	107	107
Elm–ash–cottonwood	9	29	29	29	29	29
Maple–beech–birch	0	2	2	2	2	2
Aspen–birch	0	0	0	0	0	0
Other forest types	0	0	0	0	0	0
Non-stocked	9	30	30	30	30	30
Total	388	1293	1293	1293	1293	1293

Table 13. Soil and forest floor carbon parameter values for each forest type group.†

		Forest floor parameters			
Forest type	Soil maximum C mass to a 1-m depth	*A*	*B*	*C*	*D*
	Mg ha^{-1}				
White–red–jack pine	196	20.4	27.1	12.2	3.8
Spruce–fir	193	20.4	27.1	12.2	3.8
Longleaf–slash pine (planted)	136	20.4	27.1	12.2	3.8
Longleaf–slash pine (natural)	136	20.4	27.1	12.2	3.8
Loblolly–shortleaf pine (planted)	92	20.4	27.1	12.2	3.8
Loblolly–shortleaf pine (natural)	92	20.4	27.1	12.2	3.8
Oak–pine	82	15.4	20.1	10.3	3.8
Oak–hickory	85	15.3	61.8	6	3.2
Oak–gum–cypress	152	15.3	61.8	6	3.2
Elm–ash–cottonwood	118	15.3	61.8	6	3.2
Maple–beech–birch	140	15.3	61.8	6	3.2
Aspen–birch	237	15.3	61.8	6	3.2
Other forest types	100	15.3	61.8	6	3.2
Non-stocked	100	2.7	36.3	1.4	3.6

† Soil carbon values are from Heath et al. (2003); parameters are from Smith and Heath (2002).

The forest floor deforestation equation (Eq. [1]) includes a parameter representing the average carbon emission rate for each forest type throughout its range (Table 13). 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 (for example, data shown in Fig. 4) suggest that soil carbon decomposes more slowly than forest floor carbon, an adjustment factor was applied to represent this difference. This adjustment

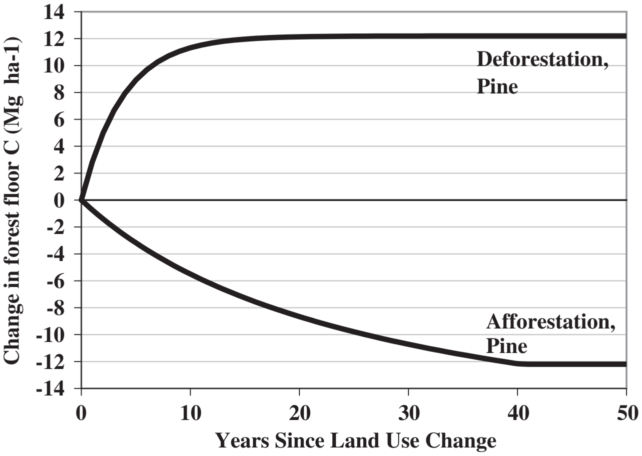

Fig. 3. Example of afforestation and deforestation effects on carbon in the forest floor of pine plantations in the Southeast region. Negative values indicate C sequestration and are afforestation. Positive values indicate carbon emission and are deforestation. The equations for pine (and other forest types, not shown) are based on those of Smith and Heath (2002), modified not to exceed average forest floor C accumulation.

Table 14. Summary of literature data on effects of deforestation on soil carbon stocks.

Source	N	Sampling depth	Time	Change in soil C
		cm	yr	%
Houghton and Hackler (2000, 2001) (mean for temperate deciduous and evergreen)	model		30	−24.6
West et al. (2004)	model		20	−30.0
Mann (1986) (summary from abstract and Table 3)	254	30		−20 to −26
Post and Mann (1990)	800	100		−23.0
Davidson and Ackerman (1993)		>30		−30.5
Mean of data for United States and Canada weighted by individual study (derived from Murty et al., 2002)	8	36	41	−23.6

factor was defined as an additional negative exponential equation shown in Eq. [3].

Equation [3] is for the adjustment factor to represent slower emission of soil carbon compared to forest floor carbon after afforestation:

$$\text{adjustment factor} = n + s \times (1 - \mathrm{e}^{-\frac{t}{r}}) \qquad [3]$$

where n is the minimum adjustment factor = 0.74, s is the maximum additional adjustment factor (with n sums to 1) = 0.26, r is the shape parameter = 7, and t is the time since land use change (yr).

Equations 1 and 3 are combined to calculate the emission of carbon after deforestation as shown in Eq. [4]. The results of Eq. [4] are shown in Fig. 4, but note that the dependent axis is the relative change in soil C, not the absolute change in soil C mass.

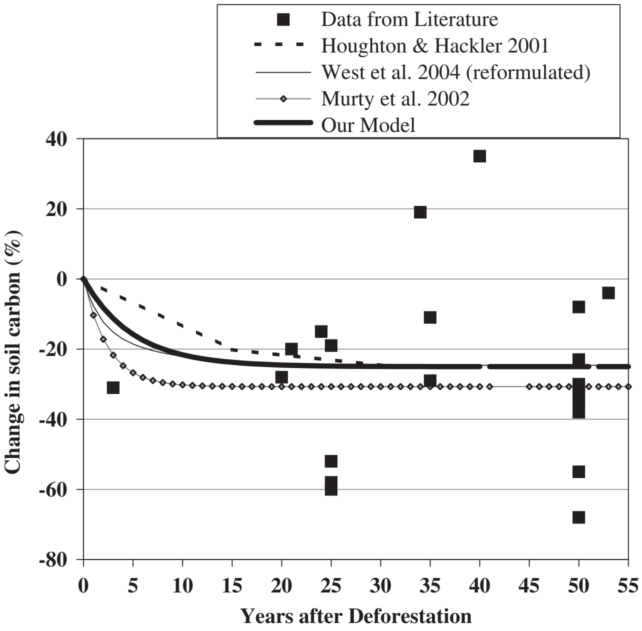

Fig. 4. Change in soil carbon after deforestation: our model equation compared to data from North America and to selected models from the literature. Literature data are from Coote and Ramsey (1983), Ellert and Gregorich (1996), Franzluebbers et al. (2000), Giddens (1957), Gregorich et al. (1995), Martel and Mackenzie (1980), and Pennock and van Kessel (1997).

Equation [4] is for the change in soil carbon mass after deforestation (Mg ha^{-1}):

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

where E is the maximum soil carbon density (Mg ha^{-1}, see Table 13), F is the decrease in soil C mass due to cultivation (%), set to 25%, and other parameters are as shown in previous equations.

Soil Carbon after Afforestation

The change in soil carbon mass after afforestation is represented by a Weibull equation as shown in Eq. [5]. An example of the effect of afforestation for a loblolly pine plantation is shown in Fig. 5, along with selected equations and available data from the literature. 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). For Eq. [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. This same step also must be applied to Eq. [1], [2], and [4] to make regional estimates.

Equation [5] is for change in soil C mass after afforestation (Tg):

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

where G is the area afforested (1000 ha), H is the time required to regain two-thirds of maximum soil carbon density (60 yr), and other parameters are as shown in previous equations.

Model Description

The model is a compilation of the information in the methods. The model is currently implemented as a series of

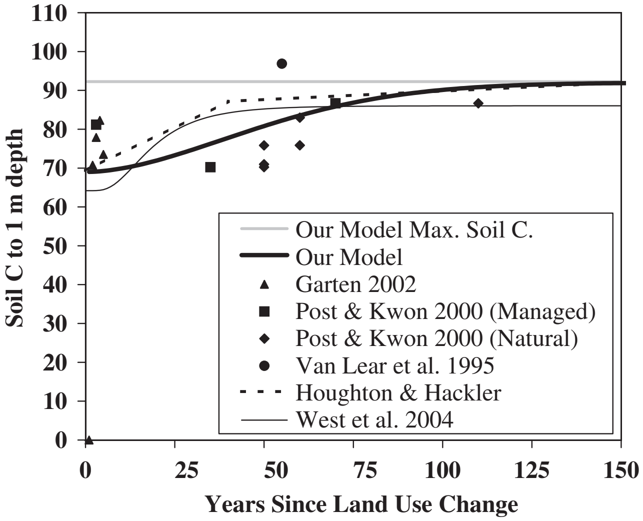

Fig. 5. Change in soil carbon after afforestation: comparison of our model equation to data for pine forest types in the Southeast and South-Central regions of the United States and to selected equations from the literature. Published data are shown as points and models are shown as lines; data are from Garten (2002), Post and Kwon (2000), Van Lear et al. (1995), Houghton and Hackler (2000, 2001), and West et al. (2004). Data from Post and Kwon (2000) are a published literature review covering many studies, other citations are data not included in that review.

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.

The following are key model assumptions:

- The model estimates the average change for each broad forest type group within a large region (Fig. 1). For example, all land in the loblolly pine–shortleaf pine type group within the Southeast region that is deforested is estimated to lose the same amount of soil and forest floor carbon, respectively, over time.
- Before deforestation, the soil and forest floor have the maximum possible soil carbon density for a given forest type.
- Before afforestation, the soil and forest floor have lost the maximum possible amount of carbon.
- When land is afforested, it is assumed that the same forest type was present before deforestation.
- There is no change in soil carbon due to transitions between plantations and naturally regenerated stands of the same forest type.
- 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.
- There is no change in soil carbon due to transition from forest to pasture, but there is loss of forest floor carbon.
- There is no change in soil carbon due to transitions between forest types.
- 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.
- 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.
- A change in land use between plowed agricultural land and forest will cause a change in soil and forest floor carbon.

Sensitivity Analysis

Because soil carbon density is a key model parameter, and because there are no published systematic survey data available in the United States for forest soil carbon, we determined the sensitivity of model predictions to soil carbon density values. Soil carbon density parameter values were increased for each forest type by 20% and decreased by either 20 or 50%.

RESULTS

Cumulative Effects of Land Use Change

Figures 6 and 7 show the cumulative effects of afforestation and deforestation on soil and forest floor carbon mass from 1900 to 2050 for each region. Note that carbon emission to the atmosphere is shown with a positive sign and carbon sequestration (removal) from the atmosphere is shown with a negative sign. For both regions, land use change caused net carbon emission during the first half of the 20th century. For the Southeast region, carbon was sequestered in most years from 1950 to 2050. For the South-Central region, the cumulative effects of land use change differ from those in the Southeast region (Fig. 7). There was net emission until the 1980s (South-Central) as compared to the 1950s (Southeast). The maximum cumulative effect was also much greater in the South-Central region: 210 Tg C (South-Central) versus 70 Tg C (Southeast). Future rates of change in carbon mass are predicted to be similar in the two regions, but because of the greater total emission in the South-Central region, this region is predicted to have a cumulative loss of 126 Tg C from 1900 to 2050 as compared to only 7 Tg C in the Southeast region.

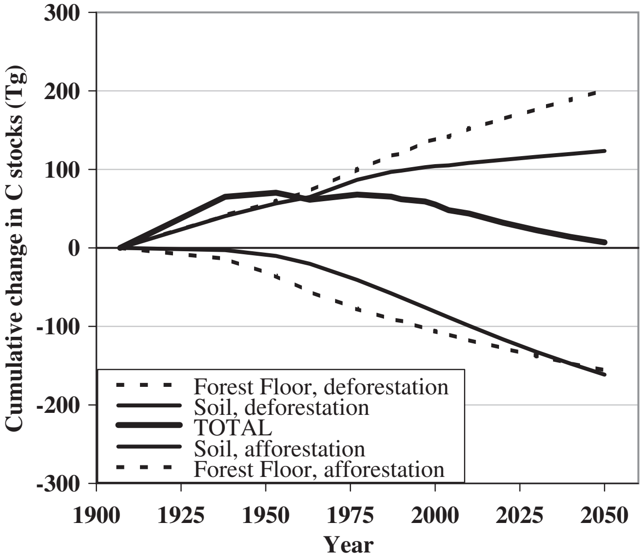

Fig. 6. For the Southeast region, cumulative effect of land use change on forest carbon from 1900 to 2050 (positive values are emission to the atmosphere, negative values are sequestration).

The different patterns of cumulative effects of land use change in the two regions are not directly due to the differences in the total area of forest, because only areas undergoing land use change are used in the model. Instead, the differences likely are due to the generally higher rates of deforestation in the South-Central region, particularly before 1938 and between 1963 and 1977 (Tables 3 and 6). Although there are some differences

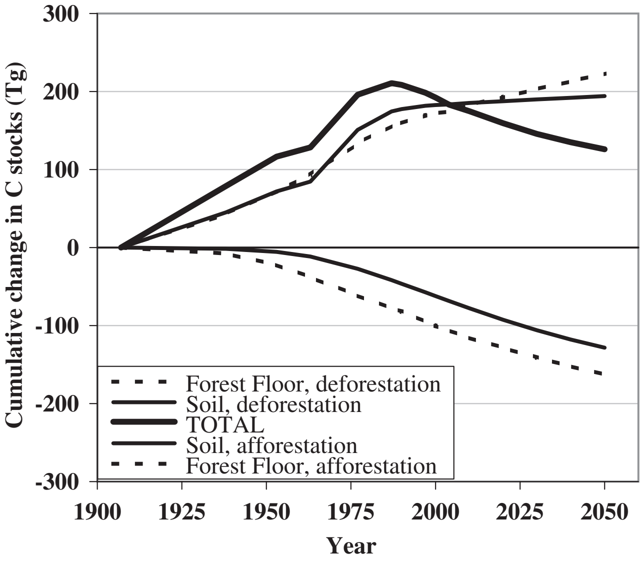

Fig. 7. For the South-Central region, cumulative effect of land use change on forest carbon from 1900 to 2050 (positive values are emission to the atmosphere, negative values are sequestration).

between the two regions in the rates of afforestation, these rates are considerably smaller than those for deforestation. Thus, afforestation contributes much less to the historical changes in carbon mass (Tables 2 and 5). The greater rates of deforestation in the South-Central region cause the total area of forest to decrease by 7.4 million ha from 1907 to 1997, while in the Southeast region this decrease is only 1.4 million ha (Tables 1 and 4).

From 1900 until 2004, the total cumulative effect of afforestation on carbon stocks in the soil and forest floor was somewhat higher in the Southeast region: 199 Tg C (Southeast) versus 175 Tg C (South-Central). The corresponding totals for deforestation were 247 Tg C (Southeast) and 358 Tg C (South-Central). Thus the net changes for both deforestation and afforestation up to the present were emissions of 48 Tg C (Southeast) and 183 Tg C (South-Central region). These cumulative effects for all years are shown in Fig. 6 and 7.

In the future, forest area is projected to decrease in the Southeast region by 1.7 million ha, while it is projected to increase in the South-Central region by 0.5 million ha (Tables 7 and 10). However, because of offsetting differences in patterns of land use change before 2004, the pattern of net carbon change from 2004 until 2050 is projected to be fairly similar in the two regions, with sequestration of 41 Tg C in the Southeast and 57 Tg C in the South-Central region. Afforestation is predicted to sequester 119 Tg C in the Southeast and 117 Tg C in the South-Central region. The emission due to deforestation is predicted to be somewhat higher in the Southeast region: 78 Tg C (Southeast) versus 59 Tg C (South-Central).

It is interesting that net carbon sequestration in the soil is predicted in the future even in the Southeast region where total forest area is projected to decrease. These contrasting trends occur because of the long predicted lag time of effects of prior afforestation. Thus land use transitions during the 20th century are predicted to continue to affect forest carbon stocks well into the 21st century. Overall, rates of afforestation are predicted to be much greater on average on an annual basis in coming decades as compared to the 20th century, but roughly similar to those in the last decade.

Annual Effects of Land Use Change

Figures 8 and 9 show the annual rates of change in the area of afforested land from 1900 to 2050 along with the annual effects of afforestation on carbon stocks in the soil and forest floor for the two regions. Area change is given a negative sign in these figures to facilitate comparison with carbon change estimates for which a negative sign indicates carbon sequestration. Thus an area change of −1 in these figures indicates that 1000 ha were afforested during that year. For the Southeast region, the area of land that is afforested is quite variable from 1925 to 2000, but is constant from 2000 to 2050 at a rate approximately half that from 1987 to 1997 (Tables 8 and 2). This constant rate in the future is predicted because a constant "base rate" of afforestation was applied (see Materials and Methods, above). No additional afforestation was predicted because there was a net decrease in forestland for each future time period (Table 7). For the South-Central region, the change in afforestation is also quite variable from 1925 to 2000, and is also predicted to be nearly constant in the future.

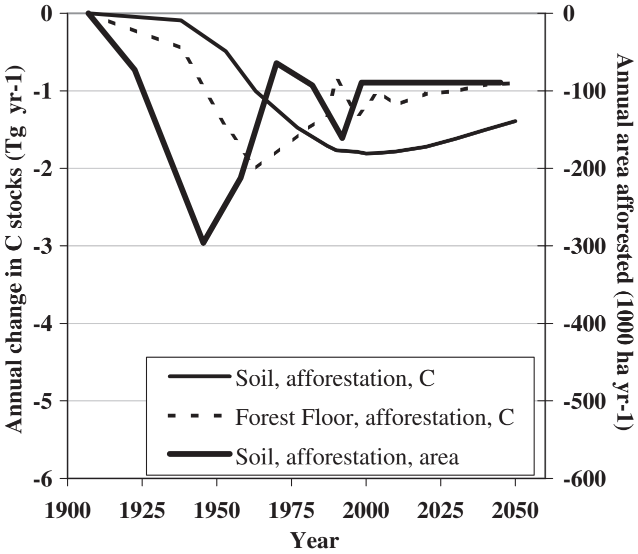

Fig. 8. For Southeast region, annual area afforested and annual effect of afforestation on carbon in the soil and forest floor from 1900 to 2050. Area change is shown as negative values for comparison with afforestation, for which negative values show carbon sequestration.

The change in the rate of afforestation during each time period is the only driving variable in the model that causes a change in carbon mass on afforested land. Therefore the effect of the model can be seen by comparing the predicted changes in soil and forest floor carbon with the area change as shown in Fig. 8 and 9. The effect of afforestation is generally both damped and lagged by the model, with greater damping and much

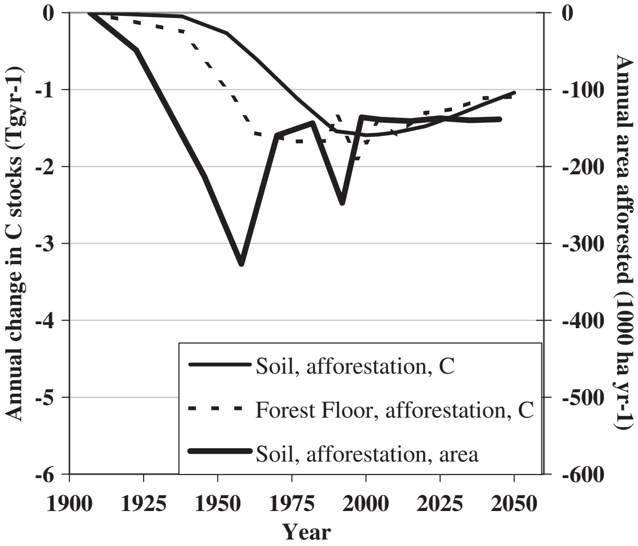

Fig. 9. For the South-Central region, annual area afforested and annual effect of afforestation on carbon in the soil and forest floor from 1900 to 2050. Area change is shown as negative values for comparison with afforestation, for which negative values show carbon sequestration.

longer lagging for the soil than the forest floor. For the Southeast region, the rate of change in carbon in the forest floor appears to stabilize by 2050, while that in the soil does not. For the South-Central region, the rates of change in forest floor and soil do not appear to stabilize by 2050. The longer lag time for soil carbon is expected since the model predicts that it takes longer to reach equilibrium for the carbon density in soil than for the forest floor (Fig. 3 and 5).

Figures 10 and 11 show the annual area deforested and the subsequent effects on soil and forest floor carbon stocks from 1900 to 2050 for the two regions. As for afforestation, the effects of deforestation on carbon stocks are lagged. The lag is shorter than for afforestation, because the model predicts a much more rapid loss in carbon stocks after deforestation compared to the slow gain in carbon after afforestation (Fig. 3, 4, and 5, and Eq. [1] and [2]). For both regions, both soil and forest floor carbon stocks appear to become relatively stable, which is not surprising since the annual area deforested is projected to be nearly constant in the future.

For both regions, the annual change in forest floor carbon mass is predicted to be quite variable from 1990 to 2010, apparently more variable than the change in area during this time period. This variability is a result of shorter time periods used by the model from 1997 to 2010. The model is capable of calculating results for any year, but results were only calculated for specific years, generally at the end of a time period. However, land use transitions were assumed to occur only at the midpoint of each time period (see Materials and Methods, above). Because of the nonlinear equations used to predict changes in soil and forest floor carbon, the model predicts rapid changes during the years immediately after a year during which land use transitions occurred. When the time periods are short, results are calculated closer to the year in which transitions occur; therefore the model predicts greater annual effects for these years. From 1997 to 2010, the periods are much shorter than those before 1997: 3 and 6 yr as compared to 10 or more years for earlier periods (Tables 1 and 7). The time periods are shorter close to the present for two reasons: (i) there is a transition from historical to projected data (from 1997 to 2000), and (ii) we calculated results for two additional years (1990 and 2004) that do not fall at the end of a time period. Results for these years were calculated to predict effects of land use change from 1990 to the present as required for national greenhouse gas accounting purposes under the UNFCCC.

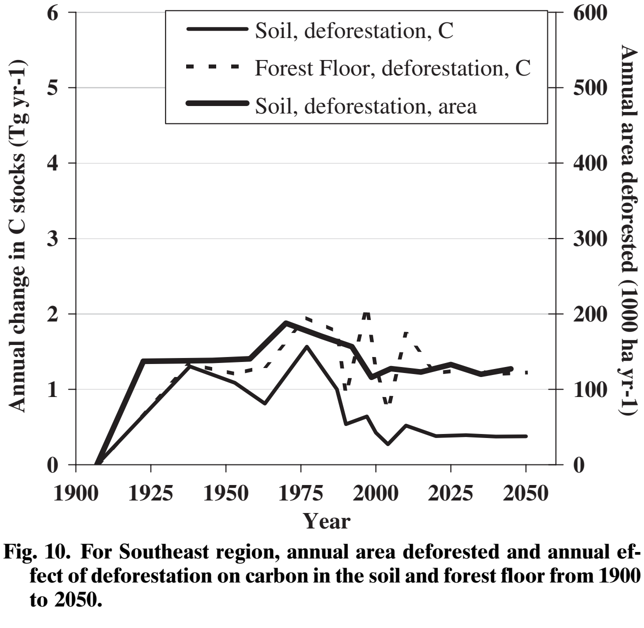

Fig. 10. For Southeast region, annual area deforested and annual effect of deforestation on carbon in the soil and forest floor from 1900 to 2050.

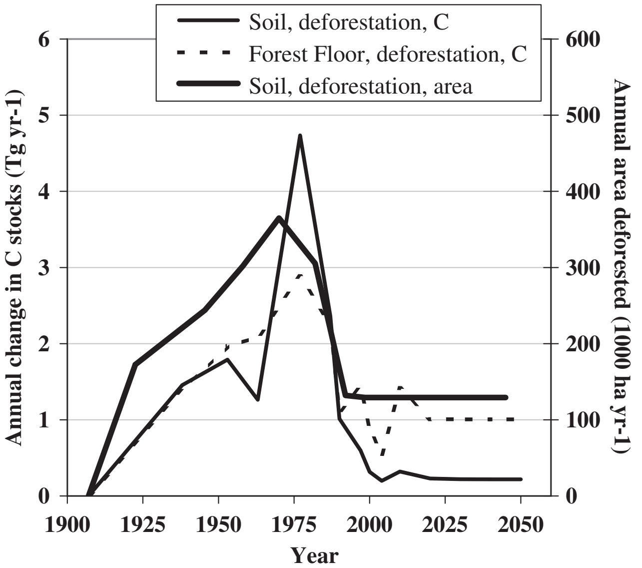

Fig. 11. For the South-Central region, annual area deforested and annual effect of deforestation on carbon in the soil and forest floor from 1900 to 2050.

Land Use Change Effects for UNFCCC Reporting Period

Each year, many counties prepare an inventory of greenhouse gas emissions and sequestration to meet commitments under the UNFCCC (USEPA, 2004). 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 U.S. greenhouse gas inventory. For the Southeast and South-Central regions together, over the period 1990–2004, afforestation caused sequestration of 88 Tg C, of which 47 Tg C was in the soil and 41 Tg C was in the forest floor. During this same period, deforestation caused emission of 49 Tg C, of which 13 Tg C was in the soil and 36 Tg C was in the forest floor. In comparing the two regions, effects on the soil were similar for afforestation and deforestation. Afforestation caused sequestration of 25 Tg C (Southeast) and 22 Tg C (South-Central) while deforestation caused emission of 7 Tg C (Southeast) and 6 Tg C (South-Central). For the forest floor, effects differed somewhat between the regions. Afforestation caused sequestration of 17 Tg C (Southeast) and 24 Tg C (South-Central) while deforestation caused emission of 21 Tg C (Southeast) and 15 Tg C (South-Central).

Model Sensitivity to Soil Carbon Density Parameter Values

Table 15 shows results of the sensitivity analysis for the period from 1990 to 2004. For this time period, the model is quite sensitive to the parameter value chosen for soil carbon density. The total predicted carbon flux results for this time period are changed nearly in proportion to the change in soil carbon density. For example, a 20% decrease in the soil carbon density parameter leads to a reduction in carbon sequestration over this period of 18%.

DISCUSSION

Estimates of Area Change

The topic of land use 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 and Hackler, 2000; Houghton et al., 2000) or forest inventory data (Heath et al., 2002).

The model improves on earlier analyses by using estimates of 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, especially from USDA Forest Service databases and reports, and from the NRI database. 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. 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.

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). For larger areas, the uncertainty in area is concomitantly smaller, and the timberland areas in Southeast and South-Central regions are indeed much larger: 85- and 116-fold, respectively. However, uncertainty is not well quantified for data early in the 20th century and is likely larger than these guidelines suggest. Additionally, for all time periods, there is much more 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.

Table 15. Sensitivity analysis of model predictions for 1990 to 2004 to variation in soil carbon density parameters.

	Standard	Minus 20%	Plus 20%	Minus 50%
	Tg C			
Soil, afforestation	−47	−38	−57	−24
Soil, deforestation	13	11	16	7
Forest floor, afforestation†	−41	−41	−41	−41
Forest floor, deforestation†	36	36	36	36
Total	−39	−32	−46	−22
Percent change	0%	18%	−18%	44%

† Forest floor results are included to provide totals.

Although there are uncertainties in the input data for the model, the input data represent the best available summary of gross (two-way) land use changes for the conterminous United States. Other published data such as the report by Alig et al. (2003) present net changes in forest area. However, because the lag times in the response of forest soil and forest floor carbon are much faster for deforestation than for afforestation, using net area change will not provide as accurate estimates of land use change effects on soil and forest floor carbon stocks as will using gross area changes. As discussed under Materials and Methods, above, 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).

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 (two-way) 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 southern United States (both regions) we project that from 2004 to 2050 there will be a net loss of 1.2 million acres of forestland (Tables 7 and 10). However, we predict that there will be net carbon sequestration of 98 Tg C during this same period (Fig. 6 and 7). A prediction based only on the net change in forest area during this period would predict emission of carbon rather than sequestration.

Comparison with Previous Historical Estimates of Land Use Change Effects

Figure 12 shows a previously published estimate of land use change effects on forest carbon for only the Southeast region (Heath et al., 2002). This previous

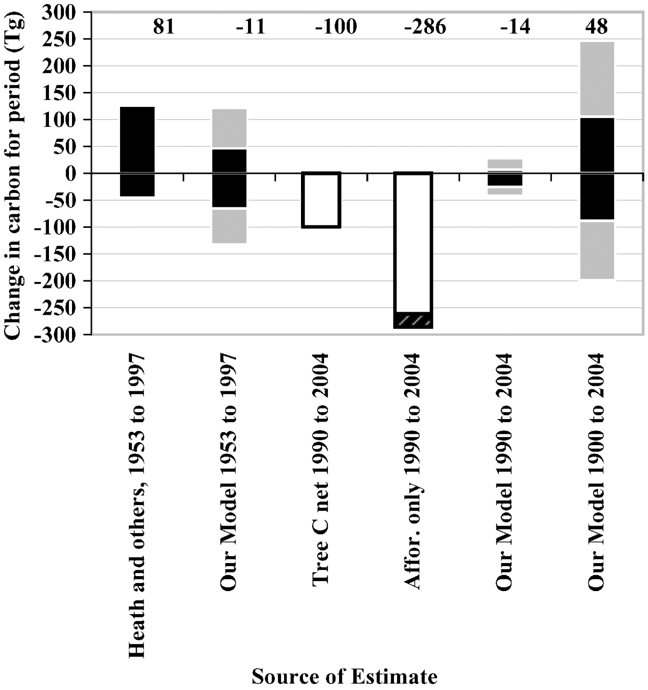

Fig. 12. For Southeast region, comparison of our model estimates of land use change effects on soil and forest floor carbon flux to previous estimates and to an estimate for other forest carbon pools. Afforestation effects are negative values and deforestation effects are positive values. The total effect is shown by the numbers above the bars. Symbol colors are: black = soil; gray = forest floor; white = tree carbon (live trees only for "Affor. only" estimate); diagonal stripes = dead tree, coarse woody debris, and understory. "Heath and others" estimates are from Heath et al. (2002), "Tree C net" estimates were contributed by us to USEPA (2004), and the "Affor. Only." estimate is for all pools except soil and forest floor on afforested lands only and was derived as described in the text.

study estimated a loss of 81 Tg C from 1953 to 1997 in the soil, while our model estimated gain of 11 Tg C in the soil and forest floor over this time period. Compared to this earlier study, our model estimated much smaller losses of carbon from the soil due to deforestation and somewhat greater gains due to afforestation. Unlike the earlier study, our model includes effects of land use change on the forest floor. However, effects of afforestation and deforestation on forest floor carbon nearly offset each other, so they are not responsible for the difference in estimates between the two models.

We believe that our model estimates are an improvement on the earlier estimates of Heath et al. (2002) for several reasons. Most importantly, our model used improved estimates of the area undergoing land use change, including data back to 1907. The model of Heath et al. (2002) used estimates of area change extending back only to 1953 based on fewer historical data sources. Using data from the first half of the 20th century improves estimates of land use change effects in the latter half of the century because of the long response times of soil and forest floor carbon after afforestation. Our model also uses improved estimates of the effects of land use change on soil carbon mass. For example, in our model, there is assumed to be no loss of soil carbon with transition of land from forest to pasture or "other" use (urban, suburban, right of way), while Heath et al. (2002) assumed a 15% loss. Although data on soil carbon in urban and other developed areas are scarce, a recent review suggests that average soil carbon densities in such lands may be similar to those in forests (Pouyat et al., 2003). A recent review of soil carbon density in pasture land suggests that carbon stocks may be similar and in some cases even greater than those in forests (Guo and Gifford, 2002). Our model also uses nonlinear equations to predict the effects of land use change on soil carbon, while the model of Heath et al. (2002) used linear equations. Although linear equations can be more tractable, we believe that nonlinear equations better represent the pattern of carbon gain and loss due to afforestation and deforestation. Finally, our model includes estimates of the effects of land use change on forest floor carbon mass. Although there is generally much less total carbon mass in the forest floor than in soil, a much greater proportion of the carbon mass in the forest floor responds to changes in land use, thus the total loss and gain of carbon in the forest floor and the soil are predicted to be of similar magnitude.

Other estimates of land use change effects on carbon stocks in U.S. forests have been made. Delcourt and Harris (1980) estimated historical changes in forest carbon stocks from 1750 to 1977 in 16 states in the southeastern United States. However, they did not provide separate estimates for the effects of land use change on forest floor and soil carbon, so their results cannot be compared directly to those of our model. Houghton and Hackler (2000) and Houghton et al. (2000) modeled the effects of land use change in the United States from 1700 to 1990. Although results from these studies are presented for separate regions of the United States, only net changes for all carbon pools are presented, so again results cannot be compared directly to ours. Some differences in assumptions and equations between these models and our model are discussed above (see Materials and Methods, above). Although the magnitudes of land use change effects cannot be compared directly, the analyses of Delcourt and Harris (1980) and of Houghton et al. (2000) do share one overall pattern in common with those of our model: there is predicted to be net emission of carbon due to land use change in the first half of the 20th century and net sequestration in the latter half.

Comparison with Future Predictions of Land Use Change Effects

One goal for our model is to use it in conjunction with the FORCARB model to predict future effects of land use change on carbon stocks in the forest sector. The effect of using our model can be determined by comparing its results to those of FORCARB. Figures 13 and 14 compare predicted cumulative changes in soil and forest floor carbon stocks from 2000 to 2050 for the two models. For the Southeast region, FORCARB predicts a fairly constant emission of carbon from soil and forest floor from 2000 to 2050 due to land use change, with a total emission of 196 Tg C from soil and 23 Tg C from the forest floor by 2050. In contrast, our model predicts a

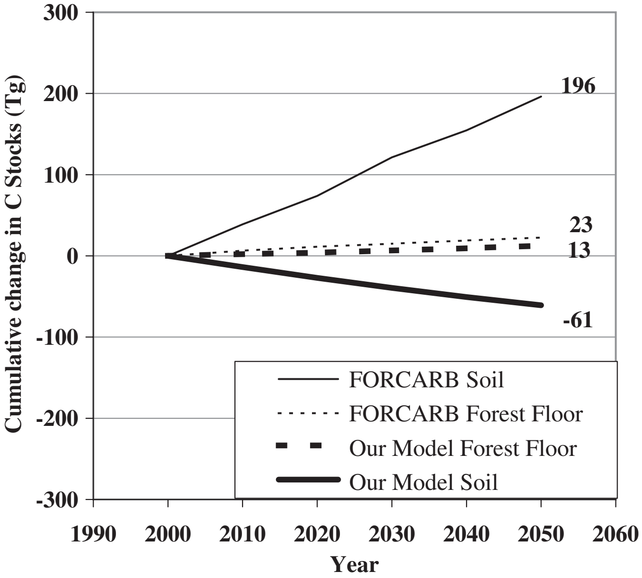

Fig. 13. For the Southeast region, cumulative predicted effect of land use change on forest carbon stocks from 2000 to 2050: comparison of our model with FORCARB model. Note that positive values are emission to the atmosphere and negative values are sequestration. Numbers in the graph are the total change from 2000 to 2050.

constant rate of sequestration by soil, with a total of 61 Tg C by 2050. For forest floor, there is a small total emission of 13 Tg C by 2050. The predicted net effect is thus quite different for the two models: FORCARB predicts emission of 219 Tg C by 2050 while our model predicts sequestration of 48 Tg C. For the South-Central region, both models predict that there will be carbon sequestration from 2000 to 2050. For soil, the FORCARB predicts sequestration of 96 Tg C while our model predicts sequestration of 55 Tg C. For the forest floor, FORCARB predicts emission of 7 Tg C while our model predicts sequestration of 12 Tg C.

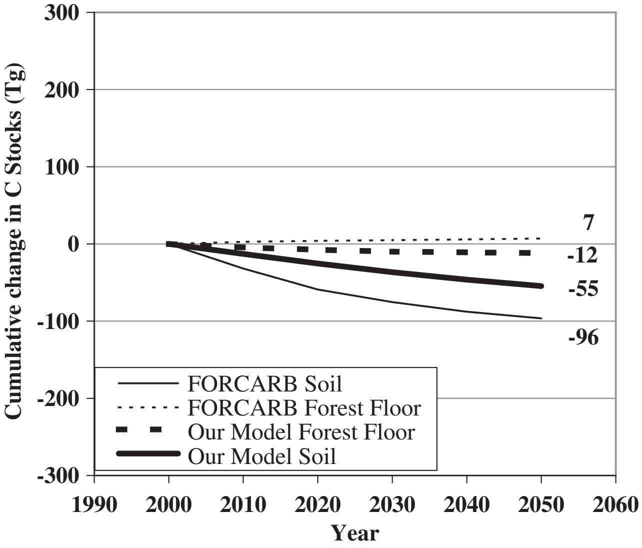

Fig. 14. For the South-Central region, cumulative predicted effect of land use change on forest carbon stocks from 2000 to 2050: comparison of our model with the FORCARB model. Note that positive values are emission to the atmosphere and negative values are sequestration. Numbers in the graph are the total change from 2000 to 2050.

These differences between the predictions of the two models occur for three reasons. First, FORCARB predicts changes in soil carbon based on net changes in the area of each forest management unit, while our model predicts changes based on gross rates of afforestation and deforestation for each forest type in each region. Second, FORCARB assumes that when forest area is lost, soil carbon is no longer counted, because it is transferred out of the forest sector into the agriculture sector, and when forest area is gained, soil carbon density is the same as that in forestland. Third, for forest floor carbon estimation, FORCARB does not distinguish between reforested land and afforested land and all land is treated as afforested. To date, these simplifying assumptions have been useful in FORCARB because of the lack of comprehensive data sets on forestland use transitions. One important reason for differences in predictions between the two models is that FORCARB assumes that land use causes instantaneous effects on soil carbon, while our model assumes that these effects will occur over many years after deforestation and for many decades after afforestation. Thus FORCARB predicts emission for the Southeast region because the total forest area decreases from 2000 to 2050 (Table 7). However, our model predicts net sequestration in the future due to the continued effects afforestation in the 20th century, as discussed above.

While any model projections of future carbon stocks in forests are subject to uncertainty, we believe that our model is a useful addition to the literature for three reasons. First, it incorporates estimates of gross rates of deforestation and afforestation rather than net changes. Second, like the previous approach of Heath et al. (2002) our model incorporates estimates of the length of time required to achieve a new carbon density value after a change in land use. Third, our model accounts for carbon stocks on all land that was formerly forest, rather than only counting land that is currently forested. Accounting for effects of land use change on all lands is useful for national and international reporting purposes and for developing effective approaches to enhance carbon sequestration. In the future, it may be useful to incorporate functionality from our model to the FORCARB model to improve predictions of total forest carbon cycling.

Implications for UNFCCC Reporting Period

Figure 12 shows effects of afforestation and deforestation, as well as the total predicted effects of land use change up to the present (2004) for the Southeast region. The right-most bar shows the total effect of land use change, while the bar second from the right shows the effect from 1990 to 2004. This latter period corresponds to the reporting requirement for national greenhouse gas inventories under the auspices of the UNFCCC. As shown in these two bars, the cumulative effect of land use change from 1900 to 2004 is a loss (emission) of 48 Tg of carbon, but that from 1990 to 2004 is a gain (sequestration) of 14 Tg of carbon. This difference is important because by capturing the dynamics of the effects of land use change, our model allows improved estimates to be made of the period from 1990 to the present. The net tree carbon results in this figure are estimates we developed for the U.S. Greenhouse Gas Inventory (USEPA, 2004). The estimates for afforested lands only were made by applying equations we developed for estimating regional average forest growth rates to the area of land estimated to have undergone afforestation (Table 2). This estimate may be somewhat high because it may not adequately account for effects of harvest on afforested land. These two sets of results are shown for comparison purposes. In comparing the net tree carbon results for 1990 to 2004 for all forestland with estimates from our model for 1990 to 2004, land use change causes approximately sevenfold greater carbon sequestration in trees than in soil and forest floor. The results for gross carbon accumulation in live and dead trees, coarse woody debris, and understory on afforested lands are nearly threefold greater than the net accumulation in trees, indicating that deforestation and harvest have important effects on forest carbon cycling in the Southeast region. Similar results are found for the South-Central region, but the difference between predicted effects of land use change on tree carbon stocks on all forestland are approximately sixfold greater than those in the soil and forest floor, and this same ratio holds for both regions together. The ratio is much greater when examining only afforested lands (Fig. 12). These results also indicate that afforestation causes much greater carbon accumulation in live trees than in the soil and forest floor, at least during the period from 1990 to 2004.

Ideally, analyses of land use change effects on carbon cycling will cover all land uses and tools for such analysis are being developed (for example, Alig et al., 2002). However, forestland and agricultural land are often analyzed separately, so it is vital to assure that such separate estimates can be combined without undercounting or double-counting any sources of carbon emission or sequestration. For example, effects of afforestation may be accounted for in the forest sector, while effects of deforestation may be accounted for in the agricultural sector. For this reason, our model produces separate estimates of the effects of afforestation and deforestation. Additionally, separate estimates are presented for the forest floor and for soil. These separate estimates allow comparisons to be made for individual pools and for results to be combined as needed to avoid double counting.

Model Sensitivity and Key Assumptions

For model predictions from 1990 to 2004, the model is quite sensitive to the parameter values selected for soil carbon density. This is not surprising because effects of afforestation and deforestation in the model are represented as proportions of the average regional soil carbon density value for each forest type, so variation in this parameter directly affects the predicted mass of carbon gain or loss. The soil carbon density values currently used in our model are based on published estimates derived by Johnson and Kern (2003) from the STATSGO soils database. More recent analyses of this database for the states of Maine and Minnesota by Amichev and Galbraith (2004) derive values of forest soil carbon density that are considerably lower than those of Johnson and Kern (2003). The authors attribute these differences to the assumption of a log-normal distribution of soil carbon density values within each forest type and to improved estimates of the volume of rock fragments. If similar results are found for the Southern region of the United States using this approach, estimates of soil carbon density for some forest types could be as much as 50% lower than those currently used our model, with concomitantly large effects as shown in Table 15. Clearly, better estimates of forest soil carbon density are important for estimating effects of afforestation and deforestation on terrestrial carbon fluxes.

Another key assumption in the model is that all soil carbon lost due 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 due 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%. In summary, 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. These considerations suggest that the changes in the tree carbon pool may be even more than sixfold greater on all forestland than those in the soil and forest floor due to land use changes.

CONCLUSIONS

The model estimates changes in the carbon mass of the soil and forest floor based on estimated land use transition rates for large regions of the United States, and the results differ among regions due to different patterns of afforestation and deforestation over time. In the South-Central region, the maximum cumulative effect of land use from 1900 to 2050 is later: during the 1980s (South-Central) as compared to the 1950s (Southeast). This total maximum effect is also much greater in the South-Central region: 210 Tg C (South-Central) versus 70 Tg C (Southeast).

Future rates of change in carbon mass are predicted to be similar in the two regions, but because of the greater total emission in the South-Central region, this region is predicted to have a cumulative loss of 126 Tg C from 1900 to 2050 as compared to a cumulative sequestration of 7 Tg C in the Southeast region. In the future, forest area is predicted to decrease in the Southeast region by 1.7 million ha, while it is predicted to increase in the

South-Central region by 0.5 million ha (Tables 7 and 10). Despite this difference, the pattern of net carbon change from 2004 until 2050 is predicted to be fairly similar in the two regions, with sequestration of 41 Tg C (Southeast) and 57 Tg C (South-Central). These similar net effects are due to similar effects of afforestation and deforestation predicted for the two regions for this time period. Afforestation is predicted to sequester 119 Tg C in the Southeast region and 117 Tg C in the South-Central region. The emission due to deforestation is predicted to be somewhat higher in the Southeast region: 78 Tg C (Southeast) versus 59 Tg C (South-Central).

The effects of land use change on soil and forest floor carbon stocks presented herein can improve the estimates used in greenhouse gas inventories produced to meet reporting requirements under the UNFCCC. From 1990 to 2004 for the entire 13-state southern region of the United States, afforestation caused sequestration of 88 Tg C, of which 47 Tg C was in the soil and 41 Tg C was in the forest floor. During this same period, deforestation caused emission of 49 Tg C, of which 13 Tg C was in the soil and 36 Tg C was in the forest floor. While these changes in soil and forest floor carbon mass are substantial, they are much smaller than changes in tree carbon stocks on all forestland that we have estimated previously. Thus both land use change effects and forest carbon cycling overall in this 13-state region are both dominated by changes in tree carbon stocks.

One important result from the model is that effects of land use change on forest floor carbon stocks are often as great as those on soil carbon stocks. The similar magnitude of effects in the forest floor and soil is surprising because the total carbon stocks in the soil are so much larger than those in the forest floor. However, land use change can cause total loss or gain of forest floor carbon, while only a portion (approximately 25%) of soil carbon stocks are likely affected by land use change. Additionally, effects on forest floor carbon occur in a period of years after a land use change, while effects on soil carbon stocks require many decades. These large predicted effects of land use change on forest floor carbon are important because previous models generally have not evaluated land use change effects on forest floor carbon stocks.

Another key result from the model is that changes in tree carbon stocks on all forestland are sixfold greater than those in soil and forest floor carbon stocks due to land use changes. This result is important because tree carbon stocks have been measured for many years in standard forest inventories, while forest soil and forest floor carbon stocks have not generally been measured in systematic surveys. For this reason, uncertainty in assessing tree carbon stocks in countries with comprehensive forest inventory programs, such as the United States, is much smaller than uncertainty in assessing forest soil and forest floor carbon stocks. Since effects of land use change on tree carbon stocks appear to be so much greater than effects on soil and forest floor carbon stocks, estimates of total forest carbon flux based on inventory appear to be robust even without comprehensive inventory data on changes in soil carbon density.

ACKNOWLEDGMENTS

Our research was supported by the USEPA via interagency agreement number DW-12-93925401-0. We thank Richard Birdsey and George Lewis for providing their estimates of historical land use changes.

REFERENCES

Agarwal, C., G.M. Green, J.M. Grove, T.P. Evans, and C.M. Schweik. 2002. A review and assessment of land-use change models: Dynamics of space, time, and human choice. Gen. Tech. Rep. NE-297. USDA For. Serv., Northeastern Res. Stn., Newtown Square, PA.

Alig, R.J., D.M. Adams, and B.A. McCarl. 2002. Projecting impacts of global climate change on the U.S. forest and agriculture sectors and carbon budgets. For. Ecol. Manage. 169:3–14.

Alig, R.J., and B.J. Butler. 2004. Projecting large-scale area changes in land use and land cover for terrestrial carbon analyses. Environ. Manage. 33:443–456.

Alig, R.J., A. Plantinga, S. Ahn, and J. Kline. 2003. Land use changes involving forestry in the United States: 1952 to 1997, with projections to 2050. Gen. Tech. Rep. PNW-587. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.

Amichev, B.Y., and J.M. Galbraith. 2004. A revised methodology for estimation of forest soil carbon from spatial soils and forest inventory data sets. Environ. Manage. 33:S74–S86.

Birdsey, R.A., and G.M. Lewis. 2003. Current and historical trends in use, management, and disturbance of U. S. forestlands. p. 15–34. *In* J.M. Kimble et al. (ed.) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Caspersen, J.P., S.W. Pacala, J.C. Jenkins, G.C. Hurtt, P.R. Moorcroft, and R.A. Birdsey. 2000. Contributions of land-use history to carbon accumulation in U.S. forests. Science 290:1148–1151.

Coote, D.R., and J.F. Ramsey. 1983. Quantification of the effects of over 35 years of intensive cultivation on 4 soils. Can. J. Soil Sci. 63:1–14.

Davidson, E.A., and I.L. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. Biogeochemistry 20:161–193.

Delcourt, H.R., and W.F. Harris. 1980. Carbon budget of the southeastern U.S. biota: Analysis of historical change in trend from source to sink. Science 210:321–323.

Ellert, B.H., and E.G. Gregorich. 1996. Storage of carbon, nitrogen and phosphorus in cultivated and adjacent forested soils of Ontario. Soil Sci. 161:587–603.

Franzluebbers, A.J., J.A. Stuedemann, H. Schomberg, and S.R. Wilkinson. 2000. Soil organic C and N pools under long-term pasture management in the Southern Piedmont USA. Soil Biol. Biochem. 32:469–478.

Garten, C.T. 2002. Soil carbon storage beneath recently established tree plantations in Tennessee and South Carolina, USA. Biomass Bioenergy 23:93–102.

Giddens, J. 1957. Rate of loss of carbon from Georgia soils. Proc. Soil Sci. Soc. Am. 21:513–515.

Gregorich, E.G., B.H. Ellert, and C.M. Monreal. 1995. Turnover of soil organic-matter and storage of corn residue carbon estimated from natural C-13 abundance. Can. J. Soil Sci. 75:161–167.

Guo, L.B., and R.M. Gifford. 2002. Soil carbon stocks and land use change: A meta analysis. Glob. Change Biol. 8:345–360.

Haynes, R.W. 2003. An analysis of the timber situation in the United States: 1952–2050. Gen. Tech. Rep. PNW-560. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.

Heath, L.S., R.A. Birdsey, and D.W. Williams. 2002. Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001. Environ. Pollut. 116:373–380.

Heath, L.S., J.E. Smith, and R.A. Birdsey. 2003. Carbon trends in U. S. forest lands: A context for the role of soils in forest carbon sequestration. p. 35–46. *In* J.M. Kimble et al. (ed.) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Houghton, R., and J.L. Hackler. 2001. Carbon flux to the atmosphere from land-use changes: 1850–1990. ORNL/CDIAC-131, NDP-050/R1. U.S. Dep. of Energy, Oak Ridge Natl. Lab., Carbon Dioxide Information Analysis Center, Oak Ridge, TN.

Houghton, R.A., and J.L. Hackler. 2000. Changes in terrestrial carbon storage in the United States. 1: The roles of agriculture and forestry. Glob. Ecol. Biogeogr. 9:125–144.

Houghton, R.A., J.L. Hackler, and K.T. Lawrence. 2000. Changes in terrestrial carbon storage in the United States. 2: The role of fire and fire management. Glob. Ecol. Biogeogr. 9:145–170.

Hurtt, G.C., S.W. Pacala, P.R. Moorcroft, J. Caspersen, E. Shevliakova, R.A. Houghton, and B. Moore. 2002. Projecting the future of the US carbon sink. Proc. Natl. Acad. Sci. USA 99:1389–1394.

Johnson, M.G., and J.S. Kern. 2003. Quantifying the organic carbon held in forested soils of the United States and Puerto Rico. p. 47–72. *In* J.M. Kimble et al. (ed.) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Lal, R. 2003. Soil erosion and the global carbon budget. Environ. Int. 29:437–450.

Mann, L.K. 1986. Changes in soil carbon storage after cultivation. Soil Sci. 142:279–288.

Martel, Y.A., and A.F. Mackenzie. 1980. Long-term effects of cultivation and land-use on soil quality in Quebec. Can. J. Soil Sci. 60: 411–420.

Miles, P.D., G.J. Brand, C.L. Alerich, L.F. Bednar, S.W. Woudenberg, J.F. Glover, and E.N. Ezell. 2001. The forest inventory and analysis database description and users manual version 1.0. Gen. Tech. Rep. NC-218. USDA For. Serv., North Central Res. Stn., St. Paul, MN.

Mills, J.R., and X. Zhou. 2003. Projecting national forest inventories for the 2000 RPA timber assessment. Gen. Tech. Rep. PNW-568. USDA For. Serv., Pacific Northwest Res. Stn., Portland, OR.

Murty, D., M.U.F. Kirschbaum, R.E. McMurtrie, and H. McGilvray. 2002. Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. Glob. Change Biol. 8:105–123.

Pennock, D., and C. van Kessel. 1997. Effect of agriculture and of clear-cut forest harvest on landscape-scale soil organic carbon storage in Saskatchewan. Can. J. Soil Sci. 77:211–218.

Pielke, R.A., G. Marland, R.A. Betts, T.N. Chase, J.L. Eastman, J.O. Niles, D.D.S. Niyogi, and S.W. Running. 2002. The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases. Philos. Trans. R. Soc. London Ser. A 360:1705–1719.

Post, W.M. 2003. Impact of soil restoration, management, and land-use history on forest soil carbon. p. 191–200. *In* J.M. Kimble et al. (ed.) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Post, W.M., and K.C. Kwon. 2000. Soil carbon sequestration and land-use change: Processes and potential. Glob. Change Biol. 3: 317–328.

Post, W.M., and L.K. Mann. 1990. Changes in soil organic carbon and nitrogen as a result of cultivation. p. 401–406. *In* A.F. Bouwman (ed.) Soils and the greenhouse effect. John Wiley & Sons, New York.

Pouyat, R., J. Russell-Anelli, I. Yesilonis, and P. Groffman. 2003. Soil carbon in urban forest ecosystems. p. 347–362. *In* J.M. Kimble et al. (ed.) The potential of U.S. forest soils to sequester carbon and mitigate the greenhouse effect. Lewis Publ., Boca Raton, FL.

Sisk, T.D. (ed.) 1998. Perspectives on the land use history of North America: A context for understanding our changing environment. Biol. Sci. Rep. USGS/BRD/BSR 1998-0003 (rev Sept. 1999). USGS, Reston, VA.

Smith, J.E., and L.S. Heath. 2002. A model of forest floor carbon mass for United States forest types. Res. Paper NE-722. USDA For. Serv., Northeastern Res. Stn., Newtown Square, PA.

Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield. 2001. Forest resources of the United States, 1997. Gen. Tech. Rep. NC-219. USDA For. Serv., North Central Res. Stn., St. Paul, MN.

USEPA. 2004. Inventory of U. S. greenhouse gas emissions and sinks: 1990–2002. EPA 430-R-04-003. USEPA, Office of Atmospheric Programs, Washington, DC.

Van Lear, D.H., P.R. Kapeluck, and M.M. Parker. 1995. Distribution of carbon in a piedmont soil as affected by loblolly pine management. p. 489–501. *In* W.W. McFee and J.M. Kelly (ed.) Carbon forms and functions in forest soils. SSSA, Madison, WI.

West, T.O., G. Marland, A.W. King, W.M. Post, A.K. Jain, and K. Andrasko. 2004. Carbon management response curves: Estimates of temporal soil carbon dynamics. Environ. Manage. 33:507–518.

Zhou, X.P., J.R. Mills, and L. Teeter. 2003. Modeling forest type transitions in the southcentral region: Results from three methods. South. J. Appl. For. 27:190–197.