• Effects of forest growth and disturbances on carbon changes in the conterminous US: 1992-2001

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INTRODUCTION

- Global terrestrial Eco. Sequestered 30% (24% by oceans) of 00-06 anthropogenic C emission, **FOREST** in particular, 73% of the world's soil C and 77% of plant C;

- Qualifying nations report GHG emissions/sinks annually under UNFCCC One method is (time2 – time1) / length of the period. Spatial identification of C sinks/sources can provide insight info for linking changes with current manage/policy and suggest place-based mitigation option for climate change.

- GHG estimation began in 1990 and data available for examining disturbance effects are limited. Available land-use/cover change statistics are net, not gross so different C dynamics following Aff/Def cannot be considered; C released during harv. but also stored in wood products/landfills; wildfire emission data are rudimentary. Inventory-based approach cannot identify areas of disturbances while land-cover approach is limited in C estimation. This study combined RS/inventory methods to estimate C change after incorporating disturbances from Harv. and fires at the national level.

- **Overall GOAL** is to estimate the effects of major forest disturbances and net growth on C sequestration in the conterminous United States, in context of the terminology and needs for reporting to the UNFCCC for national GHG inventories.

• DATASETS AND ANALYSES

- 3 regions: N, S, and W based on similar histories of forestland use for regional comparison and analyses **(Fig. 1)**.

- Datasets: 1 NLCD 1992-2001 Retrofit Change Map, 2) Harvest/In use/Landfills, 3) Growth Rate Tables (GRT, Smith *et al* 2006), and 4) F data at the state level from the MTBS **(Table 1) --** a) UN-L (7%) b) L (20%), c) M (40%), d) H (60%).

- Fire emission$_i$ = Area burned$_i$ * Carbon density * Proportion emitted$_i$ [1]

- ABG C pools: live tree, understory, standing & down dead tree, and forest floor. County-level results summarized to S/R/N for analyses. (C gains through aff. Frf. and C loss from def. -- 0.8).

- No soilC due to harvests and fires. SoilC are calculated when F-Ag or vice versa. For Aff. Go to Smith's tables, and for Def. Using a factor of 0.25 to 1-m soil depth because a) highest SoilC emissions in 1st a few year; and b) the factor is comparable.

- Evaluating Area/C changes in relative term (percentage)

- Percent change = (• • • $_{factor}$ / ForestArea$_{noeffect}$) x 100 [2]

- $C_{Net} = C_{Frf} + C_{Aff} + C_{Def} + C_{Harvest} + C_{Use+Fills} + C_{Fire}$ [3]
  Emissions are negative values, so Def., Harv., and fire caused estimates are negative.

- Comparison of our forest area estimation with FIA-based GHG inventory data in both 1992 and 2001 using regression method. Comparing our C estimation with FIA-based C estimation in 2001 to evaluate the difference.

Region	Forest type	Stand age (years)	Volume (m3/ha)	Live tree (t/ha)	Standing dead (t/ha)	Understory (t/ha)	Down dead wood (t/ha)	Forest floor (t/ha)	Soil (t/ha)	Total nonsoil (t/ha)
NE	Aspen-birch	0	0	0	0	2	18.7	10.2	87.4	31
NE	Aspen-birch	5	0	6.6	0.6	2.2	12.9	7.5	87.4	29.8
NE	Aspen-birch	15	12.9	21.3	1.8	2.1	7.1	6	87.4	38.4
NE	Aspen-birch	25	33.8	36	2.9	2.1	5.2	6.5	87.4	52.7
NE	Aspen-birch	35	58.4	50.1	3.8	2.1	4.9	7.5	87.4	68.4
NE	Aspen-birch	45	84.7	62.7	4.6	2.1	5.3	8.5	87.4	83.1
NE	Aspen-birch	55	112.4	75.1	5.3	2	6	9.3	87.4	97.8
NE	Aspen-birch	65	141.7	87.5	5.9	2	6.9	10.1	87.4	112.4
NE	Aspen-birch	75	172.6	100	6.5	2	7.8	10.7	87.4	127.1
NE	Aspen-birch	85	205	112.7	7.1	2	8.8	11.3	87.4	141.9
NE	Aspen-birch	95	238.9	125.5	7.7	2	9.8	11.8	87.4	156.7
NE	Aspen-birch	105	274.4	138.5	8.2	2	10.8	12.2	87.4	171.7
NE	Aspen-birch	115	311.4	151.7	8.8	2	11.8	12.5	87.4	186.8
NE	Aspen-birch	125	349.9	165	9.3	2	12.8	12.9	87.4	202
NE	Maple-beech-birch	0	0	0	0	2.1	32	27.7	69.6	61.8
NE	Maple-beech-birch	5	0	7.4	0.7	2.1	21.7	20.3	69.6	52.2
NE	Maple-beech-birch	15	28	31.8	3.2	1.9	11.5	16.3	69.6	64.7
NE	Maple-beech-birch	25	58.1	53.2	5.3	1.8	7.8	17.6	69.6	85.7
NE	Maple-beech-birch	35	89.6	72.8	6	1.7	6.9	20.3	69.6	107.8
NE	Maple-beech-birch	45	119.1	87.8	6.6	1.7	7	23	69.6	126
NE	Maple-beech-birch	55	146.6	101.1	7	1.7	7.5	25.3	69.6	142.7
NE	Maple-beech-birch	65	172.1	113.1	7.4	1.7	8.2	27.4	69.6	157.7
NE	Maple-beech-birch	75	195.6	123.8	7.7	1.7	8.8	29.2	69.6	171.2
NE	Maple-beech-birch	85	217.1	133.5	7.9	1.7	9.5	30.7	69.6	183.2
NE	Maple-beech-birch	95	236.6	142.1	8.1	1.7	10.1	32	69.6	193.9

Table 1. Annual mean forest area burned by wildfires from 1984 to 2006 for the 48 conterminous U.S. by state obtained from the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink *et al* 2007).

State	Record Period	Number of Year[1]	Annual Area Burned[2] (ha)
Alabama*	99-06	7	3022
Arizona^	84-06	23	24651
Arkansas*	00-06	5	5181
California^	84-06	23	39500
Colorado^	86-06	18	10289
Virginia*	01-06	4	881
Washington^	84-06	23	11902
West Virginia	NA		
Wisconsin	06-06	1	10
Wyoming^	85-06	13	17243
Total			339958

[1] Actual number of years with fire records.

[2] Annual burned areas were calculated as total burned areas (including all 4 severity classes) during the recording period divided by the number of recording years for each states.

RESULTS

- **Forest Area Changes**: In 9 yrs, 34800 - 93200 = -58 400 km2 (-2.9%, or 0.3%/yr) ranging from -1.1% in N to -5.4% in S by **REGION (Table 2)** and by **STATE** from -8.5% in LA to a 1.8% in KS. 3.1% of land experienced LCC and 53.3% was forest related.

- **Forest C Changes**: The nation sequestered 1.6 ± 0.1 Pg C in 9 yrs (or 0.18 Pg C/yr). 2/3 (1.1 Pg) in W while -0.06 Pg C in S. US **(Fig. 1)**. LA's forests is the strongest Csource (-1.82 Mg C/ha/yr) WA Csink (3.95 Mg C/ha/yr) **(Table 4)**. For total net C, OR (34 Tg C/yr) whereas GA was the largest Csource (-6 Tg C/yr) during the period **(Table 3)**.

- **Disturbances:** Distu. reduced C sink by 36% compared to without… **(Table 2),** varying from 23% in W to 51% in S. **63%** (Harv), **33%** (LCC, Aff – Def), and **4%** (Fire) **(Table 5)**. Forest Harvesting accounted for 70% of all C loss in S, compared to only 42% in W. 15% of C losses were attributed to fires in W, more than triple of the nation's average **(Table 5)**.

- **Comparison with FIA**: ***1) For C:*** 7% 5.3% (U.S.), 4.7 ± 4.5% (W), and 8.4 ± 5.0% (S) 2001 as example (Fig. 2); and ***2) For Area:*** Good correlations were observed although large differences exist (r >0.82 for both 92 and 01). r = 0.95 without TX **(Fig. 3c)**. 18.4 ± 14.9% in 2001 after area weighting **(Table 6)**. RS < FIA, especially Farea > 40 - 50 000 km2. The states with errors > 30% were caused by more wetland or large proportion of rangeland **(Table 6)**.

Figure 1. Annual rate of forest carbon sequestration over the period of 1992 and 2001 per unit forestland in the conterminous U.S. by state after incorporating major disturbances (land cover change, harvests, and fires). Negative numbers indicate a carbon source and positive numbers suggest a carbon sink.

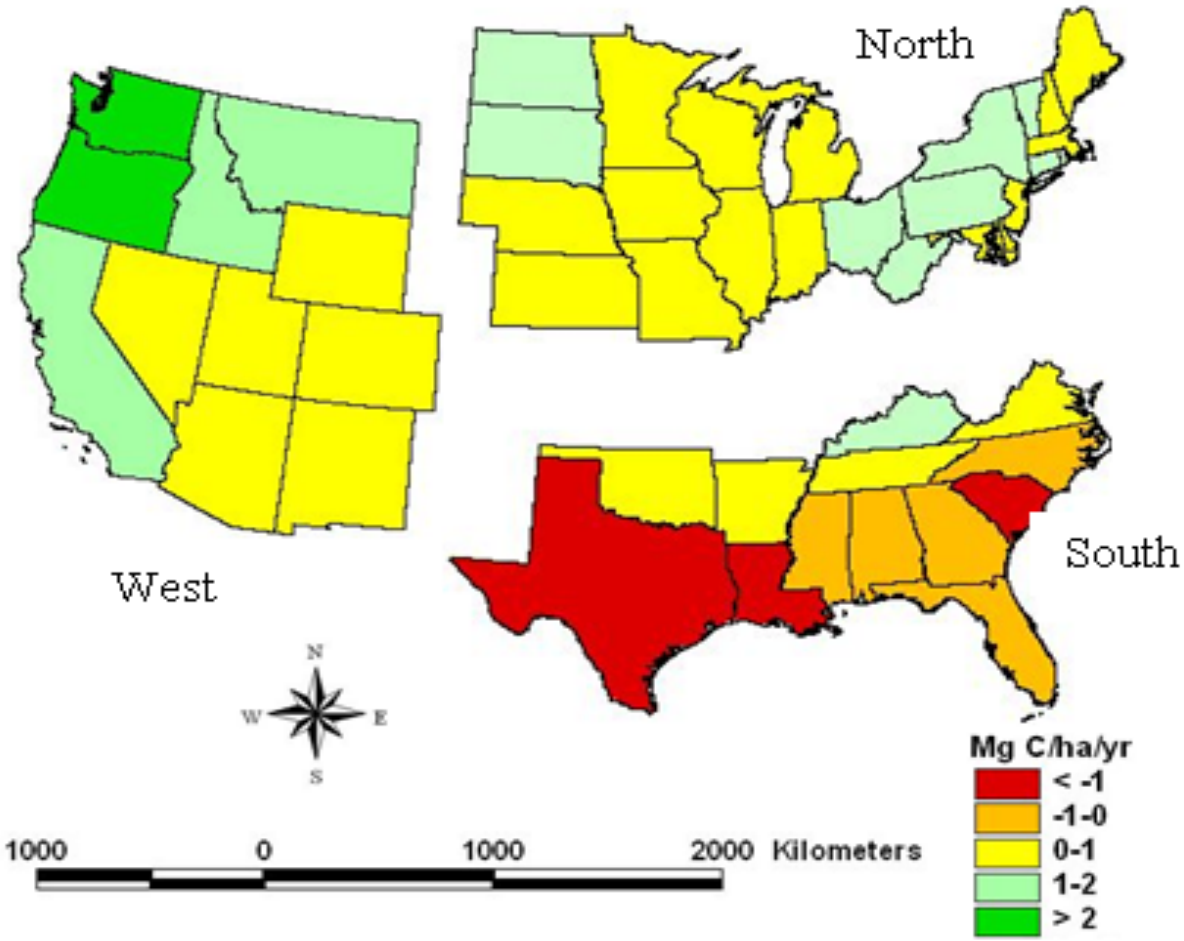


Table 2. Forest-related land cover (km^2) and carbon (1000 tonnes) changes associated with disturbances during the 9-year period (1992-2001) by region in the lower 48 US states. Aff = afforestation, Def = deforestation, Frf = forestland remaining forestland.

	Forest-Related Land Cover			Carbon Change by Land Cover, Harvest, and Fire					
Region	Aff	Def	Frf[1]	Aff[a]	Def[b]	Frf[c]	Harvest[2]	Fire	Net[d]
North	8921	16464	656418 (-1.1)	11096	-150293	1040591	-297816 (-20.0)	-9561	594017 (-30.0)
South	21308	55883	605635 (-5.4)	38066	-368218	1060052	-783490 (-35.9)	-6980	-60570 (-51.4)
West	4609	20895	712379 (-2.2)	5405	-210622	1574857	-198659 (-9.7)	-72890	1098091 (-23.2)
US48	34838	93242	1974432 (-2.9)	54567	-729133	3675500	-1279965 (-22.4)	-89431	1631538 (-35.7)

[1] Numbers in the parentheses indicated area changes in percent of net forestland cover change to that without the change: (Aff – Def) / (Frf – Aff + Def) * 100.

[2] Quantification of harvest effects (excluding the amount of carbons stored in wood products and landfills) on carbon sequestration without disturbances in the parentheses as percentages, calculated as: $C_{Harvest}$ / (C_{Frf} - C_{Aff} - C_{Def} - $C_{Harvest}$ - C_{fire}) * 100.

[a] Carbon gains including soil carbon through afforestation were estimated using carbon accumulation tables for afforestation (Smith *et al* 2006), assuming the average age of 5 years for the 9-year period.

[b] Carbon losses through deforestation were estimated using average forest aboveground carbon density by county from the latest FIA data, assuming that 20% of the aboveground forest carbon remained after forest became nonforest. Soil carbon losses were calculated using soil carbon stocks (Smith *et al* 2006) and a conversion loss of 0.25 for the period.

[c] Carbon sequestration by forestland remaining forestland was estimated using carbon accumulation rate for reforestation (Smith *et al* 2006), determined by mean total live-tree biomass of the most common forest type in a given county.

[d] Net change in C during the period = (C_{Frf} + C_{Aff} + C_{Def} + $C_{Harvest}$ + C_{fire}). Numbers in the parentheses are the disturbance rates in percentage of carbon change during the period, calculated as (C_{Aff} +C_{Def} + $C_{Harvest}$ + C_{fire}) / (C_{Frf} - C_{Aff} - C_{Def} - $C_{Harvest}$ - C_{fire}) * 100, comparing to as if no disturbance had occurred.

Table 3. Forest-related land cover (km^2) and carbon (1000 tonnes) dynamics during the 9-year period (1992-2001) by state in the conterminous U.S. caused by land cover, and other disturbances. Aff = afforestation, Def = deforestation, Frf = forest remaining forest.

State	Land Cover			Carbon Change[1] by Land Cover, Harvest, and Fires						
	Aff	Def	Frf	Aff	Def	Frf	Harv.	Use+Fills	Fire	Net[2]
Alabama*	2171	6821	69719	4248	-40775	122596	-129530	17167	-390	-26684(-3)
Arizona^	189	685	44766	200	-3112	34530	-1929	237	-3952	25974(3)
Arkansas*	840	3336	62509	1543	-22330	109118	-70383	9795	-596	27147(3)
California^	652	2325	96673	799	-30037	233653	-57077	10093	-16310	141121(16)
Colorado^	733	3331	77110	763	-25000	70437	-4134	289	-3160	39195(4)
Florida*	2609	4943	27668	3628	-27607	46296	-50073	6289	-672	-22139(-2)
Georgia*	3673	9495	69268	6116	-61648	117141	-131376	17514	-266	-52519(-6)
Louisiana*	1841	4084	24099	3609	-23544	40727	-72657	9413	-202	-42654(-5)
Maine	940	2686	57912	1414	-22462	98958	-48690	6343	-34	35529(4)
Oregon^	510	4389	93670	651	-55755	425321	-71301	14175	-10726	302365(34)
Pennsylvania	533	1262	70098	677	-12884	132734	-24971	4065	-134	99487(11)
Washington^	456	2600	74494	737	-39422	372478	-71752	14334	-7184	269191(30)
West Virginia	160	659	50585	193	-6382	99457	-17642	3225	0	78851(9)

Table 4. Annual carbon sequestration and emission rates (Mg C ha^{-1}) per unit forestland during the 9-year period by state in the conterminous U.S. Carbon sequestration includes afforestation and forest remaining forest. Carbon emission includes deforestation, harvest (after deducting the amount of carbon reserved in the wood products and landfills), and fires.

State	Sequestration	Emission
Alabama*	1.93	2.33
Arizona^	0.86	0.22
Arkansas*	1.92	1.45
California^	2.66	1.06
Colorado^	1	0.45
Connecticut	2.3	0.67
Delaware	2.25	1.47
Florida*	1.84	2.66
Georgia*	1.85	2.64
Idaho^	2.11	0.67
Illinois	1.17	0.74
Indiana	1.09	0.86
Iowa	1.4	0.78
Kansas	1.55	0.55
Kentucky*	2.05	0.76
Louisiana*	1.88	3.7
Virginia*	2.01	1.21
Washington^	5.47	1.52
West Virginia	2.17	0.45
Wisconsin	1.73	0.92
Wyoming^	0.91	0.42
North Region	1.76	0.77
South Region	1.93	2.03
West Region	2.43	0.74
Total	2.05	1.15

* 13 states in the South.

^ 11 states in the West, the remaining 24 states are in the North.

Fig. 2. Net carbon flux is the annual mean of the 9-year period (Tg C/yr). Annual mean pre-disturbance C flux excludes disturbances from deforestation, harvests, and fires. "-" = C source and "+" = carbon sinks. Carbon and area differences (%) are comparisons between our estimates and the estimates from the FIA (Reference numbers). Error bars = one standard deviation (%).

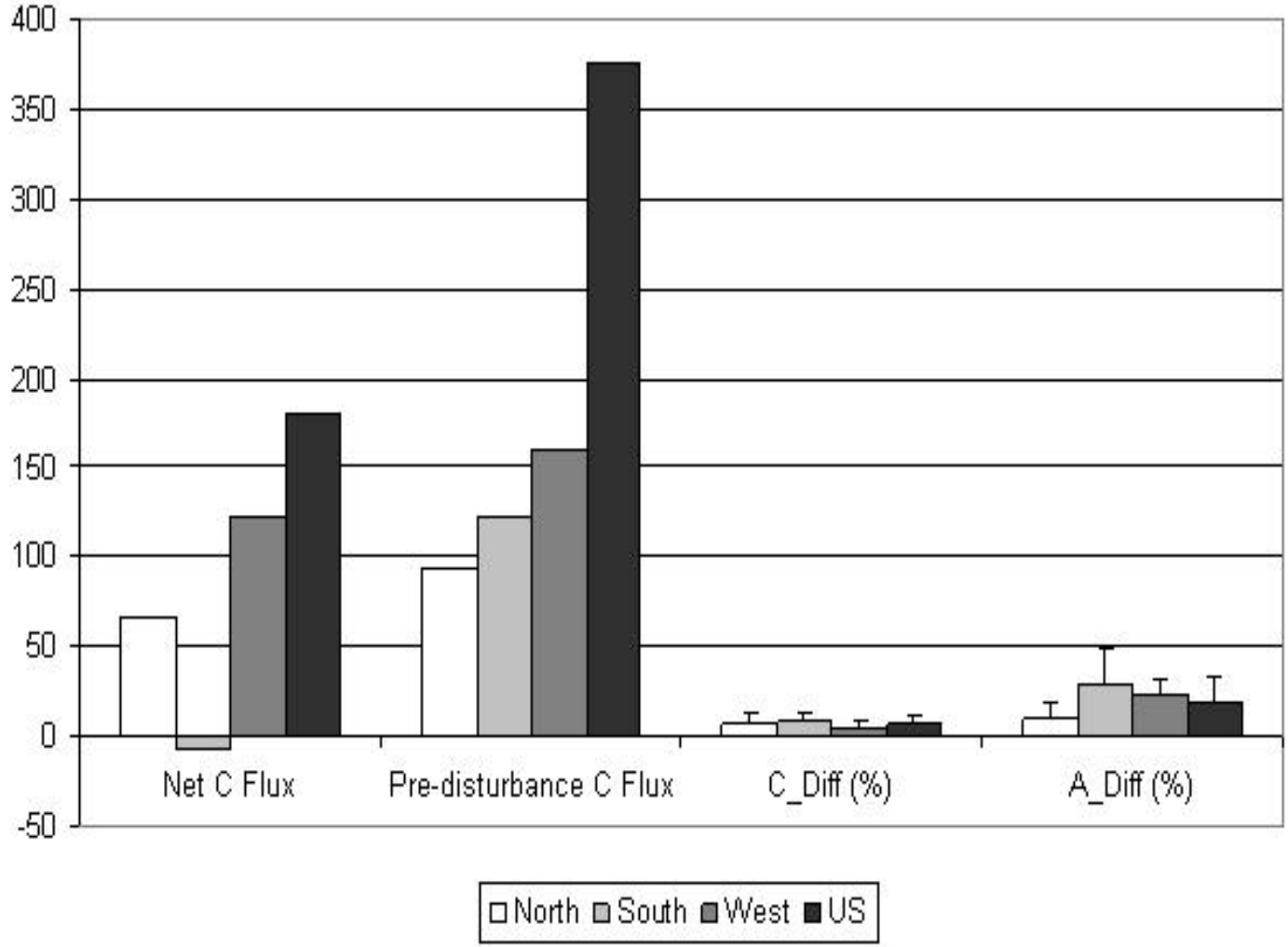
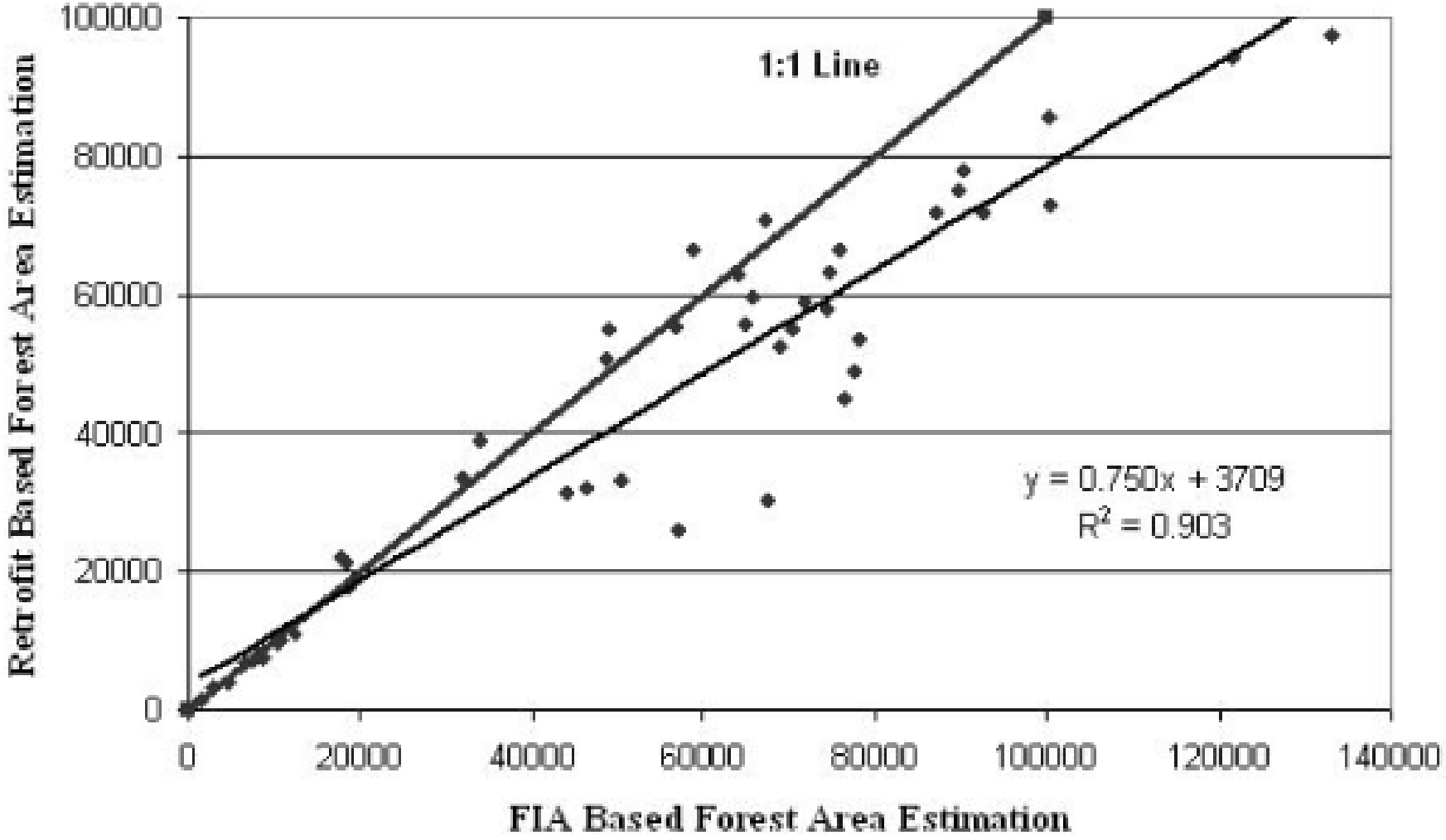


Table 5. Partitioning the effects (%) of major disturbances on forest C dynamics by region in the lower 48 states (92-01).

Region	Cover Change	Harvest	Fire
North	31.2	66.7	2.1
South	29.5	69.9	0.6
West	43.0	41.7	15.3
US48	33.0	62.6	4.4

- Fig. 3.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R2 = 0.903
Retrofit Based Forest Area Estimation
FIA Based Forest Area Estimation
0
20000
40000
60000
80000
100000
120000
140000

Table 6. Error assessments in forest carbon and forest area by comparing the estimated carbon accumulation and forest area obtained from the Retrofit Change Map approach with the corresponding FIA inventory-based estimates of 2001 in the 48 states. The differences (in percent) were calculated as ($Value_{Est/Retr}$ / $Value_{FIA}$ – 1) * 100.

State	Carbon[1] (Tg)			Area (km^2)			
	FIA	Estimated	Diff. (%)	FIA	Retrofit	Diff. in %[2]	
Alabama*	667	593	-11	92516	71896	-22.3	
Arizona^	445	485	9.1	76405	44960	-41.2	*(78)*
Arkansas*	625	645	3.1	74582	63350	-15.1	
California^	2108	2086	-1	132986	97348	-26.8	
Colorado^	894	890	-0.4	90128	77912	-13.6	
Connecticut	93	98	5.6	7349	7304	-0.7	
Delaware	17	18	2.7	1530	1281	-16.3	
Florida*	446	387	-13.4	67331	30308	-55	(35)
Kentucky*	474	530	11.8	48841	54845	12.2	
Louisiana*	447	407	-9	56922	25952	-54.5	(32)
Maine	730	781	7	71650	58947	-17.8	
Maryland	124	125	0.9	10267	9802	-4.6	
Massachusetts	166	159	-4.3	12529	11082	-11.6	
Michigan	803	850	5.9	78135	53716	-31.3	(19)
Minnesota	515	583	13.2	65743	59787	-9.1	
Mississippi*	576	494	-14.3	77576	48823	-37.1	(14)

Texas*	957	902	-5.7	243527	72571	-70.3	*(58)*[3]
West Virginia	565	622	10.2	48586	50747	4.4	
Wisconsin	592	617	4.2	64843	55650	-14.2	
Wyoming^	468	476	1.7	46254	32070	-30.7	*(80)*
Mean[4]			7.0			18.4	
Std			5.3			14.9	

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[1] Nonsoil carbon includes live tree, understory, standing dead tree, down dead wood, and forest floor (Smith *et al* 2007).

[2] Numbers in the parentheses represent the percentage of rangeland (in *italic*) or wetland in relation to the total land of a given state, the two land cover types with low classification accuracies in the Retrofit Change Map. Inventory-based forest area data were obtained from Smith *et al* (2007).

[3] The Forest Service recently designated a portion of the land in west TX as forestland rather than rangeland.

[4] Mean and standard deviation of percentage differences were obtained from absolute value.

DISCUSSION

- Our estimation (0.180 Pg C/yr) is within the range of previously reported estimates (0.079 - 0.35 Pg C/yr with varying methods RS/Invent./model.). Schimel *et al* (2000) estimated 0.1 Pg C/yr (80-93) caused by climate change, suggesting other processes like forest growth must cause a sink of about 0.2 Pg C/yr (given a total of 0.3 Pg C/yr).

- Uncertainty sources: **First** is from forest area identification caused by 1) mapping accuracy limits (80% in 92 and 85% in 01 at Anderson I); and 2 definitional differences between RS and Inventory methods.

- **Second** double counting between LCC and harvest may exist – 2 examples. Non-spatial harv. data make the spatial identification be difficult and this deserves more studies.

- **Third** Fire effects are likely underestimated because of limitations in 1) minimum mapping unit (202 ha in E U.S. and 404 ha in W U.S.); and 2) prescribed fires on private land holdings were not included and these can be common in the South.

- **CONCLUSIONS**

- Despite these uncertainties, our results are unique and informative from the following perspectives:

- 1) This study analyzes and documents the roles of growth, disturbances and land cover change across the U.S.., highlighting regional differences that are important both for ecological interpretation and policy implications.

- 2) We identify forest change status (e.g., NonF-For, For - NonF) to improve C change estimation at the national level, which is information needed for US GHG reporting to the UNFCCC;

- 3) Our methodology, combining RS-based product with Inventory data, can provide relatively consistent and comparable results on large-scale C estimation. RS-based approach and are especially useful for forest C studies, especially in remote areas and developing countries where inventory data are lacking, given the fact that periodical global land-cover maps at a 5-year interval are planned at fine and moderate resolutions (between 10m and 30m).

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