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Carbon changes in conterminous US forests associated with growth and major disturbances.

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Corrigendum

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The descriptors in table 1 were incorrectly assigned. The amended version can be found below:

Table 1. 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[a]	Aff[b]	Def[c]	Frf[d]	Harvest[e]	Fire	Net[f]
North	8 921	16 464	656 418 (−1.1)	11 096	−150 293	1040 591	−297 816 (−20.0)	−9 561	594 017 (−30.0)
South	21 308	55 883	605 635 (−5.4)	38 066	−368 218	1060 052	−783 490 (−35.9)	−6 980	−60 570 (−51.4)
West	4 609	20 895	712 379 (−2.2)	5 405	−210 622	1574 857	−198 659 (−9.7)	−72 890	1098 091 (−23.2)
US48	34 838	93 242	1974 432 (−2.9)	54 567	−729 133	3675 500	−1279 965 (−22.4)	−89 431	1631 538 (−35.7)

[a] Numbers in the parentheses indicated area changes in per cent of net forestland cover change to that without the change: (Aff − Def)/(Frf − Aff + Def) × 100.

[b] 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.

[c] 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.

[d] 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.

[e] 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: $C_{\text{Harvest}}/(C_{\text{Frf}} - C_{\text{Aff}} - C_{\text{Def}} - C_{\text{Harvest}} - C_{\text{fire}}) \times 100$.

[f] Net change in carbon during the 9-year period = $(C_{\text{Frf}} + C_{\text{Aff}} + C_{\text{Def}} + C_{\text{Harvest}} + C_{\text{fire}})$. Negative numbers indicate carbon sources while positive numbers represent carbon sinks. Numbers in the parentheses are the disturbance rates in percentage of carbon change during the period, calculated as $(C_{\text{Aff}} + C_{\text{Def}} + C_{\text{Harvest}} + C_{\text{fire}})/(C_{\text{Frf}} - C_{\text{Aff}} - C_{\text{Def}} - C_{\text{Harvest}} - C_{\text{fire}}) \times 100$. In the other words, we compared the forest carbon changes caused by disturbances during the period to the carbon change as if no disturbance had occurred.

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Carbon changes in conterminous US forests associated with growth and major disturbances: 1992–2001

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Abstract
We estimated forest area and carbon changes in the conterminous United States using a remote sensing based land cover change map, forest fire data from the Monitoring Trends in Burn Severity program, and forest growth and harvest data from the USDA Forest Service, Forest Inventory and Analysis Program. Natural and human-associated disturbances reduced the forest ecosystems' carbon sink by 36% from 1992 to 2001, compared to that without disturbances in the 48 states. Among the three identified disturbances, forest-related land cover change contributed 33% of the total effect in reducing the forest carbon potential sink, while harvests and fires accounted for 63% and 4% of the total effect, respectively. The nation's forests sequestered 1.6 ± 0.1 Pg (10^{15} petagram) carbon during the period, or 0.18 Pg C yr^{-1}, with substantial regional variation. The southern region of the United States was a small net carbon source whereas the greater Pacific Northwest region was a strong net sink. Results of the approach fit reasonably well at an aggregate level with other related estimates of the current forest US greenhouse gas inventory, suggesting that further research using this approach is warranted.

Keywords: carbon in harvested wood, forest area, harvest, greenhouse gas inventory, land cover change, wildfire emissions

S Online supplementary data available from stacks.iop.org/ERL/6/014012/mmedia

1. Introduction

Recent studies of the global carbon cycle suggest terrestrial ecosystems play a significant role of CO_2 uptake in the overall budget (Oren *et al* 2001, Canadell *et al* 2007). Oceanic sinks accounted for 24% of total anthropogenic carbon emissions from 2000 to 2006, while land sinks accounted for 30% (Canadell *et al* 2007). Temperate and boreal forests sequester about 1–2 Pg C yr^{-1} (Bousquet *et al* 2000, IPCC 2000), an amount equivalent to 15–30% of annual global emissions of carbon from fossil fuels and industrial activities (Myneni *et al* 2001). Thus, forest ecosystems play an important role in the global carbon cycle, and their management could therefore play an important role in reducing atmospheric carbon dioxide. Because of the significance of forest changes to the global carbon budget, under the United Nations Framework Convention on Climate Change (UNFCCC), qualifying nations have agreed to report their greenhouse gas (GHG) emissions and sinks annually, and forest carbon sinks continue to be a part of the active discussion regarding greenhouse gas emissions reduction commitments (UNFCCC 2011a, 2011b).

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For forests, change estimates in the GHG inventories used in the reporting process to the UNFCCC can be calculated by calculating the difference between two carbon stock inventories, dividing by the length of time between the inventories, and multiplying by the factor to express carbon in terms of CO_2 (Heath *et al* 2011b). The inventories must be transparent, consistent, comparable, and accurate (Todorova *et al* 2003). Analysis of ongoing reporting for these inventories indicates that spatial identification of carbon sink or source locations, as well as explicitly estimating growth and disturbance contributions to net forest carbon changes can enhance insight for linking changes with current management and policy, and suggest place based mitigation options for climate change. Furthermore, the area of forest and forest-related land cover changes, and forest carbon stock per area are needed as a quality check on land based carbon changes for the GHG inventories (Smith and Heath 2010). In addition, separation of disturbances into natural and human caused is of interest because these two effects can enhance our understanding of the mechanisms and processes responsible for the current sink, and for reporting to the UNFCCC because the focus is on carbon changes from human-caused activities (Fan *et al* 1998, Pacala *et al* 2001, Potter *et al* 2007).

Carbon from forests can also have benefits beyond the forest boundary. Carbon can be released during harvests, but can also be stored for long periods of time in wood products, or as discarded wood products in landfills (Birdsey *et al* 1993). Thus, estimates of carbon in harvested wood products are also important for the overall estimation of forest carbon change.

In the United States, which contains the fourth largest area of forestland among countries in the world (FAO 2010), forests including carbon in harvested wood products and urban forests, are estimated to be an average net carbon sink of 0.24 $\mathrm{Pg\ C\ yr^{-1}}$, with wildfire emissions averaging the equivalent of 0.05 $\mathrm{Pg\ C\ yr^{-1}}$ (Heath *et al* 2011a, USEPA 2010). The current GHG forest inventory approach is based on data from the USDA Forest Service, Forest Inventory and Analysis (FIA) program, whose national forest survey design was modified in the mid- to late-1990s. Carbon change is calculated as a function of forest area and net land cover change, net carbon accumulation curves per area, and harvesting. Because the GHG inventories require estimates to begin in 1990, data available from the US FIA forest inventory are such that disturbance effect calculations are limited. Wildfire emissions are rudimentary, based on a dataset for all lands, not just forestland. Land use change statistics currently used are net, meaning that even though both deforestation and afforestation may be occurring, only the overall change in land use is reported over the period. Without the separate increases and decreases of land use change, the different carbon dynamics following deforestation or afforestation cannot be included.

The goal of this study 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. Future forest disturbances such as wildfires or land cover change may greatly contribute to increased forest emissions (e.g., Kurz *et al* 2008), so an explicit recognition of disturbance effects is needed. We focus on the major disturbances of land cover change, harvesting, and forest wildfires. Wildfire is considered a natural disturbance, although if the dataset identified fire ignition type of human versus natural, we could easily incorporate that information and distinguish fires directly set by humans. Forest GHG inventory reporting related to land cover change can be summarized in three categories (IPCC 2003, 2006): non-forest becoming forest, forestland remaining forestland, and forest becoming non-forest. We call the first category afforestation, the last category deforestation, and use the term forestland remaining forestland for those areas which are observed to remain as forest over the time period, even if they are harvested. In addition to carbon estimates, the magnitudes of area or changes in forest area also play a major role in reporting, because they provide a check on the carbon changes. Forest area estimates alone can be notably different because of definitional differences. The definition of forestland is crucial because different datasets may be based on different definitions, which complicates comparisons of approaches. Thus, we compare areas estimated using two different methods to understand how much of the area and carbon differences may be based on methodological and definitional differences in forest area. Note that interpreting results of this study beyond forest boundaries should be conducted with caution because the value chain of forest-related carbon benefits is complex (Heath *et al* 2010).

2. Approach and datasets

Our study area covers the 48 conterminous states with a total area of about 7.8 million $\mathrm{km^2}$ (27% forested). We divide the United States into three regions: north, south, and west, mainly based on similar histories of forestland use (Heath and Birdsey 1993) for regional comparison and analyses (figure 1). Forest carbon pools considered include live tree, understory, standing dead tree, down dead wood, forest floor, and soil carbon. Harvested wood products (HWP) carbon includes carbon in products in use, and stored in landfills. The fate of harvest residues in the forest is accounted for in the forest ecosystem.

Forest carbon changes are calculated by multiplying the respective areas, including disturbed areas, by the appropriate carbon change per respective area. The exception is the estimation of the contribution of carbon in HWP. Harvested wood may come from intermediate treatments (treatments not intended to cause regeneration), partial harvest or clearcutting forests, deforestation, and non-forest land trees, so that area of clearcuts cannot represent all these wood sources. More details are presented in the following sections.

2.1. Forest area

We used the National Land Cover Database (NLCD), 1992–2001 Retrofit Change Map (Fry *et al* 2009) to quantify area changes during the period among the eight primary cover types at Anderson level I, a national land use and land cover classification system aggregated from the level II to meet

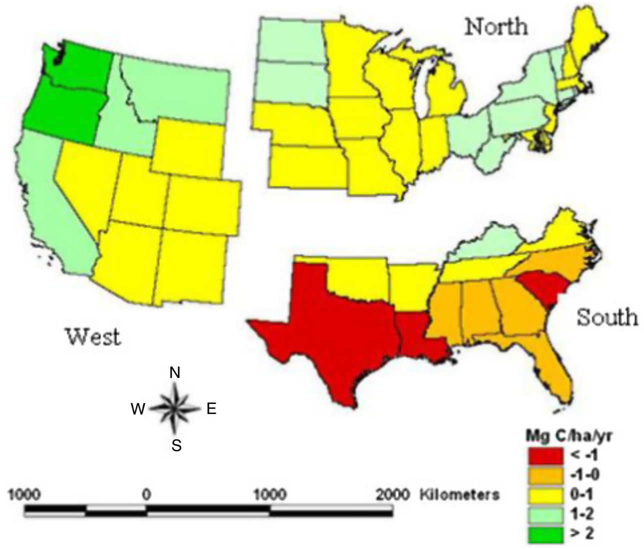

Figure 1. Annual rate of forest carbon sequestration over the period of 1992 and 2001 per unit forestland in the conterminous US by state after incorporating major disturbances (land cover change, harvests, and fires). Negative numbers indicate a carbon source and positive numbers suggest a carbon sink. Forest areas for all the states were calculated as the average of the 1992 and 2001 from the Retrofit Change Map.

the needs of Federal and state agencies for use with remote sensing data (Anderson *et al* 1976). The eight primary classes in the map are: (1) open water (2) urban, (3) barren, (4) forest, (5) grass/shrub, (6) agriculture, (7) wetland, and (8) ice/snow, with other secondary classes generated from these eight primary classes to indicate land cover type changes during the period. For example, class 64 indicates the land was converted from agriculture (primary class six) in 1992 to forest (primary class four) in 2001 and so on. We generalized all forest-related land cover changes into three categories: (1) afforestation (from non-forest to forest), (2) deforestation (from forest to non-forest), and (3) forestland remaining forestland, because the carbon dynamics differ for each of these land cover changes.

The definition of forestland from NLCD is based on land cover, not land use. Forests are defined as areas dominated by trees generally taller than 5 m, and greater than 20% of total vegetation cover, including deciduous forest, evergreen forest, and mixed forest (Homer *et al* 2004). Studies on carbon changes using FIA survey data are based on the definition of forest land use, that is an area that is at least 10% stocked with tree species, at least 0.4 ha in size, and at least 36.6 m wide, and is not developed for a non-forest land use, such as a campground. Previously forested land that is not stocked, such as a clearcut or area which has been burned by wildfire, is still considered forestland (Bechtold and Patterson 2005). Forest area based on the inventory data is calculated using the proportion of field plots which are identified as forestland, applied to land area statistics from the US Bureau of the Census (Bechtold and Patterson 2005).

Previous studies using land cover datasets focused on area and area change (Drummond and Loveland 2010, Hansen *et al* 2010), and commentary on those studies (Reams *et al* 2010), indicate that the different approaches (using gross land cover based datasets and net change inventory based datasets) have different advantages and limitations. The inventory based approach as implemented is limited in identifying areas of disturbance, and the land cover approach is limited in carbon estimation. Thus, we adopt the land cover change map for identifying areas of disturbances, and the inventory based data for per area carbon changes. We note that this method may continue to prove useful over larger scales given that periodical global land cover maps at 5-year intervals are planned at fine and moderate resolutions (between 10 m and 30 m) in the next decade (Gutman *et al* 2008, Townshend *et al* 2008).

2.2. *Growth per area and forest carbon density changes*

Forest carbon density changes for various forest types under different forestland change categories were calculated using net carbon accumulation tables (carbon growth curves by forest age) from which annual change in pools can be calculated (Smith *et al* 2006). Smith *et al* (2006) is extensively based on FIA data, and presents tables of carbon accumulation by forest age by region and forest type, and for afforestation and forestland remaining forestland. Selection of the most-representative carbon density table for each county was based on the most abundant forest type by area within each county according to FIA data. The mean carbon density in the county on forestland was used to infer average age from which the corresponding growth rate for that age interval was determined. We estimated net carbon density change on forestland remaining forestland based on the growth rate and the area determined. All county-derived results were tallied to and reported at the state level for analyses. State-level estimates were grouped into three regions and tallied for the country.

To estimate carbon gains in afforestation during the 9-year period, an annual mean growth rate for a given forest type was determined assuming a mean forest age of 5 years, which is about the midpoint of a 9-year period. The carbon growth per area was then multiplied by area of afforestation. To calculate carbon loss from deforestation, we determined mean forest carbon density (Mg C ha^{-1}) for a given county multiplied by the corresponding area of deforestation, and by an assumed loss factor of 0.80. This factor was based on the assumption that 80% of the aboveground forest carbon would be lost during conversion to non-forest (Smith and Heath 2008). The processes of deforestation and afforestation can significantly affect soil carbon dynamics, especially when forestland is converted to croplands or vice versa (Davidson and Ackerman 1993, Birdsey 1996, Heath and Smith 2000, Woodbury *et al* 2006). The highest rates of soil carbon loss usually occur within the first 5–15 years although soil carbon loss can continue for several decades after deforestation (Houghton *et al* 1991, Birdsey and Heath 1995, Woodbury *et al* 2006). In this study, we estimate soil carbon changes for afforestation and deforestation for conversions between forestland and agricultural land based on soil carbon stocks from Smith *et al* (2006). The increase for afforestation was approximately one to two per cent depending on forest type over the 9-year period to a 1 m soil carbon depth. Because Smith *et al* (2006) does not include estimates for deforestation, we adopted a factor of 25% loss over the 9 years to the 1 m soil carbon depth for the forest types in Smith *et al* (2006). This percentage is comparable with the numbers used in other similar studies (Birdsey and Heath 1995, Heath and Smith 2000, West *et al* 2004, Woodbury *et al* 2006).

Results from a recent meta-analysis of published forest soil carbon literature (Nave *et al* 2010) continue to demonstrate that mineral soil carbon does not change significantly due to harvest. Thus, we assume zero change in soil carbon due to harvest on forestland remaining forestland. Effects of harvesting on aboveground forest carbon are already excluded from the net growth increases on forestland remaining forestland at the state level. We described these data next.

2.3. Carbon in HWP

Estimates of carbon in harvested wood are based on the FIA data and standard methods for calculating carbon in harvested wood products from those data. The volume of timber removed according to roundwood products by state, county, species group, and type of product are estimated and compiled periodically and made available on the Internet by FIA as part of the timber product output (TPO) data (USDA Forest Service 2010b). Roundwood is defined as wood cut from trees for industrial manufacture or consumer uses (Johnson 2001). Factors for carbon mass per unit volume of wood are based on specific gravity and carbon content of wood. Expansion factors to account for total aboveground biomass from merchantable wood are based on averages from these components compiled from FIA forest inventory data (USDA Forest Service 2010a). Due to lack of harvest data in the western states, and the periodic nature of the data, the annual average estimates from the TPO reports for 1996 and 2001 are converted into harvested carbon at the state level, and multiplied by nine to represent the entire period.

2.4. Forest fire emissions

Fire data were obtained at the state level from the Monitoring Trends in Burn Severity (MTBS), a multi-year project designed to consistently map the burn severity and perimeters of fires greater than a threshold size across all lands of the United States for the period spanning 1984–2010 (Eidenshink *et al* 2007). This study concerned the areas burned in forest fires only. Because the dataset was not complete at the time we conducted the analyses, numbers of years with observation records varied from state to state. To deal with this issue, we obtained average annual mean burned area for each of the 48 states based on data availability (see table S1 available at stacks.iop.org/ERL/6/014012/mmedia), and then multiplied by nine to estimate burned area for the period.

To convert carbon emission from burned areas, we aggregated the burned areas by four severity classes: (1) unburned to low, (2) low, (3) moderate, and (4) high. Emissions were estimated for burned areas using equation (1) because carbon consumption rates varied substantially with burn severity ($_i$):

$$\text{Fire emission}_i = \text{Area burned}_i \times \text{Carbon density} \times \text{Proportion emitted}_i. \quad (1)$$

Carbon densities for the areas burned were set equal to the mean nonsoil forest carbon density data at state level from Smith *et al* (2006), the same source used for calculating forest carbon changes based on land cover change in this study. Not explicitly including soil has the same effect as saying there was no effect of wildfire on soil carbon. Nonsoil carbon includes all compartments (live tree, understory, standing and down dead, and forest floor) except mineral soil. The proportions of carbon density emitted from forest fires were set to 0.20, 0.40, and 0.60 respectively, of the mean nonsoil carbon density per state, for low, moderate, and high fire severity classes (Chen *et al* 2011), which were used for converting burned areas to carbon emissions, and then the per area estimates were multiplied by area burned (see equation (1)). That is, for example for this analysis, we assume that if an area is identified as having a low severity fire, then 20% of the average aboveground carbon density, multiplied by area burned, is emitted because of the fire. We applied a proportion of 0.07 to areas classified as unburned to low.

2.5. Relative contribution of disturbances

We evaluated changes in forest area and changes in carbon in relative (percentage) terms, calculated as the effect caused by a known disturbance against the base number without the effect of the disturbance being evaluated (equation (2)). In this study, the disturbance is either land cover change, harvest, or fire. Although the variable area is shown in the equation, the variable carbon is also examined, following this equation.

$$\text{Per cent change} = (\Delta\text{Area}_{\text{factor}}/\text{Forest area}_{\text{noeffect}}) \times 100. \quad (2)$$

Net carbon change during the 9-yr period among the identified components at the state level was calculated using equation (3):

$$C_{\text{Net}} = C_{\text{Frf}} + C_{\text{Aff}} + C_{\text{Def}} + C_{\text{Harvest}} + C_{\text{Use+Fills}} + C_{\text{Fire}} \quad (3)$$

where Aff = afforestation, Def = deforestation, Frf = forestland remaining forestland, and $C_{\text{Use+Fills}}$ = harvested carbon stored in wood products in use and landfills. Emissions are negative values, so deforestation, harvest, and fire estimates are negative. Consequently, adding these values in this equation results in emissions being subtracted from the carbon sinks that are positive values.

2.6. Forest area and carbon comparison

We compared our estimated forest areas by state from the Retrofit Change Map with the estimates from FIA based GHG inventory data in both 1992 and 2001 (Smith *et al* 2007), using regression analysis with each state as an observation. For carbon comparisons, we added our estimated forest carbon changes during the 9-year period to the FIA based corresponding nonsoil carbon estimates in 1992 at the state level. We then compared our estimated 2001 values to the FIA based 2001 nonsoil carbon values to calculate the differences.

Table 1. 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[a]	Aff[b]	Def[c]	Frf[d]	Harvest[e]	Fire	Net[f]
North	8921	16 464	656 418 (−1.1)	11 096	−150 293	1040 591	−297 816 (−20.0)	−9561	594 017 (−30.0)
South	21 308	55 883	605 635 (−5.4)	38 066	−368 218	1060 052	−783 490 (−35.9)	−6980	−60 570 (−51.4)
West	4609	20 895	712 379 (−2.2)	5405	−210 622	1574 857	−198 659 (−9.7)	−72 890	1098 091 (−23.2)
US48	34 838	93 242	1974 432 (−2.9)	54 567	−729 133	3675 500	−1279 965 (−22.4)	−89 431	1631 538 (−35.7)

[a] Numbers in the parentheses indicated area changes in per cent of net forestland cover change to that without the change: (Aff − Def)/(Frf − Aff + Def) × 100.

[b] 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: $C_{Harvest}/(C_{Frf} - C_{Aff} - C_{Def} - C_{Harvest} - C_{fire}) \times 100$.

[c] 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.

[d] 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 non-forest. Soil carbon losses were calculated using soil carbon stocks (Smith *et al* 2006) and a conversion loss of 0.25 for the period.

[e] 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.

[f] Net change in carbon during the 9-yr period = $(C_{Frf} + C_{Aff} + C_{Def} + C_{Harvest} + C_{fire})$. Negative numbers indicate carbon sources while positive numbers represent carbon sinks. Numbers in the parentheses are the disturbance rates in percentage of carbon change during the period, calculated as $(C_{Aff} + C_{Def} + C_{Harvest} + C_{fire})/(C_{Frf} - C_{Aff} - C_{Def} - C_{Harvest} - C_{fire}) \times 100$. In the other words, we compared the forest carbon changes caused by disturbances during the period to the carbon change as if no disturbance had occurred.

3. Results

About 93 200 km^2 of forestland nationally changed to non-forest whereas 34 800 km^2 of non-forest reverted to forestland, resulting in a net loss of 58 400 km^2 forestland (−2.9%) during the 9-year period. This represents an annual rate of 6490 km^2 net forest loss, or −0.3% yr^{-1} at the national level. Regional variation was substantial, ranging from −1.1% in the north to −5.4% in the south (table 1). Spatial variation in area change due to the land cover effect ranged from a 8.5% loss in Louisiana to a 1.8% gain in Kansas across the nation over the 9-year period. In terms of absolute values of forest area change during the period, the three top states losing forest area were Georgia (5820 km^2), Alabama (4650 km^2), and Oregon (3880 km^2). The three most forest area gaining states were Michigan (570 km^2), Minnesota (470 km^2), and Kansas (130 km^2) (table 2). About 3.1% of land at the national-level experienced land cover change. Of that change, 53.3% was forest-related (that is, forest to non-forest or non-forest to forest).

Forests of the conterminous United States sequestered 1.6 ± 0.1 Pg C during the 9-year period, which is an annual rate of 0.18 Pg C. Disturbances reduced the forest carbon sink by 36% compared to the sink without disturbance effects for the nation (table 1). By region, disturbance effects varied from 23% in the West to 51% in the South. Our results show that the South is currently a net source of atmospheric carbon, while the states of the Pacific coast, northern Rocky Mountains, and Northeast are net sinks (figure 1). In comparison with the projected sink in the absence of disturbance for the country as a whole, forest harvesting (63%) and forest cover change (33%, defined as afforestation minus deforestation) accounted for the bulk of reductions with the remaining effect of 4% from forest fires (table 3). Forest harvesting dominated disturbance in southern forests: 70% of carbon loss to disturbance in the South was attributed to forest harvests, compared to only a 42% loss from harvesting disturbance in the West. Carbon losses to forest fires represented 15% of all disturbance effects in the West, more than triple of the nation's average fire effect (table 3).

Regional variation in carbon changes across the nation was substantial. In spite of disturbances and net area loss, forests in the West sequestered 1.1 Pg C during the period, two-thirds of the US total, whereas southern forest ecosystems counted as a small net carbon source of 0.06 Pg C (table 1). Oregon and Washington were the top two states in the country in terms of net carbon sinks (figure 1). Forests in the greater Pacific Northwest (PNW) region including Idaho, Oregon, Washington, western Montana, and northern California sequestered 0.93 Pg C, 84% of total forest carbon fixed in the West during the study period, which is 57% of the nation's total (table 1). Per unit forest area, Louisiana's forests were the strongest carbon sources (−1.82 Mg C ha^{-1} yr^{-1}) during the study period, while forests in the state of Washington were estimated to be the largest carbon sink (3.95 Mg C ha^{-1} yr^{-1}) (see table S2 available at stacks.iop.org/ERL/6/014012/mmedia). In terms of total net carbon change by state, Oregon was the largest carbon sink (34 Tg C yr^{-1}) whereas Georgia was the largest carbon source (−6 Tg C yr^{-1}) during the period (table 2).

In terms of total carbon budget, forests in the West sequestered a net 122 Tg C yr^{-1}, compared to 66 Tg C yr^{-1} in the North, and −7 Tg C yr^{-1} in South (figure 2). By comparison, pre-disturbance sequestration is estimated at 159 Tg C yr^{-1}, 94 Tg C yr^{-1}, and 122 Tg C yr^{-1} in the West, North and South, respectively (figure 2). Per hectare estimates of net sequestration ranged from 0.1 Mg C ha^{-1} yr^{-1} in the South to 1.7 Mg C ha^{-1} yr^{-1} in the West, in comparison with a nationally averaged rate of 0.8 Mg C ha^{-1} yr^{-1} during the period. Results suggested that the mean difference between

Table 2. Forest-related land cover (km^2) and carbon (1000 tonnes) changes for the 9-year period (1992–2001) by state in the conterminous United States caused by land cover change, and other disturbances. Aff = afforestation, Def = deforestation, Frf = forest remaining forest.

	Land cover			Carbon change by land cover, harvest, and fires[a]						
State	Aff	Def	Frf	Aff	Def	Frf	Harv.	Use + Fills	Fire	Net[b]
Alabama[c]	2171	6821	69 719	4248	−40 775	122 596	−129 530	17 167	−390	−26 684(−3)
Arizona[d]	189	685	44 766	200	−3112	34 530	−1929	237	−3952	25 974(3)
Arkansas[c]	840	3336	62 509	1543	−22 330	109 118	−70 383	9795	−596	27 147(3)
California[d]	652	2325	96 673	799	−30 037	233 653	−57 077	10 093	−16 310	141 121(16)
Colorado[d]	733	3331	77 110	763	−25 000	70 437	−4134	289	−3160	39 195(4)
Connecticut	4	169	7296	4	−1876	15 254	−2784	197	0	10 795(1)
Delaware	24	94	1259	27	−983	2620	−845	96	0	915(0)
Florida[c]	2609	4943	27 668	3628	−27 607	46 296	−50 073	6289	−672	−22 139(−2)
Georgia[c]	3673	9495	69 268	6116	−61 648	117 141	−131 376	17 514	−266	−52 519(−6)
Idaho[d]	274	1785	71 311	323	−18 150	137 068	−20 958	4582	−9051	93 814(10)
Illinois	295	655	21 984	331	−6609	23 154	−9094	882	0	8664(1)
Indiana	231	326	21 192	262	−3377	20 597	−10 817	1366	−3633	4398(0)
Iowa	192	355	9826	220	−3054	12 370	−4304	334	−2	5564(1)
Kansas	249	120	7438	279	−923	10 172	−2420	64	−418	6754(1)
Kentucky[c]	453	2114	54 384	783	−17 695	101 525	−23 609	3680	−246	64 438(7)
Louisiana[c]	1841	4084	24 099	3609	−23 544	40 727	−72 657	9413	−202	−42 654(−5)
Maine	940	2686	57 912	1414	−22 462	989 58	−48 690	6343	−34	35 529(4)
Maryland	103	348	9665	137	−3953	18 441	−9929	576	−1	5271(1)
Massachusetts	38	391	11 037	49	−4523	18 062	−10 143	230	−30	3645(0)
Michigan	2069	1504	51 582	2492	−13 202	80 972	−36 575	5359	−569	38 477(4)
Minnesota	1526	1059	58 216	1835	−8293	84 314	−31 470	4665	−1144	49 907(6)
Mississippi[c]	2586	5005	46 235	5026	−31 026	78 255	−103 391	15 167	−198	−36 167(−4)
Missouri	593	2038	65 991	667	−17 349	69 936	−19 478	2783	−477	36 082(4)
Montana[d]	646	2012	84 452	796	−16 575	159 348	−13 874	3069	−12 588	120 176(13)
Nebraska	25	87	3797	31	−361	5559	−1943	169	−2562	893(0)
Nevada[d]	190	899	31409	184	−3912	25 142	−265	22	−883	20 288(2)
New Hampshire	79	246	18 665	120	−2948	29 143	−16 266	2287	0	12 336(1)
New Jersey	44	203	7295	58	−1924	12 908	−8840	68	0	2270(0)
NewMexico[d]	359	735	52 130	348	−4490	41 656	−1902	292	−2982	32 922(4)
New York	236	1277	66 277	354	−13 198	107 824	−21422	2282	−39	75801(8)
North Carolina[c]	1456	4508	56 552	2628	−33 545	97 197	−87 178	12 054	−176	−9020(−1)
North Dakota	18	0	3010	20	0	4539	−276	10	−104	4189(0)
Ohio	518	1103	32 946	642	−10 524	67 027	−11 737	1863	0	47 271(5)
Oklahoma[c]	284	923	20 536	540	−5539	36 152	−13 673	1689	−2866	16 303(2)
Oregon[d]	510	4389	93 670	651	−55 755	425 321	−71 301	14 175	−10 726	302 365(34)
Pennsylvania	533	1262	70 098	677	−128 84	132 734	−24 971	4065	−134	99 487(11)
Rhode Island	2	57	1298	2	−588	2725	−918	17	0	1238(0)
South Carolina[c]	2580	5336	30 558	4871	−36 256	50 645	−63 866	8438	−261	−36 424(−4)
South Dakota	77	267	6568	100	−1282	11 410	−1837	305	−412	8284(1)
Tennessee[c]	500	2796	54 992	861	−23071	102 233	−37 367	4800	−598	46 858(5)
Texas[c]	1518	4003	27 221	2909	−23 992	44 950	−68 504	9584	−361	−35 414(−4)
Utah[d]	219	1283	54 690	216	−7324	49 448	−1193	191	−2255	39 083(4)
Vermont	47	159	17 792	72	−1980	27 489	−9622	1156	0	17115(2)
Virginia[c]	797	2519	61 894	1304	−21 190	113 217	−54424	6951	−148	45710(5)
Washington[d]	456	2600	74 494	737	−39 422	372 478	−71 752	14 334	−7184	269 191(30)
West Virginia	160	659	50 585	193	−6382	99 457	−17 642	3225	0	78 851(9)
Wisconsin	918	1399	54 689	1110	−11 618	84 926	−39 605	5470	−2	40281(4)
Wyoming[d]	381	851	31 674	388	−6845	25 776	−1807	249	−3799	13 962(2)

[a] Methods used for different carbon components are identical to those used in table 1 where applicable. Negative numbers indicate carbon sources while positive numbers represent carbon sinks.

[b] Net change in carbon during the 9-year period = ($C_{Frf} + C_{Aff} + C_{Def} + C_{Harvest} + C_{Use+Fills} + C_{fire}$). Numbers in parentheses are the average for the period, in units of Tg C yr^{-1}.

[c] 13 states in the South.

[d] 11 states in the West, the remaining 24 states are in the North.

our NLCD land cover carbon estimates and land use inventory based estimates at the state level was 7.0% with a standard deviation of 5.3% in the conterminous United States, ranging from 4.7 ± 4.5% in the West to 8.4 ± 5.0% in the South (figure 2).

Across the United States, the forest areas estimated from two different sources (remote sensing versus inventory) on average were correlated, although large differences were found in some states. Correlation coefficients in both 1992 and 2001 exceeded 0.82 (data not shown). If the state of Texas, which

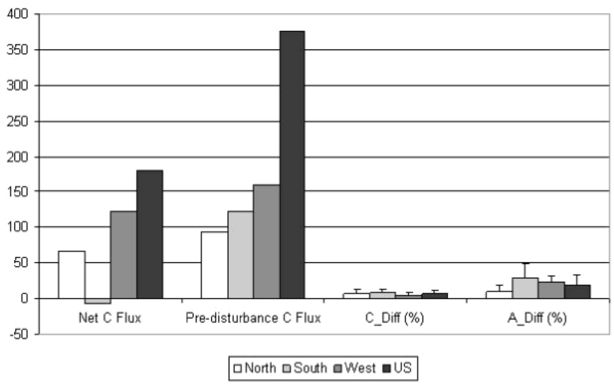

Figure 2. Statistics of forest carbon dynamics and error estimations by regions in the conterminous United States between 1992 and 2001. Net carbon flux is the annual mean of the 9-year period (unit = Tg C Yr^{-1}). Annual mean pre-disturbance C flux excludes disturbances from deforestation, harvests, and fires. Negative number indicates carbon source while positive number represents carbon sink. Carbon and area differences (%) are comparisons between our estimates and the estimates from the USDA Forest Service, Forest Inventory and Analysis (as reference numbers) for the entire period. Error bars represent one standard deviation (also in %).

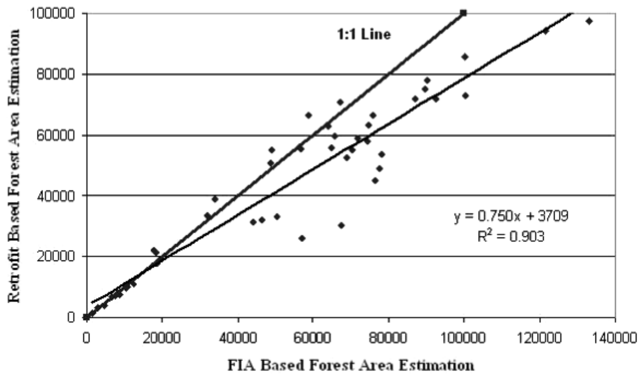

Figure 3. Comparison of FIA and Retrofit Change Map based forest area estimates in 2001 (km^2). The state of Texas was identified as an outlier, and was excluded. Each dot represents a state.

Table 3. Partitioning the effects (in per cent) of major disturbances on forest carbon dynamics by region in the lower 48 states from 1992 to 2001.

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

was a notable outlier, was excluded, the correlation coefficient in 2001 would reach 0.95 (figure 3). The forest area estimate for Texas was quite different due to a recent definitional change in the FIA program in which land cover in west Texas is defined as forestland, not rangeland (see section 4). Taking the comparison in 2001 as an example, the average difference was 18.4 ± 14.9% after area weighting across the 48 states (see table S3 available at stacks.iop.org/ERL/6/014012/mmedia). In general, remote sensing based area estimates were lower than those from the inventory data when forest area of a given state exceeded 50 000 km^2. The states with area estimation errors larger than 30% either contained more wetland or had large proportions of rangeland (see table S3 available at stacks.iop.org/ERL/6/014012/mmedia), or featured larger harvesting rates.

4. Discussion and concluding remarks

It has been recognized that forests in the PNW (including states of Idaho, Oregon, and Washington) and northern California can have high carbon stocks (Smith *et al* 2006, Hudiburg *et al* 2009, Heath *et al* 2011b). PNW forests could play a substantial role in addressing the nation's greenhouse issues if forests in the region were managed to maximize carbon sequestration (Hudiburg *et al* 2009). Our results support the importance of PNW forests even under current management regimes. In general, high rates of carbon sequestration resulted from higher growth rates, lower disturbance rates during the period, or a combination of both. For example, more than half of the nation's net forest carbon sequestration occurred in the greater PNW region (including western Montana and northern California) where the overall disturbance rate was 35% lower than that of the nation's average (table 1). Net forest carbon sequestration was greater despite substantial differences in forest growth rate between the coastal west and dry eastern portions of the greater PNW region.

In contrast, that forest ecosystems are a carbon source in the South is attributed to relatively high disturbance rates, even though the pre-disturbance carbon sequestration rate in the southern forests as a whole was about 10% higher than that of northern forests on average (see table S2 available at stacks.iop.org/ERL/6/014012/mmedia). The rate of forestland loss (−5.4%) in the South was estimated to be 86% greater than that of the nation's average (−2.9%), and 61.2% of the nation's harvests during the period occurred in the South. The resulting harvest disturbance rate is −35.9%, 60% greater than the nation's average of −22.4% (table 1).

4.1. National-level estimates

Our estimated national net annual carbon sequestration rate of 0.180 Pg C is within the range of previously reported estimates. Previous estimates range from 0.079 to 0.280 Pg C yr^{-1} in the conterminous United States (Birdsey *et al* 1993, Birdsey and Heath 1995, Turner *et al* 1995, Heath and Smith 2004, Heath *et al* 2011a). Houghton *et al* (1999) estimated a range of 0.15–0.35 Pg C yr^{-1} using reconstructed historical data and a modeling approach. Schimel *et al* (2000) estimated that carbon sink in the US terrestrial ecosystems for the period of 1980–93 caused by increasing atmospheric CO_2 concentration and climate was about 0.1 Pg C yr^{-1}, suggesting other processes like forest growth must cause a sink of about 0.2 Pg C yr^{-1} given the total sink of about 0.3 Pg C yr^{-1} for the United States from other previous studies (Birdsey and Heath 1995, Houghton *et al* 1999, Potter *et al* 2007, Woodbury *et al* 2007).

4.2. Uncertainties

We evaluated several potential sources of uncertainty in this approach. The most influential source of error is forest area identification using the remote sensing product, which is critical to our carbon estimation accuracy. Forest areas estimated from remote sensing and FIA inventories were significantly correlated, and were generally lower under the remote sensing approach. Much larger differences in the South were likely caused by the mapping accuracy limits in the remote sensing based product. For example, five of the eight states with area estimation differences exceeding 30% were in the South (see table S3 available at stacks.iop.org/ERL/6/014012/mmedia). Recently Nowak and Greenfield (2010) showed that tree cover inaccuracies vary across the US in the NLCD, such that overall NLCD significantly underestimates tree cover in 64 of the 65 zones used to create the NCLD cover maps, with a national average underestimation of 9.7%. How these inaccuracies play through forest vegetation type assignment could have a large effect on the results.

Previous studies indicated that the wetlands have proven difficult to map with satellite data because they are relatively rare in occurrence at the national level (Stehman *et al* 2003), and their spectral and spatial characteristics are highly context-dependent (Wright and Gallant 2007). Among the seven Anderson level I categories in the NLCD maps, rangeland and wetlands were reported to have consistently low classification accuracies for various reasons (Stehman *et al* 2003, Hollister *et al* 2004). The five states in the South with high estimation differences had high percentages of either wetland or rangeland. For example, 58% of Texas' territory was classified as rangeland whereas the mean percentage of wetland in Florida, Louisiana, Mississippi, and South Carolina was 25% (see table S3 available at stacks.iop.org/ERL/6/014012/mmedia), which is 400% higher than the national average of 5% (based on the Retrofit Change Map). In the states of Florida and Louisiana, where the estimated differences exceeded 50%, wetland proportions accounted for 35% and 32% respectively. Harvested areas may also appear as non-forest land in a land cover dataset and the detection of lands as afforested may be delayed (Drummond and Loveland 2010, Hansen *et al* 2010). Harvesting tends to be greater in the South, so the differences in forest area may also be due to inaccuracies concerning harvested lands.

Definitional difference in forest area based on land cover (i.e., from remote sensing) and land use (i.e., from FIA) was another cause for the mismatch between the two estimates. For example, forest area in Texas estimated from remote sensing was about 72 600 km^2 in 2001 comparing to that of 243 500 km^2 from the FIA, suggesting many rangelands recently designated as forestland in west Texas by the FIA appeared not to be recognized in the remote sensing based observation (see table S3 available at stacks.iop.org/ERL/6/014012/mmedia).

Secondly, estimates of uncertainty were not available for the harvest dataset that covered all 48 states. However, analogous data—FIA volume removals—were analyzed for uncertainty in terms of estimates of harvested carbon; uncertainty about conversion of volume to carbon was relatively small in comparison with sampling error. Estimates of overall uncertainty obtained for these data were generally inversely proportional to a state's wood production; values ranged from just under 10% in some heavily forested and harvested states, such as those in the South, to 70% or more in some of the sparsely forested states such as those in the Great Plains.

Thirdly, double counting of C removals may occur between deforestation and harvesting. Two major types of double counting are expected: (1) areas that are regenerated under even-aged harvesting could be classified as non-forest types in the NLCD data; and (2) the FIA removals might also include some timber removals due to terminal harvest and land use conversion associated with correctly mapped deforestation in the NLCD (Zheng *et al* 2011). However, non-spatial harvest data at the county level do not sufficiently allow us to pursue such separation and this challenge deserves further exploration.

A fourth possible major error source is carbon emissions from fires. Although a complete dataset to support a quantitative analysis is not available, the fire effect from this study is likely underestimated because: (1) the dataset from the MTBS only maps fires greater than 202 ha in the eastern United States (east of 97W longitude) and greater than 404 ha in the western United States; (2) prescribed fires on private land holdings were not included and these can be common in the South; and (3) we did not provide estimates of non-CO_2 emissions. Double counting on carbon emissions may also exist between deforestation and fires, but it is difficult to accurately identify the issues due to differences in spatial resolutions of minimum mapping units between the two datasets (i.e., 30 m in land cover change map versus 2 or 4 km in fire data). It was not the focus of this study to identify and reconcile all sources of error in the land cover dataset in terms of areas, but to use the existing datasets to estimate sequestration by forests and emissions from disturbances and compare the results to estimates from other approaches to assess if the results are similar.

4.3. Conclusions

Despite the uncertainties, this study demonstrates that remotely sensed information that quantifies land cover, combined with ground inventory based data from various sources, can be applied to quantify carbon sinks or sources spatially over large scales with overall results similar to estimates from standard methods. Our estimated national net annual carbon sequestration rate of 0.180 Pg C is within the range of previously reported estimates, from 0.079 to 0.280 Pg C yr^{-1}. Our estimated carbon changes also provide geographically explicit estimates and attribution of changes to different types of disturbances, which has not previously been determined. For the three identified disturbances, forest-related land cover change contributed 33% of the total effect of reducing the forest carbon potential sink, whereas harvests and fires accounted for 63% and 4% of the reduction, respectively. Because of the large influence of harvesting on forest carbon, these results also indicate the importance of including harvest effects when estimating forest carbon and forest carbon changes in US forests. However, more research is needed to reduce the uncertainty of the estimates.

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