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Assessing Double Counting of Carbon Emissions Between Forest Land-Cover Change and Forest Wildfires: A Case Study in the United States, 1992–2006

Daolan Zheng,[1]* Linda S. Heath,[2] Mark J. Ducey,[1] and Brad Quayle[3]

[1]*Department of Natural Resources & the Environment, University of New Hampshire, Durham, New Hampshire 03824, USA;* [2]*USDA Forest Service, Northern Research Station, Durham, New Hampshire 03824, USA;* [3]*USDA Forest Service, Remote Sensing Application Center, Salt Lake City, Utah 84119, USA*

Abstract

The relative contributions of double counting of carbon emissions between forest-to-nonforest cover change (FNCC) and forest wildfires are an unknown in estimating net forest carbon exchanges at large scales. This study employed land-cover change maps and forest fire data in the four representative states (Arkansas, California, Minnesota, and Washington) of the US for the period from 1992 to 2006 to evaluate forest carbon double counting effects based on land-cover change map, forest fire data, and USDA Forest Service Forest Inventory and Analysis data. The analyses were conducted at the county level and tallied to state level. Although the effects were small in the two eastern states because of small burned areas and low burn severity, substantial effects were found in the two western states. Carbon double counting was about 10 TgC (teragram 10^{12}) in California and 6 TgC in Washington for the period 1992–2006 (at rates of 0.7 and 0.4 TgC per year), or 21.9 and 7.6% relative to total forest carbon emissions through FNCC in the two states, respectively. The effects were 0.2 and 0.1% in Arkansas and Minnesota, respectively. Variation in double counting effects within the states was also much higher in the western states compared with the eastern states. Our results suggested a general pattern that rates and amounts of double counting in forest carbon emissions between FNCC and fires were more evident and substantially different on a west–east dimension than that on a north–south dimension across the conterminous US during the study period.

Key words: forest fire carbon emission; land-cover change; disturbance; burn severity; carbon double counting; relative contribution.

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**Corresponding author; e-mail:* daolan.zheng@unh.edu

Introduction

Forests contain 86% of the earth's aboveground carbon (C) and play a dominant role in terrestrial C cycle. Major components for calculating net forest C budget dynamics include forest growth, land-cover change, harvests, forest wildfires, and insect outbreaks

(Houghton 1995, 1999, 2010; Volney and Fleming 2000; Gustafson and others 2011; Zheng and others 2011). Because these components often interact in a complicated way, complex data and knowledge-rich multiple-constraint approaches including process models, atmospheric inversions, and field data may be needed to fully characterize C changes at a fine resolution landscape scale (Turner and others 2011a). However, information requirements may limit the size of the study areas and systems, and may limit the accessibility of analysis approaches to other research. Even within one component, such as forest fires which are a major disturbance affecting net forest C estimation (Randerson and others 2002; Turner and others 2011b; Zheng and others 2011), there can be considerable inter-annual variation in C emissions from ecosystems (Cairns and others 2000). Simplified methods that can be more readily applied to larger areas, focusing on selected variables, using publically available and relatively accessible approaches are often effective in enhancing our understanding and in quantifying the amount, magnitude, locations, uncertainty, and relationships between the identified components and their interactions. Simple, transparent methods are also important for informing policy decisions.

Approaches based on remote sensing-derived products have been proven to be relatively effective, consistent tools to monitor and quantify C estimation, especially over large scales. They have often been used to represent the fundamental component of land-cover change (DeFries and others 2002) which influences forest C budgets over large scales. Considerable effort has been made in recent decades by remote sensing communities to provide satellite-derived maps at various resolutions (for example, National Land Cover Datasets (NLCD) maps at 30 m, Advanced Very High Resolution Radiometer (AVHRR), and Moderate Resolution Imaging Spectroradiometer (MODIS) maps at 1 km) for monitoring and quantifying land-cover changes at large scales (DeFries and Townshend 1994; Friedl and others 2002; Fry and others 2009). Owing to increasing availability of remote sensing data, our ability to quantify many factors relevant to the estimation of wildfire greenhouse emissions also has been improved in the last three decades (French and others 2011).

Current methodologies employed in the US forest greenhouse gas inventory estimation are primarily based on net changes in forest area estimated from field plot data, and calculated by subtracting forest area estimates from consecutive surveys (land-use-based estimation). Zheng and others (2011) presented a new methodology to estimate US forest ecosystem carbon dynamics using land-cover change derived from remote sensing observations combined with other major disturbance data, such as harvests and wildfires. Major improvements and advantages of the new methodology include (1) ability to identify gross changes in forest cover status over a period. These changes encompass afforestation (that is, nonforest changing to forest), forest to nonforest cover change (FNCC), and forest remaining forest. We focus on these basic land-cover changes at large scales to refine forest carbon estimation because of the differences in forest carbon implications (afforestation represents a process of gradual carbon accumulation, whereas FNCC usually indicates a sudden carbon loss); and (2) increasing availability of periodic global land-cover maps at 5-year intervals at fine and moderate resolutions in the next decade (Gutman and others 2008; Townshend and others 2008).

Effects of forest fires on carbon dynamics have been widely recognized (French and others 2008, 2011; Meigs and others 2009; Chen and others 2011). However, little is known about the effects of co-occurrence of forest fires and FNCC on estimation of forest carbon emissions. In a study based on publically available remote sensing and ground-based datasets, Zheng and others (2011) provided estimates of components of C dynamics in US forests, including emissions related to land-cover change from forest to non-forest and forest fires. The interactions between these components were not investigated, because of the limited available data sources at that time, but the interactions were identified as an area that needed further investigation. The aim of this study is to investigate the importance of the interactions between land-cover change and forest wildfires in US forests, and the effect on C emission estimates.

We note that "FNCC" used in this study is a land-cover designation, not a land-use designation. Thus, some cover changes, such as harvesting of older forests resulting in young forests which give only temporary land-cover change and do not constitute long-term land-use change, are included in this component. FNCC also includes more permanent land-cover changes that also entail land-use changes, such as conversions of forests to agriculture or development. Furthermore, the definition of forestland is crucial for forest area estimation because different datasets are often based on different definitions. Differences in definitions can complicate the carbon estimates and comparisons of approaches. Throughout this analysis, we use the terminology of FNCC instead of the term deforestation because the change may likely not be deforestation, defined as a land-use conversion from forest use to nonforest use. Our approach, however, is consistent over the period and also may be used to estimate changes attributed directly to disturbance factors.

Specific objectives that targeted improving our current understanding of these interactions include (1) examining the magnitude of double counting in C emissions between FNCC and forest wildfires from 1992 to 2006 in representative areas of US forests; (2) illustrating regional differences in double counting effects between eastern and western states, as well as spatial patterns of such effects at the county level across the selected states; and (3) exploring a hypothesis about the relationship between proportion of FNCC in the ending years (2006) and burn severity as lengths of study period vary from 14 years (1992–2006) to 6 years (2000–2006), and its impact on double counting calculations.

Methods and Materials

Although methods to estimate fire C consumption can be refined for studies at varying scales or extended to include information on additional parameters (Kasischke and others 1995; French and others 2000; Campbell and others 2007), three basic parameters are usually required for quantification of C emissions from fire: area burned, C density (C per unit area), and the proportion of biomass or C consumed (Seiler and Crutzen 1980). Our approach is similar to that of Zheng and others (2011), but focuses on a subset of the US for which more data were available and cover a longer time period. We use publically available remote sensing datasets for the variables such as land-cover change status, area burned, and proportion of C consumed (characterized by severity of burn) coupling with forest C density estimates based on ground-based measurements. New methodologies developed from this study include spatial identification of interactions between FNCC and forest fires across landscapes for a longer period (1992–2006) and estimation of double counting. Although forest fire emissions are often reported in terms of CO_2 equivalent, we focus on emissions in units of carbon. Results can be converted to CO_2 equivalent by multiplying by a carbon factor of 3.67 (Heath and others 2011). We do not account for non-CO_2 emissions, but generally about 10% of total direct GHG emissions from fires are non-CO_2 emissions (Heath and others 2011). Our study area, major datasets, and methodology are described below.

Study Areas

Four states selected from the continental United States for this study were: (1) to be geographically representative of forest types and fire regimes; (2) to contain a relatively large amount of forest; and (3) to have relatively complete fire records. As a result, the states of Arkansas, California, Minnesota, and Washington were selected (Figure 1). All analyses were conducted at the county level and summarized to the state level as necessary. For this study, we only used counties having forest C density data that were available from the USDA Forest Service Forest Inventory and Analysis (FIA) program, and which were generally counties with at least 5% forest land area.

Land-Cover Change Maps

Two land-cover change maps from the USGS National Land Cover Datasets (NLCD) derived from 30-m Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) satellite data (MRLC 2011) were used in this study: (1) NLCD change map of 1992–2001 (Fry and others 2009); and (2) NLCD change map of 2001–2006 (Xian and others 2009). The first change map contained eight primary classes at Anderson Level I (Anderson and others 1976): (1) open water, (2) urban, (3) barren, (4) forest, (5) grass/shrub (G/S), (6) agriculture, (7) wetland (However, Class 8 ice/snow was excluded from this analysis). Any secondary classes (2-digit numbers) generated from the primary classes indicated land-cover change from one type to another during the period. For example, class 42 meant that land was converted from forest in 1992 to urban in 2001. The second change map indicated land-cover change at

Figure 1. Locations of four representative states: Arkansas (*AR*), California (*CA*), Minnesota (*MN*), and Washington (*WA*).

Anderson Level II from 2001 to 2006. To conduct a consistent analysis, we aggregated the land-cover change classes in the 2001–2006 map from the Level II to Level I. This insured that a comparable land-cover change map from 1992 to 2006 at the Level I could be obtained (Personal Communication, USGS G. Xian, May 2011) because land-cover mapping protocols used during NLCD 2006 processing are similar to those used to label the NLCD 2001 product (Homer and others 2004). In the 1992–2006 change map, the FNCC lands included (1) the lands were forested in 1992 but converted to nonforest in 2001 and remained nonforest in 2006 (that is, classes of 41, 42, 43, 45, 46, and 47); and (2) the lands that were forest remaining forest in 2001 but were ''newly'' converted to nonforest in 2006; and excluded the lands that were identified as nonforest lands (classes of 41–47) in 2001 but converted to forest in 2006. A longer study period could improve the analyses by obtaining relatively more reliable fire characteristics related to estimation because inter-annual variations in fire severity and size of burned area are substantial. The error level in the merged 1992–2006 change map should be comparable to the original accuracies of the NLCD products (discussed later). No additional errors were introduced from the aggregation and procedures because they are all based on the NLCD land-cover products. State-level change maps for the study areas were a subset from the national datasets.

It should be noted that the NLCD land-cover change map for a given period resulting from two land-cover maps may contain estimation errors because of differences in classification schemes and processing or classification techniques between the products at the starting and ending years. For example, the overall classification accuracy (a total of 21 classes) in the NLCD 1992 map was 80.4%, whereas it was improved to 85.3% in the NLCD 2001 map with a total of 16 classes (Homer and others 2012). Although an overall accuracy report for the NLCD 2006 map (a total of 16 classes) is unavailable yet (in process), we assume the accuracy in the 2006 map will maintain a similar or improved accuracy because information technologies that give poorer accuracies are generally not adopted. The effects of such inconsistency in our study could be more constrained because our change detection only focused on forestlands (deciduous, evergreen, and mixed). Previous study indicated that forestlands in the NLCD maps had relatively higher classification accuracy (along with water and urban covers) than other land-cover types in general (Hollister and others 2004).

Forest Fire Data

This study focuses on NLCD forested land-cover types only (deciduous forest, evergreen forest or mixed forest) affected by fire in between and including the years 1992 and 2006 for the four representative states. Fire mapping and characterization data compiled by the Monitoring Trends in Burn Severity (MTBS) project were used to identify the location, extent and burn severity of fires occurring during the study period. The MTBS project is conducted by the USDA Forest Service and the US Geological Survey (USGS), and maps documented large fire events from 1984 to the present occurring in federal, state, and private lands using Landsat TM and ETM+ imagery (Eidenshink and others 2007). The USGS Landsat TM and ETM+ image archive has been providing a consistent and continuous source of 30-m resolution data since 1984 for mapping burn severity of all larger fires. Large fire events are defined as greater than 404 ha in the western US (including Washington and California) and greater than 202 ha in the eastern US (including Minnesota and Arkansas). We use the term ''wildfire'' in this study, although fire data for the four states could include some prescribed fires. However, the total area of forested land affected by prescribed fire is a negligible amount of the total acreage of burned forested lands considered over the study period, particularly in the western US states. Furthermore, prescribed fires would likely be small in size and not meet the minimum size. Prescribed burn areas would likely be in the very low or low burn severity category, which contribute little per hectare in terms of C emissions. More importantly, the difference in compositions of prescribed fires has no effect on our analyses and the results because the methods we used to calculate forest C double counting do not vary with fire types.

MTBS fire mapping datasets for fires occurring from 1992 to 2006 in the four representative states were acquired from the project (MTBS 2010). The 30-m resolution burn severity data for the individual fires were mosaicked to produce annual datasets for each year during the study period. Thematic burn severity classes for each annual state dataset consisted of four burn severity classes: (1) very low, (2) low, (3) moderate, and (4) high. The annual burn severity raster datasets for each state were overlaid with forested land cover in NLCD 1992, 2001, or 2006 datasets to identify burned areas corresponding to forested land-cover types (Vogelmann and others 2001; Homer and others 2004; Xian and others 2009; Fry and others 2011).

In other words, the burned areas occurring on the lands that were once classified as forests in any one of these 3 years were included in the fire datasets. Further analysis was conducted on the resulting annual datasets for each state to produce three derivative datasets summarizing forest fire characteristics. The first two were for the entire period of 1992–2006, and the third one was for three individual years during the period.

(1) Burn/reburn frequency (*BurnFreq*):The number of times a given forested pixel burned during the 14-year period;
(2) Maximum burn severity ($MaxSev_{14}$):The maximum recorded burn severity for a given forested pixel during the 14-year period; and
(3) Burn severity file for burned-once fires only in each of the three individual years at a 4-year interval: 1992, 1996, and 2000.

The first two datasets (burn frequency and severity datasets) were used for calculating C double emissions from the fires that occurred on the lands that were identified as FNCC in the land-cover change map by the terminal year (2006) of the study period. The third dataset was employed to explore the relationship between proportion of FNCC and burn severity over different lengths of study period using a pattern analysis approach. Areas of multiple burns were removed to reduce the effects of biases that would be introduced by multiple burns.

Forest Carbon Emissions in FNCC (as Denominator)

Forest C pools considered in this study include all nonsoil components: live tree, understory, standing dead tree, down dead wood, and forest floor. Forest areas experiencing FNCC during the study period at the county level were determined from the NLCD change maps. County-level mean C density was taken from Smith and others (2006), which was based on FIA data, and categorized by region and the most abundant forest type by area within each county. These data were chosen because they were adopted in 2007 as the official US default factors for the Department of Energy's 1605(b) Voluntary Reporting Program. To calculate C loss from FNCC, we used a conversion factor of 0.8. This factor was based on the assumption that 80% of the nonsoil forest C would be lost during conversion of forest to nonforest (Smith and Heath 2008). These forest C losses through FNCC were used as reference numbers to determine how much of these estimates were double counted (in relative terms of percent) as C emissions from forest fires.

Methods to Calculate Double Counting in Forest Carbon Emissions Through Fires (as Numerator)

Spatially explicit MTBS forest fire maps at 30-m resolution were overlaid with the aggregated NLCD change map (1992–2006) to determine the areas of fires occurring in pixels that were designated as FNCC in 2006. Carbon emissions from these burned areas were defined as double counting because emissions from the FNCC on the same land areas also would have been counted. To estimate C emissions from burned areas, we followed the method of Chen and others (2011) given in equation 1 to calculate C consumption through forest fires, which vary substantially with burn severity (i):

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

The above method is similar to the approach proposed by Seiler and Crutzen (1980) in concept. Carbon densities for the areas burned were set equal to the mean nonsoil forest C density data at the county level from Smith and others (2006), the same density data used for calculating C losses from FNCC (used as reference numbers). The proportions of C density emitted from forest fires were set to 0.20, 0.40, and 0.60, respectively, of the mean nonsoil C density per county, for low, moderate, and high fire severity classes based on the study from the US Utah High Plateaus (Chen and others 2011), which were used for converting burned areas to C emissions. For example, if a burned area is identified as having a low severity fire, then 20% of its nonsoil forest C is emitted from the fire. We applied a proportion of 0.07 to the burned areas classified as very low (Zheng and others 2011). In each pixel, the maximum burn severity was recorded, and the corresponding C consumption rate was used in the first-round calculation using equation 1. For those areas that were burned in the second fire, we repeated the calculation using equation 1 but applying a lower C density because of reduction in C density caused by the first fire. If an example area (100 ha in size with a mean density of 50 Mg C/ha) was burned two times during the study period with the maximum burn severity of moderate (carbon consumption rate of 0.4), then the amount of C emitted from the first fire was 100 × 50 × 0.4 = 2,000 Mg C. The emitted C from the second fire was 100 × 30 × 0.2 = 600 Mg C. Thus, a total of 2,600 Mg C was considered double counting from fires in the area.

Carbon density used for calculation in the second fire was reduced from 50 to 30 Mg C/ha because of C losses from the first fire. Furthermore, we used a consistent consumption rate of 0.2 for all calculations in the second fire for two reasons: (1) the highest consumption rate (0.6) would have been used in the first-round calculation (if the highest severity occurred), because, for any given pixel, it was assigned the maximum severity. As a result, only three consumption rates remained (0.07, 0.2, and 0.4 for very low, low, and medium burn severity, respectively) for options in the second-fire calculation; and (2) among the three remaining options, low-severity burn was the intermediate class and represented the majority in all states but Washington (Figure 2).

We realized that the fire consumption rates used in this study could be too general because, in reality, C emissions from wildfires are affected by many factors and combinations of these factors such as weather, timing of the year, fuel moisture, and forest types and fuel loading (for example, Keane and others 1996; van der Werf and others 2010). However, the datasets (NLCD and MTBS) used in this study for identifying double counting area are also somewhat generalized, and do not contain sufficient information to model the sources of variation in consumption. For example, the definition of forest cover in the NLCD datasets includes only deciduous, evergreen, and mixed forests, and so information on fuel loadings and moisture at the time of fire is not available. The MTBS dataset provided generalized burn severity categories but no intensity records were available. This study is designed to examine the relative magnitude of the effect in C double counting between FNCC and wildfires (that is, compounding effects of FNCC and forest fires on carbon emissions, as compared to carbon emissions through FNCC without considering double counting effects); and to compare regional differences in such effects between eastern and western states over the large scale, rather than to estimate C emissions from fires alone with high precision and spatial nuance. Using generalized forest fire consumption rates for different forest types across the country may affect the accuracy of carbon double counting estimation, but in the meantime, it somewhat simplifies the issue allowing a more transparent analysis. Furthermore, the simple transparent analysis does yield important information about the sensitivity of double-counting to the consumption rates, providing potential directions for future research.

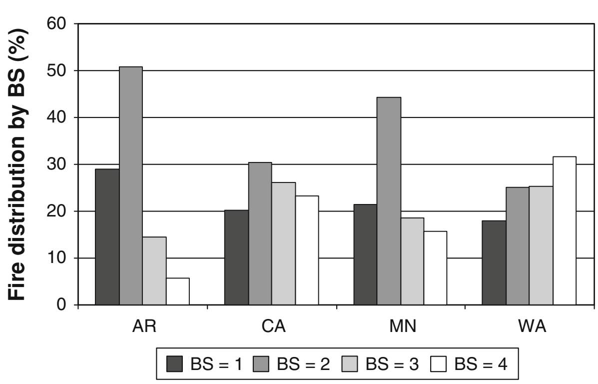

Figure 2. Forest fire percentage by burn severity (*BS*) class based on total burn area from 1992 to 2006 among the four states: Arkansas (*AR*), California (*CA*), Minnesota (*MN*), and Washington (*WA*). 1 = Very low, 2 = low, 3 = medium, and 4 = high.

Fire data indicated that the maximum burn frequency on the same area during the study period was three times for the states of Arkansas and Washington, four times for Minnesota, and five times for California. To simplify our analyses, we intentionally excluded the calculations of C emissions from any third, fourth, and fifth burns for the same area (see example above). This simplification was based on the facts that forests burned once during the period accounted for 87% of all the burned areas (including all areas burned in multiple fires) in Arkansas and for up to 99% in Washington (Figure 3). The cumulative percentages increased to 98.2% in Minnesota up to almost 100% in Washington if second burns were included. Furthermore, initial C density available for fire consumption decreased as fire frequency increased with low burn severity. As a result, omitting those calculations should have little impact on double counting estimates.

Patterns Between Proportion of FNCC and Burn Severity Over Time

Although the temporal relationship between FNCC and fire characteristics does not by itself directly effect double counting calculations, this provides useful information for better understanding the issue. First, we examined the relationship between burn severity and the resulting land-cover statuses (FNCC or forest remaining forest) for the terminal year of 2006 using burned-once fire data in the three individual years: 1992, 1996, and 2000. With other conditions constant, it is likely that forests burned with higher severity should have a higher proportion of lands (on average) remaining as nonforest status in 2006 than those forests burned

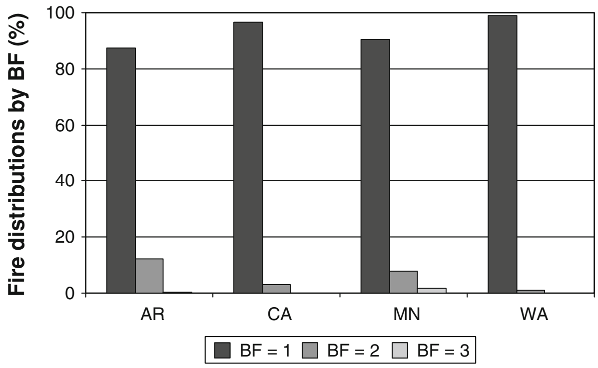

Figure 3. Forest fire distributions by burned frequency (*BF*) based on all fires from 1992 to 2006 among the four states: Arkansas (*AR*), California (*CA*), Minnesota (*MN*), and Washington (*WA*). Frequencies for forests burned more than three times are not shown because of rare occurrence.

with lower severity. This is because given a fixed and limited time period for vegetation regrowth, the proportion of FNCC lands, with higher burn severity likely to recover to a condition in which they will be mapped as forest again, will be smaller than the proportion of FNCC lands with lower burn severity.

To test the hypothesis, we used the relative measure of percentage to eliminate bias caused by varying sizes in burned areas among the states. The percentage was calculated as $Area_{def}/Area_{def+frf} \times 100$. $Area_{def}$ was the sum of burned forest land classified as FNCC in 2006, and $Area_{def+frf}$ was the sum of burned forest land classified as FNCC and forest remaining forest in 2006.

Results and Discussion

Double Counting of Carbon Emissions in Absolute Values

Burned areas from 1992 to 2006 that remained to be classified as FNCC in 2006 varied substantially from 460 ha in Minnesota to 130,600 ha in California (Table 1). These burned areas translated to about 10 TgC (teragram 10^{12}) and 6 TgC double-counted C emissions between FNCC and forest fires in California and Washington, respectively, in absolute value for the entire period, compared to 0.06 TgC in Arkansas and 0.01 TgC in Minnesota (Table 1). The corresponding annual rates for 1992–2006 in C double counting were 0.7, 0.4, 0.004, and 0.001 TgC for the states of California, Washington, Arkansas, and Minnesota, respectively.

Burn severity can substantially affect calculations in double counting C emissions for two reasons: (1) higher burn severity likely results in a higher proportion of burned area remaining to be FNCC at the terminal year of the study period so that larger areas would be double counted; and (2) more C is emitted during fires that have higher burn severity. For example, about two-thirds or more of the fire activity from 1992 to 2006 were classified as low burn areas (including very low) in Arkansas and Minnesota, whereas low burn areas accounted for 50% in California and 43% in Washington (Figure 2). A previous study illustrated that C emissions from fires in the western region accounted for 82% of the emissions from fire over the 48 lower states (Zheng and others 2011). Because of this high proportion, the issue deserves more attention in the western US forests for refining net changes in forest C estimation.

Carbon Double Counting in Relative Terms

Forest C double countings in relative terms were small in the two eastern states during the period (both were less than 0.23% relative to total emissions from FNCC) because of lower burn severity and less-burned areas than those in the two western states (Table 1), although the minimum identified areas burned in the east were half the size of those in the west. Our results suggested double counting effects were 7.6 and 21.9% in the states of Washington and California, respectively (Table 1). High-severity burns accounted for 23% of all burned forest areas in California and 32% in Washington, compared to 6 and 16% in Arkansas and Minnesota (Figure 2). County-level variations in double counting effects within the states were also much higher in the western states (Std. of 15.4% in California and 15.6% in Washington) ranging from close to zero to more than 50% at the county level (Table 1), compared to those in the eastern states. In the two eastern states, the variation was much smaller with Std. values of 0.6% in Arkansas and 0.7% in Minnesota. The largest double counting effects at the county level were 3.4, 57.6, 6.0, and 53.2%, respectively, in the states of Arkansas, California, Minnesota, and Washington (Table 1).

Spatial Patterns in Carbon Double Counting

Distributions of forest fires during the study period were relatively clustered in Arkansas and Washington and less so in the other two states, especially in Minnesota. However, distributions of double-counted

Table 1. Forest Fire Severity Information, Burned Area, and Double Counted C Emissions

State	Low[1] burn frequency (%)	Burned FNCC areas (ha)	Double counted C (1,000 tonnes)	Double counted C in percent[2]
AR	79.7	2,313	60	0.22 (0.0, 3.4, 0.6)
CA	50.5	130,609	9,642	21.89 (0.0, 57.6, 15.4)
MN	65.6	463	11	0.11 (0.0, 6.0, 0.7)
WA	43.2	90,031	6,083	7.58 (0.0, 53.2, 15.6)

[1] Including very low severity class in Arkansas (AR), California (CA), Minnesota (MN), and Washington (WA) from 1992 to 2006.
[2] Percentage of double-counted emissions was calculated as carbon emissions from fires that occurred within FNCC divided by total carbon emissions estimated from FNCC (summarized from county-level estimation). Numbers in the parentheses are minimum, maximum, and standard deviation (Std.), respectively, in percent at the county level.

areas obtained from overlaying the fire maps with land-cover change maps showed very scattered and fragmented patterns across all the three states except Washington (Figure 4). Statistics, however, showed that the effects of forest fires on FNCC were much higher in the two western states than those in the two eastern states. About 38.3 and 16.3% of FNCC lands during the study period were caused by fires in California and Washington, respectively; however, only about 0.5 and 0.3% of FNCC lands resulted from fires in Arkansas and Minnesota (Table 2).

Within-state analyses indicated that small double counting effects (<1%) in forest C emissions between FNCC and wildfires were observed in western and southern counties of Arkansas, accounting for 85% of total counties that had double counting effects during the study period except in four counties (Figure 5A). In California, C double counting was more evident, especially in the southern portion of the state. In Minnesota, the double counting effects at the county level were concentrated in the northern portion of the state and primarily fell in the low-error class (<2%) (Figure 5C). Carbon double counting patterns in Washington state were unique. Counties with double counting estimates were either in the low-error class (0–10% in light blue) with a mean class value of 2.3% or fell in the high-error class (>20% in red) with a class mean value of 48.1% during the study period (Figure 5D).

Double-counted forest C emissions tended to increase from north to south in general across the state of California (Figure 5B) because of either increases in burn severity or proportion of double-counted area from north to south, or both. All counties but two in the low-error class of double counting were concentrated in the northern portion of the state (shown in light blue with a county mean value of 4.6%). Most counties with moderate double counting error percentages (20–30% in pink with a class mean of 25.4%) were located in the middle portion of the state. Counties with error estimation larger than 30% (shown in red with the class mean of 41.2%) tended to be scattered from the central portion to the southern portion of the state (Figure 5B).

The county-level distribution patterns in double counting of forest C emissions showed much greater extremes in the two western states than those in the two eastern states. For example, only one county in Washington was in the middle-error class (shown in yellow). Although low double counting counties were concentrated in northern and south-central portions of the state, high double counting counties occurred in the north-central and southeast portions of the state (Figure 5D).

Relationships Between FNCC and Fire Severity at the State Level

Our results demonstrated that recovery of FNCC lands after fires was negatively correlated to burn severity (that is, the higher the severity the less the recovery given the length of our study period) at the state level except Minnesota (Figure 6). The proportions of burned areas that were classified as FNCC lands at the terminal year (that is, 2006) increased from 1.3% in the very-low severity class to 9.6% in the high severity class in Arkansas. The corresponding values increased from 2.6 to 69.0% in California and from 6.5 to 66.1% in Washington (Figure 6). One explanation for the unexpected pattern in Minnesota is that the state has a relatively small burned area (Table 1) involved in the pattern analyses over the period, and therefore does not feature an adequate sample size for this analysis. All burned areas could theoretically become forest if the post-fire period is long enough without interruption of other disturbances. The lengths of the post-fire period needed to complete the recovery of forest likely vary by region depending on how favorable the general climate and biophysical factors are to forest regeneration and growth, which deserves further investigation

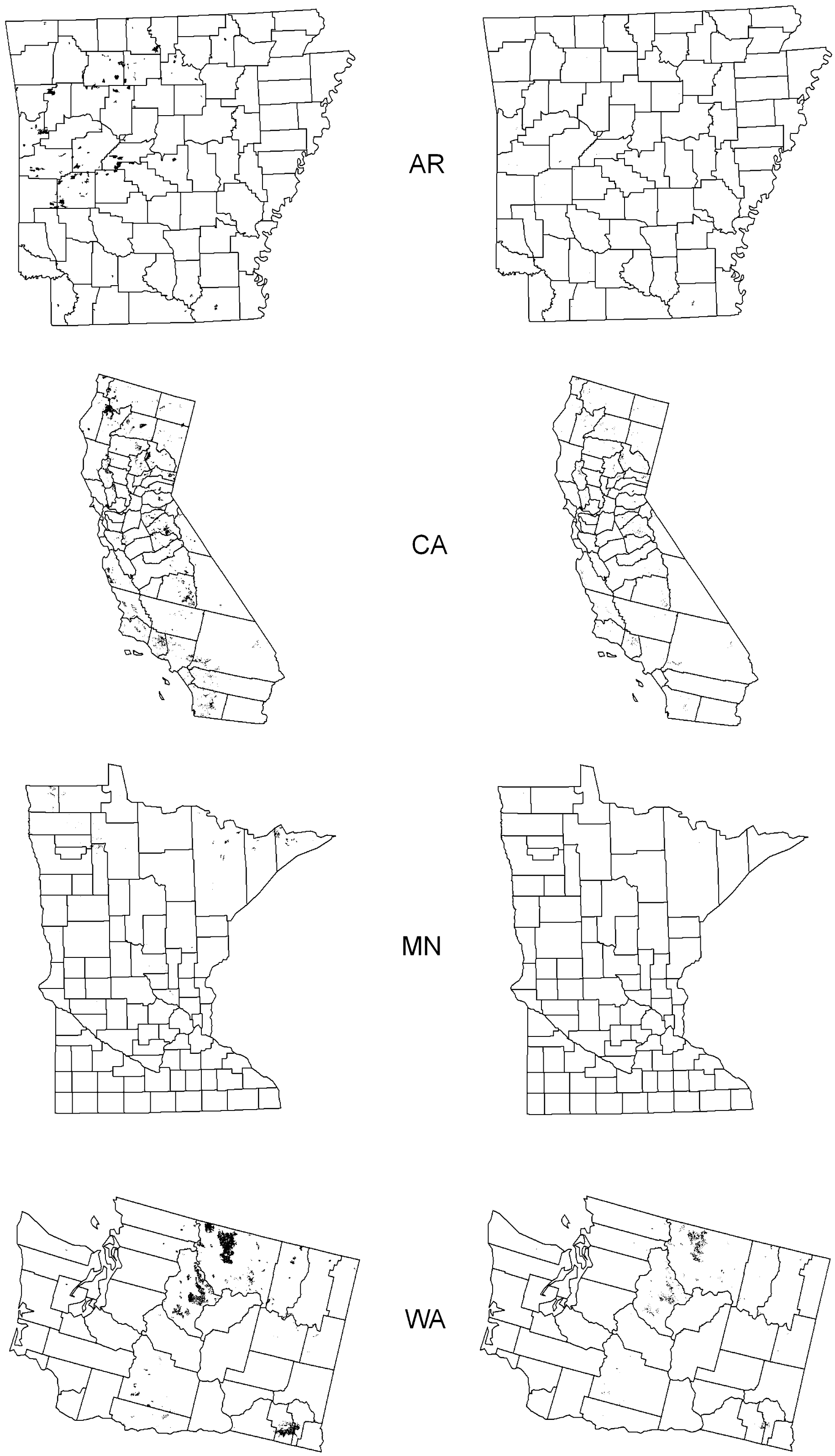

Figure 4. Spatial distribution of forest wildfires from 1992 to 2006 in the four states: Arkansas (*AR*), California (*CA*), Minnesota (*MN*), and Washington (*WA*). *Left* burned areas before overlaying with the land-cover change map; *right* areas identified as double counting after overlaying. Due to small amounts of burned areas, scattered patterns, and limitation in presentation scale, double-counted areas in the states of Arkansas and Minnesota are difficult to tell intuitively but the corresponding statistics are shown in Table 2.

(for example, Oliver and Larson 1996, pp. 174–175). Regional dynamics of forest recovery on FNCC lands after fires were mainly determined by the interaction between the length of recovery and burn severity. In theory, as the length of recovery for a burned area increases, a smaller proportion of

Table 2. Areas of FNCC, Burned Forest, and Carbon Double Counting 1992–2006

Area (ha)	AR[1]	CA	MN	WA
FNCC	434,148	343,855	148,267	551,739
Fire burn	104,018	1,006,439	35,844	331,704
Double counted	2,313	130,609	463	90,031

[1] *The four states are Arkansas (AR), California (CA), Minnesota (MN), and Washington (WA).*

burned area should remain in the status of FNCC than the proportion of a burned area with a shorter recovery period assuming other conditions, such as burn severity and burn frequency, and regrowth rate, are constant. In summary, burn severity can affect quantification of double counting in forest carbon emissions between FNCC and fires in two general ways: (1) the amount of forest carbon emitted through fires; and (2) the amount of areas that were involved in the calculations for a given study period that is not long enough for a full recovery of burned forestlands after fires.

Uncertainties and Implications

Uncertainties in our estimated forest C double emissions for confounded FNCC and forest fires' interactions may come from the following sources. First, there is the uncertainty that can be related to identification of FNCC status using the change map, which affects the quantification of FNCC area and C emissions used as reference numbers to assess the double counting effects. Such mapping

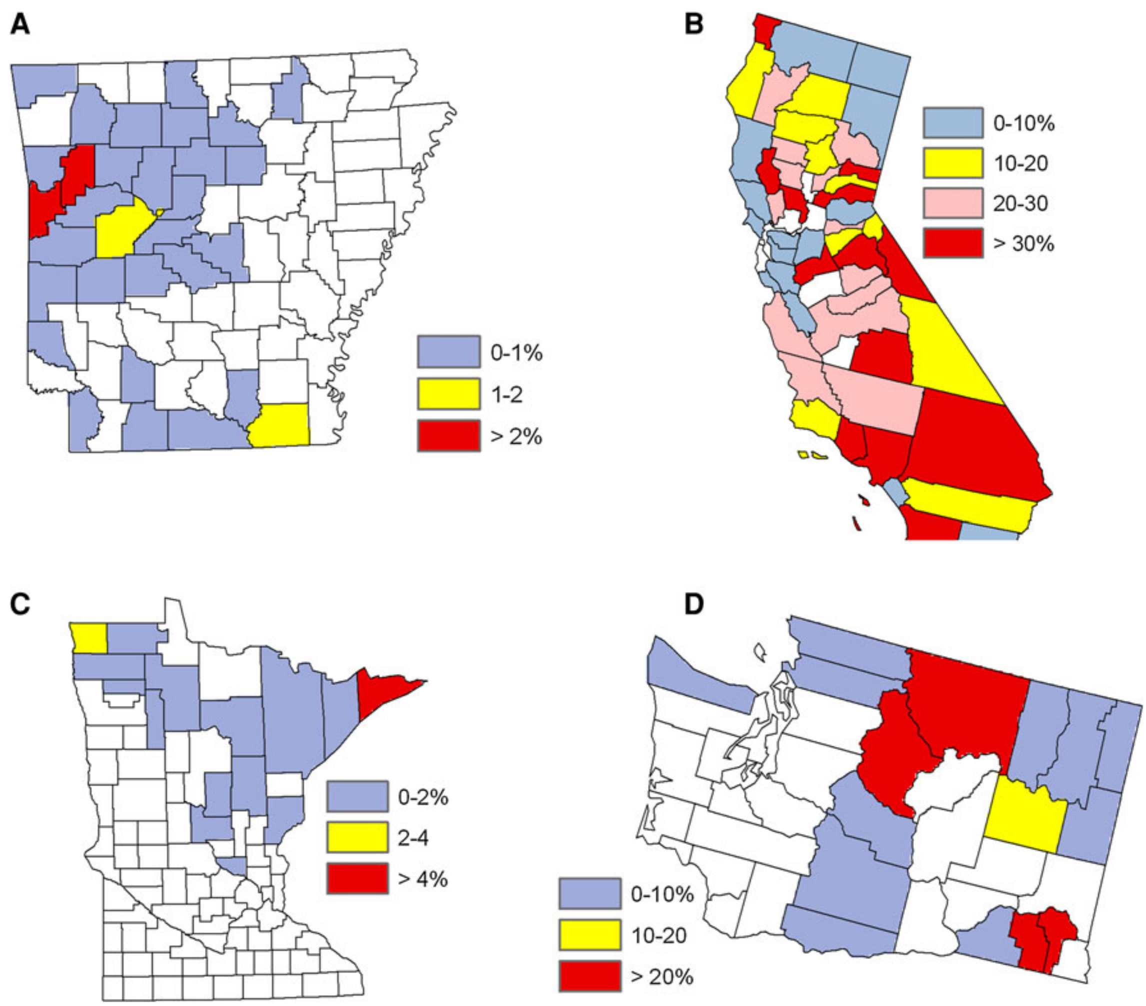

Figure 5. Spatial distribution of carbon double counting estimates (in percent) at the county level between forest fires and FNCC from 1992 to 2006 in the four states: **A** Arkansas, **B** California, **C** Minnesota, and **D** Washington. All counties in *white* signify lack of data for such assessments (either because there was no fire record within the lands classified as FNCC at the terminal year (2006) of the period or there were no mean forest carbon density data available from Smith and others (2006)).

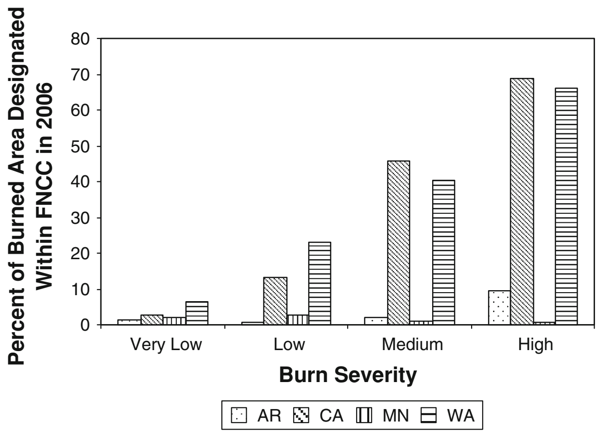

Figure 6. Pattern analyses on relationship between severity of burned areas (using data in 1992, 1996, and 2000 excluding forests with multiple fires) and proportion (averaged %) of FNCC in relation to total burned area plus forest remaining forest (frf) at the terminal year of the study period (that is, 2006), calculated as $Area_{def}/Area_{def+frf} \times 100$ in the four states: Arkansas, California, Minnesota, and Washington.

Table 3. Distribution (in Percent) of Carbon Double Counting Between FNCC and Forest Fires by Burn Severity Classes (S1 = very low, S2 = low, S3 = medium, and S4 = high) in the Four Representing States in the Conterminous United States from 1992 to 2006

State	S1	S2	S3	S4
AR[1]	2.2	15.8	44.3	37.7
CA	0.3	4.2	28.4	67.2
MN	2.5	31.3	32.9	33.3
WA	0.2	3.5	19.8	76.4

[1] *See Table 1 for the full names.*

errors ranged from 10 to 20% for the conterminous US (Homer and others 2012). Second, we used a factor of 0.8 to estimate C emissions through FNCC and C emission rates for different severities obtained from Utah High Plateaus for both the western and eastern states. If refined site-specific conversion factors were used, then the results would likely differ. Third, fires recorded in the current MTBS datasets only contained fire sizes larger than certain threshold values. The results for the states in the western US are missing an unknown number of fires smaller than 404 ha, but which would have been included in states of the eastern US. Keeping all other conditions constant, carbon emissions from high severity forest fires in the western US are likely the major source of uncertainty in double counting calculations between FNCC and wildfires because the emissions from the high-severity class accounted for over two-thirds of all the double-counted emissions in California and Washington states (Table 3). Fourth, our simplified method to calculate C emissions through fires uses a limited number of severity classes to reflect what percentage of the C on the site is emitted. More refined classes and techniques should produce more precise results. Despite these limitations, our study presents a method for improving our current understanding on the issue, and illustrates the magnitude and general pattern of such double counting effects across the country, which can be useful for refining net forest C change estimates at large scales and for future studies of this kind. Our results suggested a general pattern that the amount of forest C emissions double-counted between FNCC and fires, in both absolute and relative terms, was more evident and substantially different on a west–east dimension than that on a north–south dimension across the conterminous US during the study period. More regional-level studies on this together with improved data and technology would be beneficial to test whether this pattern is general and robust to decadal-scale variations in climate and fire severity.

Conclusion

The magnitudes of forest C double counting between FNCC and forest fires estimated from this study ranged from an average 0.04 TgC per year in the two eastern US States during 1992–2006 to an average 0.6 TgC per year in the two western states. In relative terms, these double counting estimates accounted for 14.7 and 0.2% of C emissions through FNCC in the two western (on average) and two eastern states, respectively. We expect that these patterns are similar to those in other states in their respective regions, and that carbon double counting between FNCC and forest fires in a 14-year period was more evident in the western states of the US, whereas the effect was likely limited in the eastern states because the majority of fires were low-severity burns and the area burned was smaller. The double counting issue deserves more attention in studies related to quantifying forest net C estimations in the areas where FNCC and fires are frequently intermingled.

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