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Comparing field- and model-based standing dead tree carbon stock estimates across forests of the US

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Summary

As signatories to the United Nation Framework Convention on Climate Change, the US has been estimating standing dead tree (SDT) carbon (C) stocks using a model based on live tree attributes. The USDA Forest Service began sampling SDTs nationwide in 1999. With comprehensive field data now available, the objective of this study was to compare field- and model-based estimates of SDT C stocks across the US to evaluate potential directions for improving National Greenhouse Gas Inventory (NGHGI) reporting and C dynamics research. Field inventory data indicated that most forests have relatively little SDT C stocks (<1 Mg/ha), whereas large SDT C stocks (>25 Mg/ha) are infrequent. Models used for past NGHGIs to predict SDT C stocks do not accurately reflect what was observed in inventory plots, resulting in an overestimation (~100 per cent) of SDT C stocks at the national scale. These results indicate that the current estimate of the Nation's total forest C stock is overestimated by ~4.2 per cent due to overestimation of SDT C stocks that are a relatively small component of the total forest C stock. A field-based approach is suggested for use in future C reporting efforts to reduce estimation bias.

Introduction

The United Nations Framework Convention on Climate Change (UNFCCC, 1992) requires signatory countries to develop and report their national inventories of forest carbon (C) sources and sinks (Brown, 2002), due to the recognized role that forests play in the global C cycle (Dixon *et al.*, 1994; Bonan, 2008; Malmsheimer *et al.*, 2008; Ryan *et al.*, 2010). One important pool of forest C is deadwood (Goodale *et al.*, 2002; Woodall *et al.*, 2008; USEPA, 2011), but there has been a lack of consistent inventories of deadwood for many nations due to the historical focus on inventorying standing live trees for commercial utilization during forest inventories (Woodall *et al.*, 2009). Deadwood C stock estimates are often based on various combinations of field measurements and ecosystem models (Goodale *et al.*, 2002). Deadwood C stocks are typically separated into standing dead tree (SDT) and downed dead (DD) pools as their associated methods of estimation vary substantially (USDA Forest Service, 2007a, 2007b). While there have been many studies and sampling methods developed specifically for estimating the DD pool (e.g. Woodall and Monleon, 2008; Woodall *et al.*, 2008), there have been few studies examining SDT C stocks in the context of National Greenhouse Gas Inventories (NGHGIs). Given the possibility of increased tree mortality events associated with climate change (IPCC, 2007; van Mantgem *et al.*, 2009), accurate assessments of SDT C are of increasing importance.

The US's official NGHGI (i.e. Land Use, Land Use Change and Forestry; USEPA, 2011) is based on the national forest inventory conducted by the US Department of Agriculture's Forest Inventory and Analysis (FIA) Program (Heath *et al.*, 2011) using a system of models incorporated into the Carbon Calculation Tool (CCT) (Smith *et al.*, 2007; USEPA, 2011) to transform field inventory data into C stock estimates. SDT C estimates from 1990 onward are required by NGHGI reporting agreements. As numerous FIA periodic inventories conducted prior to 2000 did not inventory SDTs, the preferred method for meeting UNFCCC reporting requirements has been to predict SDT C from live tree attributes using models in the CCT. The FIA program began sampling SDTs in 1999 on a nationally consistent, annual inventory system (Bechtold and Patterson, 2005) in recognition of the importance of SDTs to numerous forest ecosystem attributes/processes such as C stocks/fluxes. Annual inventories were gradually implemented state by state across the US, with the final states being incorporated into the national annual inventory system in 2010 (USDA Forest Service, 2010). As a nationally consistent inventory of SDTs is now available, estimates of SDT C predicted from the CCT model can be comprehensively compared with those derived from field inventories.

In this study, it was hypothesized that using field estimates of SDT C stocks in lieu of modelled stocks would reduce C stock uncertainty and/or bias while improving understanding of C stock dynamics in the face of disturbance events occurring over multiple spatial and temporal scales (e.g. large-scale mortality events such as beetle epidemics). Woodall *et al.* (2008) conducted an initial exploration of modelled DD wood C stocks from the CCT system of models compared with field inventories and found reasonable agreement at large scales. However, the analysis by Woodall *et al.* (2008) did not draw comparisons between modelled and empirical SDT C stocks. The goal of this study was to compare model- and field-based estimates of SDT C stocks guided by four specific objectives: (1) compare estimates of SDT C stocks based on model and field estimates by study strata (e.g. ownership), (2) examine distribution of individual plot-level differences between field and model estimates of SDT C stocks, (3) assess differences in national population estimates based on field and model approaches to SDT C stock estimation and (4) suggest future research and refinements that facilitate the transition from model- to field-based estimates of SDT C stocks in the US's NGHGI.

Methods

Data

The FIA program is the primary source for information about the extent, condition, status and trends of forest resources in the United States (Smith *et al.*, 2009). FIA applies a nationally consistent sampling protocol using a systematic design covering all ownerships across the US (national sample intensity is one plot per 2428 ha, Bechtold and Patterson, 2005). Land area is stratified using aerial photography or classified satellite imagery to increase the precision of estimates. Remotely sensed data may also be used to determine if plot locations have forest cover; only forested land is sampled by field crews and it is defined

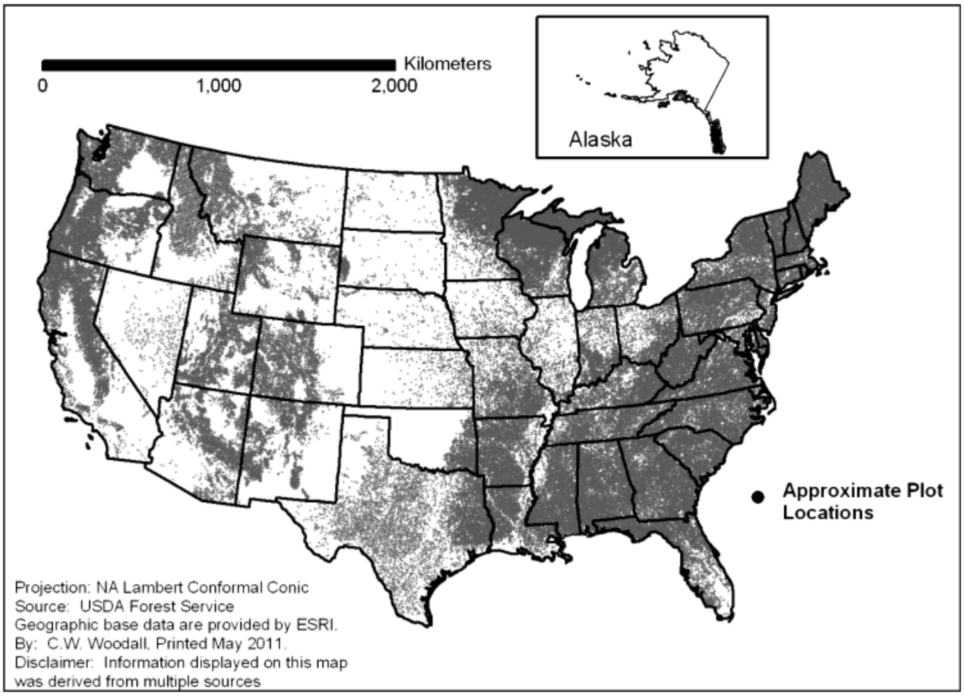

Figure 1. Approximate plot locations of forest inventory plots used in analysis, conterminous US and coastal Alaska, 1999–2010.

as areas at least 10 per cent stocked with tree species, at least 0.4 ha in size and at least 36.6 m wide (Bechtold and Patterson, 2005). FIA inventory plots established in forested conditions consist of four, 7.32-m fixed-radius subplots spaced 36.6 m apart in a triangular arrangement with one subplot in the centre (USDA Forest Service, 2007a; Woudenberg *et al.*, 2010). All trees (live and SDT) with a diametre at growth at breast height (d.b.h.) of at least 12.7 cm are inventoried on forested subplots. A SDT is considered DD (i.e. part of the DD C pool) when the lean angle of its central bole is greater than 45 degrees from vertical (USDA Forest Service, 2007a). Within each subplot, a 2.07-m microplot offset 3.66 m from subplot centre is established where only live trees with a d.b.h. between 2.5 and 12.7 cm are inventoried.

Field data USDA Forest Service (2010) for this study were taken entirely from the FIA database (Woudenberg *et al.*, 2010) using the forest inventory in the conterminous 48 states (western Oklahoma was not available at the time of this study) and coastal Alaska for a total of 137,426 unique inventory plot conditions (Figure 1). Annual/periodic inventories for most states were initiated since 1999 and run through 2010, so sample intensities vary by state. It should be noted that Wyoming was an exception; a complete periodic inventory was conducted in 1999 using the national plot design ensuring compatibility with all other state inventories. The associated field data are available for download at the following site: http://fiatools.fs.fed.us (FIA Datamart; USDA Forest Service, 2011).

Analyses

In the US's current NGHGI (USEPA, 2011), SDT C stocks are modelled as a function of live tree growing stock volume based on the FIA plot network. This study used all available FIA plot-level data, sampled between 1999 and 2010, to determine field- and model-based estimates of SDT C stocks for each plot. In order to facilitate valid comparisons, FIA's regional volume equations (Woodall *et al.*, 2011) were used for computation of standing tree volumes for input into the SDT C model (Smith *et al.*, 2007; USEPA, 2011) and field-based SDT C calculations. This differs from the methods used in past US NGHGI's where live tree growing stock volume (as a coefficient within the SDT C model) was computed using equations from Jenkins *et al.* (2003), but was necessary to standardize the comparison of the two methods.

The SDT C model was originally developed for the purpose of providing plot-level model-based regional average SDT C densities by forest type group that was parameterized using periodic inventories where available nationwide (Smith *et al.*, 2003). By early 2005, as more annual inventories were implemented across the US, the SDT C model was refit using more nationally consistent SDT inventories with model output currently incorporated into the NGHGI (Smith *et al.*, 2007; USEPA (2010)). The SDT C stock model (inclusive of saplings; d.b.h. > 2.54 cm) is a function of live tree growing stock volume (including a single structural deduction of ~15 per cent; Smith *et al.*, 2003) with coefficients parameterized by region and forest type (USEPA, 2011, see Annex 3.12 Table A-220) using FIA field inventories documented in Smith *et al.* (2007):

$$\mathrm{SDTC} = (a(\mathrm{GSvol})^{b})0.5, \tag{1}$$

where GS_{vol} is growing stock volume (m^3/ha), 0.5 is a biomass to C conversion constant and a and b are coefficients. These modelled SDT C estimates are available for many forested conditions in the FIADB condition table (USDA Forest Service, 2007a; Woudenberg *et al.*, 2010).

The analytical process for determining field estimates of SDT C stocks is an evolving science. Many of the estimation procedures within the FIADB follow merchantability paradigms intended for estimation of sound volumes on timberland (Domke *et al.*, 2011). Some basic SDT analytical tenets have been adopted in this study to facilitate initial comparison of modelled and field SDT C stock estimates; as such, the results should not exactly match future US NGHGI results. As these procedures (e.g. Domke *et al.*, 2011) are refined and/or new science thoroughly vetted, they may eventually be adopted in the US's NGHGI. This study employed a series of basic steps towards estimation of SDT C stocks based on national field inventories. First, the SDT gross volume was calculated based on regional volume equations (Woodall *et al.*, 2011). Second, SDT sound volume was calculated based on regional volume equations along with merchantable stem deductions (through tree class code in FIADB) due to rotten and missing cull. Third, the sound volume was converted to bole biomass using species-specific wood density values (Miles and Smith, 2009, Woudenberg et al, 2010). In order to account for the reduced wood density due to decay, decay reduction factors by SDT decay class and hardwood/softwood were used based on emerging work by Harmon *et al.* (2011). Fourth, total tree biomass was calculated using the component ratio method (CRM; Heath *et al.*, 2009; Woodall *et al.*, 2011). Briefly, the CRM facilitates calculation of tree component biomass (e.g. tops and limbs) as a proportion of the bole biomass based on component proportions from Jenkins *et al.* (2003). Fifth, as SDTs in advanced stages of decay lack some or all of the components calculated using CRM (e.g. decay class 5 SDTs lack tops, USDA Forest Service, 2010a), SDT structural reduction factors based on emerging work by Domke *et al.* (2011) were broadly applied by decay class and hardwood/softwood. The sixth and final step was the conversion of SDT total biomass to C mass assuming 50 per cent C content of woody biomass. For both the field- and model SDT C estimates, belowground estimates of coarse root C were included and were calculated as a proportion of aboveground C in both estimates (see coarse root component equation in Jenkins *et al.*, 2003). Although future determination of SDT C stocks may involve refinement of these afore mentioned steps or incorporation of emerging research (e.g. adjustment of 50 per cent deadwood biomass to C factors), they broadly define the steps necessary to estimate SDT C stocks using forest inventory data and specifically describe the methods that were employed for this analysis.

The distribution of SDT C values for all FIA plots based on field- versus model-based estimates was examined along with the absolute and relative difference between field- and model-based estimates at each plot. Means and associated standard errors of field- and model-based estimates of SDT C stocks were compared within three strata: ownership groups, classes of latitude and major forest type groups of the US. The first stratum was chosen assuming that ownership can be used as a surrogate for large-scale differences in land management. Latitude was determined to be an important determinant in forest detritus variations across large scales in a study by Woodall and Liknes (2008), so it was also included here. Lastly, it was expected that field- and model-based estimates of SDT C stocks should be significantly different between major forest communities. To examine the differences in a spatial context, a county-level map of the difference between a plot's field and model estimates of SDT C was created. Finally, in order to approximate the effect of using field instead of model estimates of SDT C stocks on the NGHGI, national population estimates of SDT C were calculated. Simple random sampling was assumed with each observation weighted by the result of each plot's constituent state forestland acreage (Smith *et al.*, 2009) divided by the total number of observations in that respective state.

Results

When comparing field and model estimates of SDT C at the plot level (difference = field – model), there is a strong tendency for the model estimates to greatly exceed the field estimates (Table 1 and Figure 2). Almost 20 per cent of observations had model estimates exceed field by over

Table 1: Percentile distributions of field- and model-based estimates total SDT C stocks on forest inventory plots along with absolute and relative differences (field minus modeled), conterminous US and coastal Alaska, 1999–2010

Percentile	Field estimate (Mg C/ha)	Model estimate (Mg C/ha)	Field–model standing dead estimates (Mg C/ha)	Field–model standing dead C stocks as per cent of field stocks
100	340.70	259.61	340.61	100.0
99	28.58	23.25	17.43	100.0
95	9.09	14.43	2.55	66.4
90	4.69	8.69	−0.09	39.3
75	1.40	5.42	−1.36	−43.2
50	0.14	3.84	−2.88	−277.2
25	0	2.36	−4.47	−956.8
10	0	1.03	−6.77	−2718.2
5	0	0.50	−9.94	−5334.7
1	0	0.12	−18.33	−28 582.6
0	0	0.06	−259.46	−870 484.1

Percentiles are determined for each set of estimates individually.

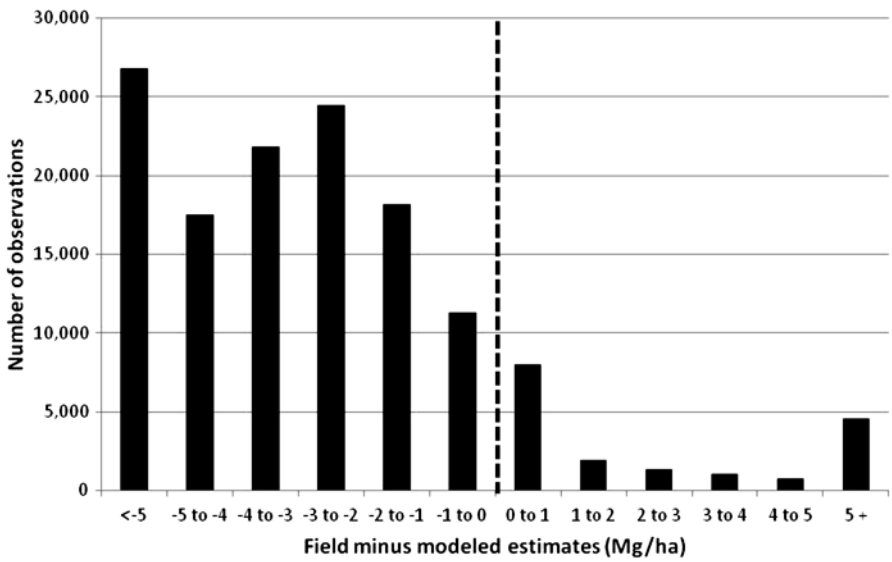

Figure 2. Histogram of observations of field estimates minus model estimates of SDT C on inventory plots, conterminous US and coastal Alaska, 1999–2010

5 Mg/ha (Table 1). Relative to field estimates of SDT C, nearly half of modelled stocks exceeded field estimates by over 300 per cent (Table 1). Given that the model sometimes estimated considerable SDT C (>5 Mg/ha), where field measurements indicated very little stock (<0.1 Mg/ha), the relative difference in SDT C estimates reached as high as the hundreds of thousands of per cent (Table 1). In contrast, field estimates exceeded model by over 5 Mg/ha for only 3 per cent of observations. The median absolute difference in estimates was an overestimate of SDT C stocks of 2.88 Mg/ha by the model with a corresponding median relative difference of 277 per cent (Table 1). The distribution of field observations of SDT C was highly right skewed emphasizing that many plots had little or no SDT C with few plots having substantial C stocks (>25 Mg/ha) (Table 1). This was dramatically different when compared with model estimates predicted on the same plots where the field inventory was conducted, indicating a large discrepancy in the distributions of field and model SDT C stocks. Almost two-thirds of observations had a field estimate of SDT C <1 Mg/ha, while model estimates in the same category accounted for only 10 per cent of total observations (Table 1). Of particular note, no (zero) SDT C (d.b.h. ≥ 12.7 cm) were observed on 61 884 out of the total 137 426 field plots, whereas the model only predicted no (zero) SDT C at 5907 of these field plots. This resulted in overpredicted SDT C stocks across the bulk of locations, except for some locations where there was a very large amount of SDT C (Table 1).

Across all forest types, the means of model estimates of SDT C greatly exceeded means based on field measurements, indicating a relatively large bias towards overestimating SDT C when using the CCT models (Table 2). By forest type groups, means of model SDT C estimates ranged from 1.52 to 17.01, while field estimates ranged from 0.62 to 6.76 (Table 2). The discrepancy between field and model estimates increased with increasing latitude (Figure 3). For latitudes below 33, the discrepancy was −1.6 Mg/ha, with the divergence increasing up to −3.7 Mg/ha above latitudes of 45.0 degrees. There were also sharp differences between model- and field-based estimates between different ownerships, with the largest difference between state and private ownerships; the means of model estimates exceeded means of field estimates by a factor of nearly 3 (Figure 4).

Across the US, model estimates of SDT C exceed field estimates by the largest absolute amount along the west coast, in areas of the central Rocky Mountains, and southern Florida, with the converse occurring primarily in more isolated pockets of northern Rocky Mountain and southeastern forests (Figure 5). As the SDT C model has separate coefficients by regions of the US, these regional differences are obvious along certain state boundaries (IL, IN, OH and WV versus KY and VA). The cumulative differences between field and model estimates of SDT C results in a halving of national SDT C estimates (from

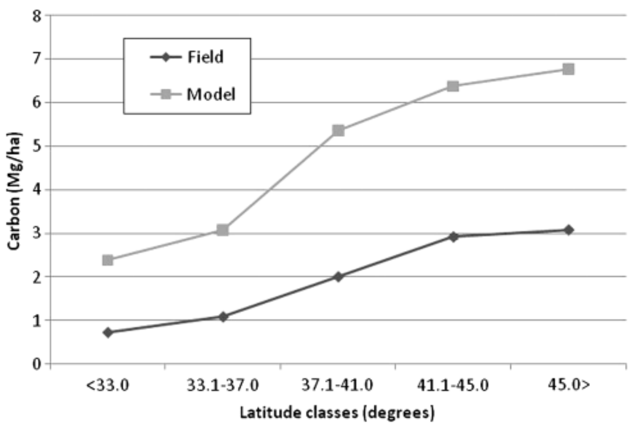

Figure 3. Means and associated standard errors of field- and model-based estimates of total SDT C by classes of latitude, conterminous US and coastal Alaska, 1999–2010.

Table 2: Means and associated standard errors of field- and model-based estimates of total SDT C by forest type group, conterminous US and coastal Alaska, 1999–2010

		Field estimate (Mg C/ha)		Model estimate (Mg C/ha)	
Forest type group	*n*	Mean	SE	Mean	SE
Northeastern pines	3099	1.215	0.041	4.113	0.033
Eastern spruce/fir	4870	1.225	0.034	4.819	0.035
Southern/Tropical pines	16 715	0.62	0.019	1.522	0.007
Western pines/pinyon/juniper	15 106	2.401	0.059	3.916	0.02
Western spruce/firs	12 371	7.205	0.115	13.697	0.056
Other western conifers	1757	6.764	0.278	17.006	0.224
Oak/pine	6642	0.969	0.032	2.522	0.016
Oak/hickory	32 452	1.134	0.015	3.423	0.006
Oak/gum/cypress	5512	1.042	0.042	3.613	0.017
Elm/ash/cottonwood	8702	0.97	0.027	4.233	0.021
Maple/beech/birch	11 696	1.417	0.024	5.607	0.016
Aspen/birch	7713	1.731	0.051	4.832	0.033
Other western hardwoods	7159	1.631	0.085	4.599	0.023
Other/non-stocked	3353	4.711	0.278	5.929	0.209

2000 to 1000 Tg nationwide, Table 3). Across all classes of live tree C stocks, the SDT C model overestimates SDT C stocks by 159–324 per cent of field estimates (similar to median divergences seen at the plot level, Table 1). The greatest population divergences appeared to occur in forests with relatively low live tree C stocks. When compared with the entire forest C stock (live, dead, soils, forest floor, etc.), the national difference between the model and field estimate of SDT C is −4.2 per cent, in other words, model estimates of SDT C appear to inflate the estimate of total US forest C stocks by 4.2 per cent.

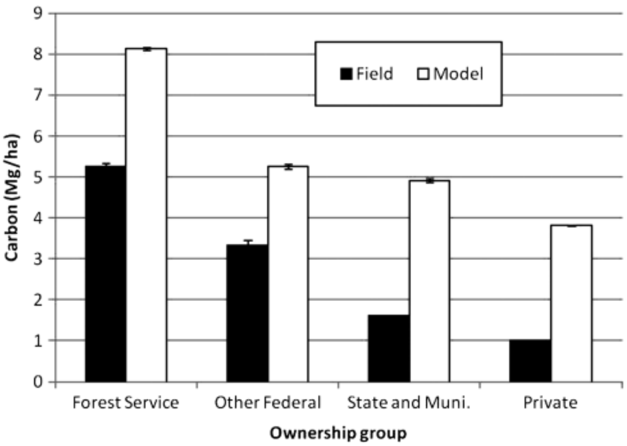

Figure 4. Means and associated standard errors of field- and model-based estimates of total SDT C by classes of ownership, conterminous US and coastal Alaska, 1999–2010.

Discussion

As the US currently has a fully implemented field SDT C inventory, the results of this study suggest that field SDT C estimates immediately replace model estimates in the US's NGHGI. Although this will result in a reduction in the reported US forest C stocks merely due to a change in modelling/estimation procedures, it will more closely estimate the true SDT C population along with more meaningful sampling statistics (e.g. estimated variance). The SDT C modelling approach may have been adequate for past NGHGI reporting as the difference between the field and model estimates only results in a 4.2 per cent change in the US's total forest C stocks. As the field inventory of SDT C indicates that SDT C stocks are relatively minimal (<1 Mg/ha) with only stochastic disturbance/mortality events increasing this C stock (> 10 Mg/ha), even substantial differences in field and model estimates (100 per cent difference at national scale) result in minor changes to total forest C stocks (e.g. <5 per cent of total stocks). When considering the SDT C individually, the model approach dramatically underestimates the number of plots that have very low SDT C stocks (<1 Mg/ha), in large part because as the SDT C model is currently configured, if there is any live tree growing stock volume then the SDT C stock will be estimated to be non-zero. Even if the forest stand is classified as non-stocked (i.e. no growing stock volume), the SDT C model will provide a positive estimate of SDT C (USEPA, 2011). With the incorporation of a national scale SDT inventory in the US's NGHGI, uncertainty associated with the Nation's SDT C stock should be reduced along

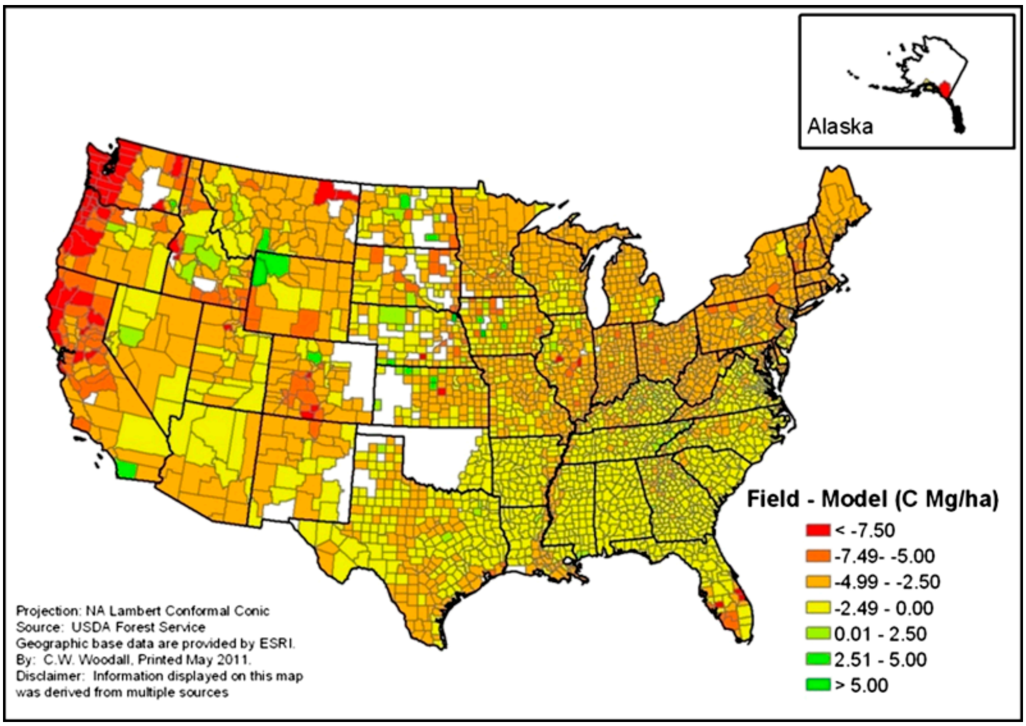

Figure 5. County-level estimates of differences (field based minus model based) in SDT C estimates derived from inventory plots, conterminous US and coastal Alaska, 1999–2010 (white areas delineate counties with no data or lack of forestland).

Table 3: Field and model estimates of SDT C stocks by classes of live tree C, conterminous US and coastal Alaska, 1999–2010

Live tree C class (Mg/ha)	Field population estimate (Tg)	Model population estimate (Tg)	Field–model population estimate (Tg C)	Sampling error (%)	All stocks (Tg C)	Model difference as per cent of standing dead (%)	Model difference as per cent of total stocks (%)
0–10	119.7	188.4	−70.8	4.01	6422.4	159.1	3.0
10–20	54.2	175.8	−121.6	9.53	4348.9	324.2	4.0
20–30	56.7	157.8	−101.1	8.16	3767.9	278.3	4.2
30–40	54.2	142.1	−87.9	8.34	3387.2	262.2	4.2
40–50	59.6	135.1	−75.5	7.96	3182.7	226.6	4.2
50–60	56.5	116.3	−59.8	8.17	2851.4	206.0	4.1
60–70	53.6	119.7	−66.1	8.87	2802.2	223.2	4.3
70–80	54.2	107.5	−53.3	9.06	2547.8	198.4	4.2
80–90	44.9	84.3	−39.4	9.95	2072.8	187.9	4.1
90–100	45.1	82.4	−37.3	9.67	1937.6	182.7	4.3
100+	359.9	611.8	−251.9	1.33	12 747.8	170.0	4.8
Total	958.8	1,921.4	−964.8	0.37	46 068.7	200.6	4.2

Model difference = SDT C field estimate minus model SDT C estimate.
Sampling error = sampling error associated with both field and model estimates as they are derived from same plot network.
Total stocks = down dead + standing dead + live tree + litter + soil organic C + understorey.

with improved correlation with non SDT forest C stocks (e.g. standing live tree C).

The US's SDT C model may be improved by addressing numerous shortcomings identified in this study. First, the SDT C model was fitted years ago using an incomplete annual inventory across the US. A full range of forest conditions (e.g. C stocks and forest types) should be better reflected in the SDT C model coefficients when the model is fit. Second, tree volume models and biomass reductions for SDTs can vary between field and model approaches. The SDT C model was fit assuming a constant 15 per cent biomass reduction, whereas the field estimate of SDT C uses a more refined system of decay and structural reduction constants (based on Domke *et al.*, 2011 and Harmon *et al.*, 2011). Finally, the SDT C model uses static model coefficients by region and forest type, a problem highlighted by Krankina and Harmon (1995) in Russia.

The model and field estimates were quite divergent across classes of ownership with field estimates less than half as large as model estimates for state and private ownerships, indicating that there are likely differences in forest management which affect the relative abundance of SDTs; managed forests typically have lower proportions (Radtke *et al.*, 2009). It should be recognized that forest ownership patterns are strongly regionalized, so that differences in management (ownership), geographic location and major forest community types are not independent (Smith *et al.*, 2009). Forests in the southeastern US are generally more heavily managed and are predominantly privately owned (Wear and Greis, 2002). In contrast, higher tree mortality rates on federally owned forests in the western US (Smith *et al.*, 2009) may be an important driver of national SDT C stocks. Forest health conditions cannot be easily ascribed to levels of SDT C stocks nor do mean SDT C stocks among this study's strata prescribe changes to SDT C models. Future research should explore the relationships between ownership (i.e. management intensity), climate (i.e. rates of decay) and forest types (i.e. stand dynamics) that appear to drive SDT C dynamics. Taken together, the population estimate disparity between the field and model estimates of national SDT C might be reduced if the SDT C model was refit using the larger inventory dataset, perhaps a different model form incorporating ownership/decay attributes, and refined structural/density deductions.

While this study appropriately considers the field estimates as much closer to the truth than the model output, it is possible that part of the discrepancy between field- and model estimates is due to field-approach limitations. One issue is that the field inventory only samples SDTs with a d.b.h. ≥ 12.7 cm, while the live tree inventory samples trees with a d.b.h. ≥ 2.54 cm. Because live trees with a d.b.h. between 2.54 and 12.7 cm only account for ~8 per cent of the nation's aboveground live tree biomass, this portion of SDT C stocks should not substantially bias study results, although it does increase the uncertainty between live and SDT correlations. As suggested by previous work (Fiedler and Morgan, 2000), the mortality of small-sized trees may be an important driver of deadwood accumulation; thus, this size class of SDT trees deserves future scrutiny. To account for sapling-sized SDTs, field estimates of SDT C may need to include an adjustment factor, include a SDT sapling model, redefine the SDT C stock as only including SDTs with a d.b.h. > 12.7 cm (i.e. acknowledging the transitory nature of small tree C stocks) or include this tree size in national field inventories to account for this omission.

Another issue with the field inventory data is that a larger proportion (nearly 45 per cent) of FIA plots contained no SDTs due to the relatively small plot sizes (relative to the forest area they represent), suggesting that FIA's SDT data are likely zero inflated (Eskelson *et al*., 2009). As such, the empirical estimation of SDT C may be influenced by zero inflation and the SDT C model may have been calibrated with FIA plot data similarly zero inflated. The influence of zero-inflated SDT data under the FIA plot design and refined population estimators are under investigation (An and MacFarlane, in press).

A third issue related to this analysis relates to interpolation/extrapolation techniques between earlier time period-modelled SDT C estimates in the US (prior to 1999) and later time period (post-2000s) field estimates. To adjust for this, an interpolation technique could be adopted where a relationship is developed between model and field estimates over time to "smooth" the transition in estimates (see inventory panel rotation concepts, Roesch, 2007). In contrast, an extrapolation technique could be adopted where older reporting year (e.g. 1990) estimates of SDT C are based on a current SDT C attributes (e.g. C density) pro-rated by forestland area trends across reporting times.

Finally, the field methods require ascribing the decay class and structural reduction of SDTs (Domke *et al*., 2011). Procedures for estimating individual tree SDT C are inherently based on live tree standards; perhaps, SDTs require varying procedures (e.g. continuum of decay and structural reduction instead of one factor for the entire tree) outside of standing live tree volume/biomass/C estimation paradigms. Despite the need for some further research and refinements of field-based SDT C estimation procedures, this study suggests that the US is ready to adopt a field-based approach to SDT C stock reporting that meets UNFCCC reporting requirements (e.g. baseline year reporting).

Conclusions

The establishment of a National SDT C field inventory allowed for improved estimation of SDT C stocks across the US. The results of this study indicate that previous model estimates of US SDT C stocks from live tree stocks via models were seriously biased, overestimated by nearly 100 per cent, which resulted in an over statement of the Nation's total forest C stocks by 4.2 per cent. The transition from model to field SDT C should provide a greater sensitivity to actual tree mortality events, increased certainty of estimates and more refined forest C dynamic models. Continued research into interpolation/extrapolation techniques for development of reasonable baseline SDT C stock trends and refined SDT C estimation procedures (e.g. decay and structural reductions) is strongly suggested to meet UNFCCC reporting requirements (e.g. 1990 to the present).

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Conflict of interest statement

None declared.

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