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The lack of adequate quality assurance/quality control data hinders the assessment of potential forest degradation in a national forest inventory

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ABSTRACT

Hardwood lumber harvested from the temperate broadleaf and mixed broadleaf/conifer forests of the east-central United States is an important economic resource. Forest industry stakeholders in this region have a growing need for accurate, reliable estimates of high-quality wood volume. While lower-graded timber has an increasingly wide array of uses, the forest products sectors in those states would be negatively affected if there is ongoing forest degradation due to the relative loss of higher graded timber. The United States national forest inventory provides data that could answer whether the supply of higher graded timber is decreasing despite an overall increase in merchantable wood volume. To study trends over time, however, one must take into account the partial lack of independence within forest inventory and monitoring datasets with repeated measurements on the same permanent plots and the trees within them. By doing this, we demonstrate that the data show significant decreases in the relative saw-log volume found in higher-graded, commercially valuable hardwood trees in the states of Kentucky and Tennessee from 2001 to 2013, most notably a decrease in the percentage of tree grade 1 saw-log volumes in Kentucky and a decrease in tree grade 2 saw-log volumes in Tennessee. We also identified a potential increase in lower quality (tree grade 4) saw-log volume in both states. These findings would be consistent with indirect and anecdotal evidence of degradation in hardwood resource in portions of the region. However, substantial annual fluctuations in the volume percentages by grade led us to question the validity of those observed trends. Quality assurance and quality control (QA/QC) data collected in conjunction with those tree grade data were not sufficient or consistent enough to allow us to verify whether we are observing real trends or data collection anomalies, thereby compromising our ability to provide important information to land managers and decision makers. The occurrence of hardwood tree grade fluctuations over time illustrates the need for robust QA/QC procedures in national forest inventories. More frequent QA/QC data collection and analysis, field data collection training consistency across regions, and potentially simplifying field measures of tree stem quality could provide more clarity and confidence when assessing the condition of forest resources.

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1. Introduction

The temperate broadleaf and mixed broadleaf/conifer forests of the east-central United States (U.S.) are an important ecological and economic resource. The production of hardwood lumber makes a substantial contribution to these states' economies. In 2011 Kentucky had 213 sawmills and production of 3.15 million cubic meters of hardwood lumber while Tennessee's 244 sawmills produced 3.27 million cubic meters of hardwood lumber (Bentley et al. 2014a, 2014b). Despite high annual production levels and overall trends of increasing sawtimber volume, some analyses (Oswalt 2015; Oswalt and King 2014; Oswalt et al. 2012, 2015) and anecdotal evidence have suggested a progressive degradation in the hardwood saw-log resource in these states. If true, a trend of declining resource quality could indicate forest management shortcomings or large-scale demographic changes in the hardwood forests of these southern states. Such trends have been observed in the past in other southern states; for example, Kelly and Sims (1989) noted a decrease in the amount of higher quality saw-log volume in Mississippi from the late 1970s to the late 1980s amid a statewide increase in merchantable hardwood volume. They attributed the decrease in tree quality to increasing amounts of

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rot and other log quality degradation factors; they also noted the negative effects of "the inattention given to replacing harvested trees" (Kelly and Sims, 1989), which might indicate the removal of higher quality trees and the retention of lower quality ones. More recently, Cumbo et al. (2003) and Luppold and Bumgardner (2003) expressed concern about evidence of increasing amounts of low-value, small-diameter timber in the hardwood forests of the eastern United States.

The aforementioned analyses have shown decreasing prevalence of higher quality trees as defined by their tree grade in the national forest inventory data collected annually by the U.S. Forest Service's Forest Inventory and Analysis (FIA) program. Tree grade is a description of the quality of the standing live tree; better grades indicate that greater quantities of clearer lumber can be sawn from the stem. Hardwood tree grade, as used in the FIA program, is defined as the log grade of the 16-foot butt log or the log grade of the best 12-foot section within the 16-foot butt log, whichever is higher. Log grade is based on the specifications for Forest Service standard grades for hardwood factory lumber logs, as described by Rast et al. (1973).

It would seem reasonable, therefore, to use the decrease in the proportion of total volume that is in higher graded trees as estimated by FIA as an indicator of forest degradation. Although forest degradation is commonly used to refer to the loss of carbon storage or sequestration capacity, it is more broadly defined as the reduction in the capacity of a forest to deliver ecosystem services (Miles and Kapos, 2008; Thompson et al., 2013). For this study, we define forest degradation as the loss of higher-quality hardwood sawtimber volume even while total timberland area and total volume are stable or increasing. The in-depth analysis of volume by tree grade required to assess this situation, however, also requires scrutiny and understanding of the methods used in the field to grade a tree. Tree grading is one of the most subjective evaluations made on an FIA plot and requires that field crew members have considerable training and experience before accuracy and repeatability of evaluations are achieved.

To address the question of whether the hardwood resources of Kentucky and Tennessee were being degraded over time, we investigated trends in hardwood tree grade for a subset of high-value timber species in those states. We used as a response variable the proportion of net cubic foot saw-log volume on FIA plots measured from 2001 to 2013. For this examination, we considered different statistical methods to make statistically valid comparisons of means between individual years of annualized forest inventory permanent plot data that were remeasured at regular intervals. We also examined older, periodic forest inventory data to better understand long-term trends in tree grade. Then, we explored the Quality Assurance/Quality Control (QA/QC) data for tree grade collected from 2001 to 2013 to analyze whether field crew members' assessments consistently differed from the assessments of more experienced QA/QC foresters. This final part of the study was meant to help us determine how confident we could be in deciding whether the observed trends were real and providing this information to forest resource stakeholders.

2. Methods

2.1. Study area

The hardwood-dominated forests of Kentucky and Tennessee fall primarily within the Central Hardwoods and Southeastern mixed-forest ecoregions of the U.S. (Bailey, 1983). The oak-hickory forest type is the most common and stands frequently have a significant oak (*Quercus* spp.) species component. Historically these forests were extensively cleared for agriculture, and the remaining forests on less-arable land were selectively harvested. Socioeconomic changes across the region resulted in partial reforestation through both natural and artificial regeneration starting in the first half of the twentieth century. More recently, timberland area continues to slowly increase across the region despite increasing urbanization. Merchantable volume has also increased (Brandeis et al., 2012), as can be seen in Kentucky and Tennessee (Oswalt, 2015; Oswalt and King, 2014; Oswalt et al., 2012).

2.2. Forest inventory and tree grading procedures

The FIA program maintains a permanent plot network across the U.S., associated territories and commonwealths that shares a consistent sampling design, plot layout and field data collection procedures. More information on this program and detailed documentation on its methods and estimation procedures can be found in Bechtold and Patterson (2005). National and regional variations of field data collection procedures, such as the southern regional field manual (U.S. Department of Agriculture Forest Service, 2014), are also available.

There is one permanent, systematically located forest inventory and monitoring plot for every 2428 hectares (5998 acres) of land on the continental U.S. Each of these plots is a cluster of four subplots with a total sampled area of 0.07 ha (one-sixth acre). Where there is forest, all trees with a d.b.h. (diameter at breast height, 1.37 m (4.5 ft) of 12.7 cm (5.0 in.) or greater are identified and measured. Each tree is individually tracked and remeasured at 5-year intervals in Kentucky and Tennessee. Tree height and d.b.h., along with deductions for defect and cull, are used to estimate net tree volume using volume equations detailed in Oswalt and Conner (2011).

Volume of the saw-log portion of the tree is estimated for sawtimber-size trees that meet certain minimum requirements. This is the variable VOLCSNET in the publicly accessible FIA database, FIADB, the calculation of which is described in Oswalt and Conner (2011) and Woudenberg et al. (2010). For southern hardwood timber species, the tree must have a d.b.h. greater than or equal to 27.9 cm (11.0 in.) and the saw-log portion of the main stem must have a merchantable log that is at least 3.6 m (12 ft) long to a minimum 22.9 cm (9 in.) diameter (outside bark) at the top (Oswalt and Conner, 2011). In the southern states, trees that meet these sawtimber size requirements are graded for tree quality. There are five possible tree grades. Grading is judged within the lower 4.9 m (16 ft) of the stem, and the stem section actually graded represents the best 3.6 m (12 ft) of log within that zone. Tree grades 1 through 4 are in descending order of quality. Put in simplified terms, a grade 1 tree is larger than lower-grade trees, with a minimum d.b.h. of 40.6 cm (16 in.), and has more clear wood free of defects within the saw-log. Grades 2, 3 and 4 are of smaller d.b.h. or have less clear wood in the saw-log. Grade 5 is different. Trees of this grade do not meet the requirements for grades 1 through 4 but have a saw-log located somewhere in the tree other than in the butt portion (e.g., upper stem or branch), or have at least two non-contiguous 2.4 m (8 ft) long logs. Additional detailed rules for tree grading can be found in the FIA southern regional field manual (U.S. Department of Agriculture Forest Service, 2014).

2.3. Data queried from the FIA database

We queried the FIADB in August of 2015 to extract data on selected sawtimber-size hardwood trees measured in Kentucky and Tennessee from 2001 to 2013. Annualized inventory data were available for 1999 and 2000, but we chose to start our query with 2001 data due to the limited number of plots measured in the previous 2 years. Both states were on a 5-year remeasurement cycle this entire period. We confirmed with FIA data acquisition and information management personnel that forest inventory field manual and database procedures for taking tree measurements used for volume estimation, cull deduction, tree grading, and volume calculation had remained consistent throughout the period queried. Although the national FIA program is responsible for designing field data collection protocols, providing training and conducting QA/QC assessments, the actual data collection is currently done by the respective state forestry agencies in Kentucky and Tennessee.

The hardwood species chosen, based on expert knowledge of the resource and demand by the forest products industry, were white oak (*Q. alba*), northern red oak (*Q. rubra*), southern red oak (*Q. falcata*), chestnut oak (*Q. prinus*), black oak (*Q. velutina*), cherrybark oak (*Q. pagoda*), yellow-poplar (*Liriodendron tulipifera*) and black walnut (*Juglans nigra*). The query was limited to live growing-stock trees with a minimum d.b.h. of 27.9 cm (11 ft). We also queried the database for data from earlier periodic forest inventories of Kentucky (1988) and Tennessee (1989, 1999) and then annualized the inventory moving average VOLCSNET results by state and tree grade. We filtered on the same hardwood species, for a longer-term but coarser look at trends in saw-log volume by tree grade over time. Percentages of VOLCSNET by tree grade were calculated by dividing the volume in each tree grade by the total volume for that inventory. Saw-log volume by tree grade estimated from periodic inventory results provided an approximate comparison to the current results. We chose not to make formal comparisons between those estimates and the current annualized inventory results due to the major changes in plot design and field data collection. These historical data were used only as additional reference points.

Blind- and cold-check QA/QC data for tree grade were also extracted for Kentucky and Tennessee. Data were available only from 2002 to 2013, however. Blind-check data are recorded when a QA/QC forester visits the same plot and measures the same trees as the field crew but without having knowledge of the field crew's assessments. During a cold check, the QA/QC forester has the field crew's data for reference while making his or her assessment. The former is intended for data quality control while the latter is primarily used for training purposes. U.S. Forest Service personnel collected field data in both Kentucky and Tennessee during the periodic inventories. But since the implementation of annualized inventories starting in 2001, data collection has been done by state natural resource agency personnel.

2.4. Statistical methods

The response variable chosen was the proportion of VOLCSNET that is in each tree grade on each plot. Initial explorations indicated that the data approximated a normal distribution. We used a sample survey design to generate estimates and standard errors for the proportion of VOLCSNET in each tree grade and year using a ratio of means estimator. This method used the individual tree volumes instead of proportions, thus incorporating the effect of varying sample size (Zarnoch and Bechtold, 2000).

Then, zero values were generated for plots that lacked trees of some grades so that each of the five tree grades had a value on every plot. We next compared the proportion of VOLCSNET in each tree grade from year to year to see whether there were changes over time. Although FIA data are commonly used to compare estimates of forest attributes averaged over a full inventory cycle (e.g., the average value for an attribute over the 5-year-cycle ending in 2004 compared to the average for the 5-year cycle ending in 2009), we did not compare the averages of multiple years. Rather, we compared individual years (e.g., comparing 2001 to 2002 and 2002 to 2003). We were interested in differences in tree grade data from specific measurement years not only to identify any trends in the resource over time but also to see if an examination at the finer, yearly resolution would indicate issues with field data collection training.

One complication that arises when working with FIA data is the lack of independence between observations made on remeasured plots. All FIA plots are permanent and remeasured on 5- to 10-year intervals. This means, for example, that measurements taken on a plot in Kentucky in 2006 are dependent on the previous measurement made in 2001 because that state is on a 5-year remeasurement cycle. Additionally, in the early years of moving to an annualized forest inventory system (described in detail in Bechtold and Patterson, 2005), plot remeasurement did not occur on a strict 5-year basis; instead, some plots were remeasured on shorter or longer intervals.

If we were working with data that were not from remeasured plots, it would have been appropriate to use a sample survey design to generate estimates and standard errors (based on a Taylor series expansion) to compare between grades and years. For our study, however, we wished to compare estimates from both independent and dependent (remeasured) panels of data. Therefore it would not have been appropriate to treat each year's data as independent from all other years. Nor would it have been appropriate to compare estimates averaged over a cycle because again, this would violate the assumption of sample independence; we would then have to use other methods to evaluate statistical differences (Westfall et al., 2013). Instead, we tested for differences in the proportion of VOLCSNET in each tree grade with repeated measures analysis, treating forest inventory plots as a random factor and plots by years as the repeated measures factor for each tree grade and state separately. This testing was done using the PROC MIXED procedure in the Statistical Analysis System (SAS) version 9.3 (SAS Institute Inc., 2011). We used this method to correctly account for having repeated measurements on the same plots and trees at approximately 5-year intervals. The estimation method used for the covariance parameters was Restricted Maximum Likelihood method.

We selected the first-order autoregressive structure (AR(1)) as the covariance matrix after examining our assumptions, testing other covariance structures and looking to minimize the corrected Akaike's information criterion (AICc) values generated. The AR(1) covariance structure implies that the remeasurement periods are evenly spaced and the correlations between remeasured plots decrease as the amount of time between remeasurements increases (Littell et al., 2000). Banded Toeplitz covariance structures, which treat correlations between widely separated measurements as approaching zero and therefore band the covariance matrices by setting correlations between these measurements to zero (Littell et al., 2000), would also have been appropriate for this study, but AR(1) had a lower AICc value. An unstructured covariance structure had slightly lower AICc values than those produced by AR(1), but we did not feel that its underlying assumption, that there were no patterns in the covariance matrix, made biological sense and was appropriate for this dataset. We assumed homogeneous variance at each remeasurement visit; that is, the variance around the measurements of tree grade was assumed not to vary from remeasurement to remeasurement. The Kenward-Roger method was used for computing the denominator degrees of freedom for the fixed effects. Least-Squares Means estimation was used to compare proportions of VOLCSNET from year to year for each grade, with the Tukey-Kramer adjustment.

The accuracy and repeatability of tree grading by the field crew and QA/QC foresters were assessed using matrices of frequency distributions. It was assumed that the more experienced, highly trained QA/QC foresters provided a truer assessment of tree grade against which the field crew calls were judged. While variation around the relatively subjective tree grade assessment is to be expected, we focused our examination on whether field crews showed any consistent bias toward over- or under-estimating the tree grade.

3. Results

3.1. Tree grade results

The numbers of trees extracted from FIADB for a single measurement year ranged from a high of 591 trees in Tennessee in 2010 to a low of 353 trees in Kentucky in 2002. For Tennessee and Kentucky combined, the average count (standard error of the mean) was 40.9 (2.8) for grade 1, 107.8 (4.0) for grade 2, 178.7 (4.3) for grade 3, 99.7 (10.3) for grade 4 and 23.7 (1.1) for grade 5 trees. Plots from which data were extracted and their percentages of VOLCSNET by tree grade were mapped in a GIS. The distribution of VOLCSNET by tree grade appeared relatively uniformly distributed across the forest land in both states without evident clusters.

In Kentucky the proportion of VOLCSNET in tree grade 1 reached a high value in 2002, then steadily decreased through 2006; in 2004, the year-over-year difference was statistically significant from 2002 (Fig. 1, Table 1).

The proportion of VOLCSNET in tree grade 1 then remained lower than pre-2004 estimates except for a slight spike in 2011.

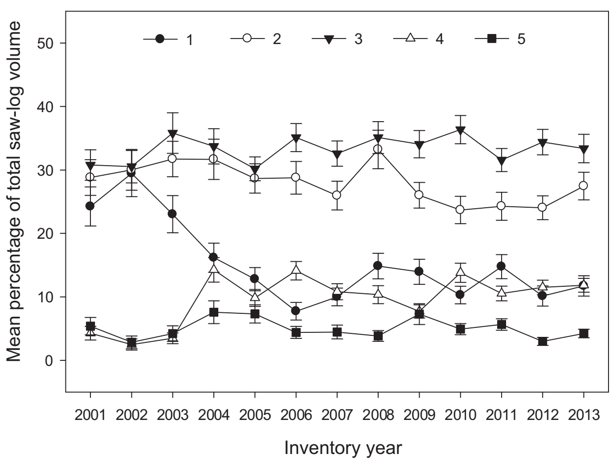

Fig. 1. Mean proportion of plot net saw-log volume (cubic feet) by tree grade with standard errors of the mean, Kentucky, 2001–2013.

In Tennessee the trend in tree grade 1 had both similarities and differences when compared to the trends observed in Kentucky (Fig. 2, Table 2). The proportion of VOLCSNET in tree grade 1 decreased annually from 2003 through 2006, when the year-over-year difference was significant. The percentage in grade 1 gradually increased from the 2006 estimates through 2013 but did not exceed the 2005 estimate until 2009. The grade 1 percentage reached the pre-2005 levels in 2013. For tree grade 2, the percentages in Kentucky held relatively stable with some statistically non-significant indications of a slight downward trend across the study period. In Tennessee, percentages in tree grade 2 showed greater annual fluctuations and a significant drop after 2005 to levels that lasted through 2009. There was a non-significant increase in the estimated percentage in tree grade 2 in 2010, then another drop in 2011.

There were no indications of trends in the proportion of VOLCSNET in tree grade 3 in Kentucky. In Tennessee, however, the percentage in tree grade 3 fluctuated, and values from 2011 through 2013 were significantly lower than many of those observed earlier in the study period (Table 3). In both states, tree grade 4 percentages had large fluctuations over time. In Kentucky they increased from 2003 to 2004 and then remained somewhat stable for the rest of the study period, while in Tennessee there were substantial, significant increases and decreases. Neither state showed any clear trends in the proportion VOLCSNET in tree grade 5, which remained stable in both states throughout the study period.

We examined longer-term trends in tree grade by looking at data for the same subset of commercially valuable hardwood species from the earlier periodic forest inventories (Table 4). Specific year and grade values from periodic inventories or annualized inventory moving averages will not match exactly those presented in Figs. 1 and 2. Figs. 1 and 2 are averages calculated from individual plots, while Figs. 3 and 4 were derived by taking already compiled statewide VOLCSNET estimates by each tree grade and calculating the corresponding percentages. Also, moving averages represent trends from the 5 years prior to the nominal inventory year so there will be a tendency for these to lag behind trends seen when looking at individual years of data. (See Bechtold and Patterson, 2005 for details on annualized inventory moving average calculations.) Kentucky data shown in Table 4 are from the periodic forest inventory of 1988 and annualized inventories of 2004, 2009 and 2012. For Tennessee, Table 4 presents the proportion of VOLCSNET in each tree grade for the periodic inventories of 1989 and 1999, then annualized inventory moving averages for 2004, 2009 and 2013.

There are notable fluctuations in the percentage of VOLCSNET in tree grade 1 in Kentucky and tree grades 1, 2 and 4 in Tennessee.

Table 1
Pairwise comparisons of the percentage change in total net volume in the saw-log portion of sawtimber trees, in cubic feet, on timberland, by inventory year and hardwood tree grades 1 and 4, Kentucky, 2001 to 2013. Adjusted (Tukey-Kramer) p-values ≤0.05 are highlighted.

	Grade 1												
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
2001	–	5.20	−1.24	−8.09	−11.48	−16.54	−14.28	−9.41	−10.32	−13.98	−9.50	−14.13	−12.54
2002	−1.78	–	−6.43	−13.28	−16.68	−21.74	−19.47	−14.61	−15.52	−19.18	−14.70	−19.33	−17.74
2003	0.80	−0.98	–	−20.74	−21.19	−21.64	−21.63	−21.02	−21.05	−21.64	−21.14	−21.44	−21.42
2004	−9.98	−11.76	−10.78	–	−3.39	−8.45	−6.19	−1.33	−2.24	−5.90	−1.41	−6.04	−4.45
2005	−5.55	−7.33	−6.35	4.43	–	−5.06	−2.80	2.06	1.16	−2.51	1.98	−2.65	−1.06
2006	−9.84	−11.63	−10.65	0.13	−4.30	–	2.26	7.13	6.22	2.55	7.04	2.41	4.00
2007	−6.54	−8.32	−7.34	3.44	−0.99	3.31	–	4.86	3.95	0.29	4.78	0.15	1.74
2008	−6.07	−7.85	−6.87	3.91	−0.53	3.77	0.47	–	−0.91	−4.57	−0.09	−4.72	−3.13
2009	−3.43	−5.21	−4.23	6.55	2.11	6.41	3.11	2.64	–	−3.66	0.82	−3.81	−2.22
2010	−9.52	−11.31	−10.33	0.46	−3.98	0.32	−2.99	−3.45	−6.09	–	4.48	−0.14	1.44
2011	−6.26	−8.04	−7.06	3.72	−0.71	3.59	0.28	−0.18	−2.82	3.27	–	−4.63	−3.04
2012	−7.22	−9.00	−8.02	2.76	−1.67	2.63	−0.68	−1.15	−3.79	2.30	−0.96	–	1.59
2013	−7.54	−9.33	−8.35	2.43	−2.00	2.30	−1.01	−1.47	−4.11	1.98	−1.29	−0.33	–
	Grade 4												

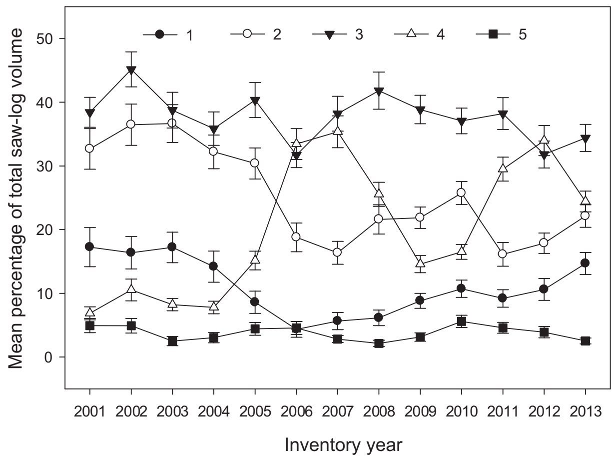

Fig. 2. Mean proportion of plot net saw-log volume (cubic feet) by tree grade with standard errors of the mean, Tennessee, 2001–2013.

Tree grade 1 in Kentucky was 13.4% of the VOLCSNET in 1988 and 24.2% in 2004 (moving average of annualized data from 2001 to 2004). Tree grade 1 also showed volatility in Tennessee as it increased from 8.6% in the 1989 periodic inventory to 22.7% in the 1999 periodic inventory, then dropped below the 1999 levels in the following annualized inventory moving averages. In Kentucky in 1988, tree grade 2 was 30.4% of the saw-log volume and tree grade 3 was 37.3%, estimates that are comparable to those found in the respective annualized moving averages in 2004. Tennessee tree grade 2 peaked in 2004, then returned to periodic inventory levels in 2009 and 2013. Tree grade 4 in Kentucky was 11.4% and tree grade 5 was 7.4% in 1988; the respective percentages decreased to 5.6% and 5.4% in 2004. Tree grade 4 in Tennessee displayed a sharp decrease from 1989 to 1999, low estimates through 2004, and then an increase in 2009 that continued in 2013.

3.2. QA/QC results

On the field plots that were revisited by QA/QC foresters to conduct checks on field crew measurements, 428 trees were graded by both QA/QC and field personnel in Kentucky from 2001 to 2013 (Table 5). In some cases, there was not agreement on whether a tree should be graded; hence the sometimes-lower values in column 3 of the table. Of those trees that were graded by both QA/QC foresters and field crew in Kentucky, on average across all years there was a 66% agreement on the tree's grade. In Tennessee 209 trees were graded at both visits with 65% agreement on grade. Notable in the QA/QC data were the small number of trees that were checked in some years, such as 2008 in both states, and the year-to-year variability in the numbers of trees checked by either group. Extremes ranged from only 7 trees in Tennessee in 2002 and 2012 to 104 trees in Kentucky in 2005.

Frequency distributions of tree grade agreement and disagreement were also calculated and examined. For example, in 2002

Table 2
Pairwise comparisons of the percentage change in total net volume in the saw-log portion of sawtimber trees, in cubic feet, on timberland, by inventory year and hardwood tree grades 1 and 2, Tennessee, 2001 to 2013. Adjusted (Tukey-Kramer) p-values ≤0.05 are highlighted.

	Grade 1												
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
2001	–	−0.88	−0.04	−3.06	−8.65	−12.90	−11.60	−11.10	−8.43	−6.54	−8.05	−6.64	−2.58
2002	3.79	–	0.84	−2.19	−7.78	−12.02	−10.73	−10.22	−7.55	−5.66	−7.17	−5.77	−1.70
2003	3.98	0.19	–	−7.83	−12.05	−15.30	−14.23	−13.47	−10.69	−9.16	−10.70	−9.98	−5.93
2004	−0.47	−4.26	−4.45	–	−5.59	−9.83	−8.54	−8.04	−5.36	−3.47	−4.99	−3.58	0.49
2005	−2.30	−6.09	−6.28	−1.83	–	−4.25	−2.95	−2.45	0.23	2.12	0.60	2.01	6.08
2006	−13.90	−17.69	−17.88	−13.43	−11.60	–	1.30	1.80	4.47	6.36	4.85	6.26	10.32
2007	−16.33	−20.12	−20.32	−15.87	−14.03	−2.43	–	0.50	3.18	5.07	3.55	4.96	9.03
2008	−11.07	−14.86	−15.06	−10.61	−8.77	2.83	5.26	–	2.67	4.56	3.05	4.46	8.52
2009	−10.82	−14.61	−14.80	−10.35	−8.52	3.08	5.52	0.26	–	1.89	0.38	1.78	5.85
2010	−6.94	−10.72	−10.92	−6.47	−4.63	6.96	9.40	4.14	3.88	–	−1.51	−0.11	3.96
2011	−16.58	−20.37	−20.56	−16.11	−14.28	−2.68	−0.25	−5.51	−5.76	−9.65	–	1.41	5.47
2012	−14.83	−18.62	−18.81	−14.36	−12.53	−0.93	1.50	−3.75	−4.01	−7.89	1.75	–	4.07
2013	−10.55	−14.34	−14.53	−10.08	−8.25	3.35	5.78	0.53	0.27	−3.61	6.03	4.28	–
	Grade 2												

Table 3
Pairwise comparisons of the percentage change in total net volume in the saw-log portion of sawtimber trees, in cubic feet, on timberland, by inventory year and hardwood tree grades 3 and 4, Tennessee, 2001 to 2013. Adjusted (Tukey-Kramer) p-values ≤ 0.05 are highlighted.

	Grade 3												
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
2001	–	6.74	0.33	−2.57	1.92	−6.72	−0.22	3.39	0.44	−1.35	−0.20	−6.62	−4.02
2002	3.68	–	−6.41	−9.31	−4.82	−13.46	−6.96	−3.35	−6.30	−8.09	−6.94	−13.36	−10.76
2003	1.37	−2.31	–	−2.90	1.59	−7.05	−0.55	3.06	0.10	−1.68	−0.53	−6.96	−4.36
2004	0.93	−2.75	−0.44	–	4.49	−4.15	2.35	5.96	3.01	1.22	2.37	−4.05	−1.45
2005	8.30	4.62	6.93	7.37	–	−8.64	−2.14	1.47	−1.49	−3.27	−2.12	−8.55	−5.95
2006	26.61	22.93	25.24	25.68	18.31	–	6.50	10.11	7.16	5.37	6.52	0.10	2.70
2007	28.53	24.85	27.16	27.60	20.23	1.92	–	3.61	0.66	−1.13	0.02	−6.40	−3.80
2008	18.71	15.03	17.34	17.78	10.41	−7.90	−9.82	–	−2.95	−4.74	−3.59	−10.01	−7.41
2009	7.73	4.05	6.36	6.80	−0.57	−18.88	−20.80	−10.98	–	−1.79	−0.64	−7.06	−4.46
2010	9.67	5.99	8.30	8.74	1.37	−16.94	−18.86	−9.04	1.94	–	1.15	−5.27	−2.67
2011	22.66	18.98	21.29	21.73	14.37	−3.95	−5.87	3.95	14.93	12.99	–	−6.42	−3.82
2012	27.14	23.47	25.77	26.21	18.85	0.54	−1.38	8.43	19.42	17.48	4.48	–	2.60
2013	17.58	13.90	16.21	16.65	9.28	−9.03	−10.95	−1.13	9.85	7.91	−5.08	−9.56	–
	Grade 4												

Table 4
Percentage of net volume of saw-log portion of sawtimber trees, in cubic feet, on timberland, by hardwood tree grade for Kentucky and Tennessee for periodic inventories (KY 1988, TN 1989, TN 1999) and annualized moving averages (KY and TN 2004, 2009, 2012).

Grade	Inventory year- Kentucky				Inventory year- Tennessee				
	1988	2004	2009	2012	1989	1999	2004	2009	2012
1	13.4	24.2	13.0	13.8	8.6	22.7	16.2	6.9	9.5
2	30.4	31.5	31.2	29.3	20.6	29.7	33.5	23.3	21.7
3	37.3	33.2	37.9	39.0	46.6	35.6	38.2	40.2	39.0
4	11.4	5.6	11.5	12.2	18.9	7.2	8.0	25.6	25.2
5	7.4	5.4	6.4	5.7	5.4	4.7	4.1	4.0	4.6

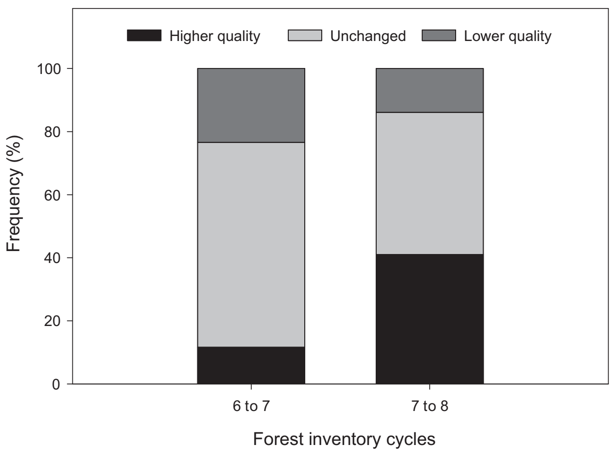

Fig. 3. Frequency of trees having lower, higher or unchanged grades upon remeasurement in Kentucky from the sixth (2000–2004) to the seventh (2005–2009) and the seventh to the eighth (2010–2013) forest inventory cycles.

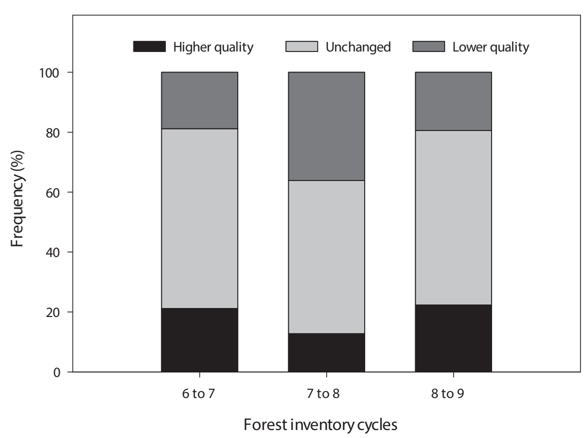

Fig. 4. Frequency of trees having lower, higher or unchanged grades upon remeasurement in Tennessee from the sixth (1999) to the seventh (2000–2004), seventh to the eighth (2005–2009), and eight to the ninth (2010–2013) forest inventory cycles.

in Kentucky, how often did field crews call a tree grade 1 while QA/QC foresters assigned it a grade 2? All possible combinations of field crew and QA/QC tree grade calls were put in matrices by state and year. A visual examination of these sparse data suggests a slight trend toward field crews calling tree grades higher than QA/QC foresters when they were in disagreement. But overall, this possible trend was weak and based on too few instances to judge adequately.

To better understand the frequency with which tree grade changes over time in this dataset, we took those trees that were remeasured at least once and calculated the percentage having lower, higher or unchanged grades upon remeasurement. For Kentucky, data were available from the sixth (2000–2004), seventh (2005–2009) and eighth (2010–2013) forest inventory cycles. For Tennessee there were four possible remeasurement periods: the sixth (1999, a periodic inventory close-out done in one year), seventh (2000–2004), eighth (2005–2009) and ninth (2010–2013) forest inventory cycles. For the three cycles of data from Kentucky, tree grade remained unchanged for 65.0% of the trees from cycles 6–7, and for 45.1% of the trees from cycles 7–8 (Fig. 3). The percentage of trees that changed to a tree grade of higher quality from cycle 7–8 (41.0%) is notable. In Tennessee, 60.0% of trees remained in the same grade from cycles 6–7, 51.1% from cycles 7–8, and 58.2% from cycles 8–9 (Fig. 4). The percentage of trees changing to a lower quality tree grade in Tennessee was 18.8%, 36.1% and 19.4% for those same periods. Trees changing to a tree grade of higher quality ranged from a high of 22.4% to a low of 12.8% across the two states.

4. Discussion

"Forest degradation" can have many meanings. Any characteristic or property of the forest that can be reduced in quality—its ability to function, resist and recover from disturbance, and deliver ecosystem services—can be used as an index of degradation. A decrease in canopy cover leading to poorer watershed protection, the loss of stored carbon to the atmosphere and impairment of future sequestration ability, a reduction in the number of species and possible loss of forest ecosystem resilience are just a few examples of forest degradation with loss of ecosystem services as a consequence. A reduction in the higher-quality harvestable hardwood products in the states of Kentucky and Tennessee would also be a form of forest degradation with serious economic implications.

Unfortunately, even though there were indications of trends over the study period, most notably a decrease in the percentage of saw-log volume in tree grade 1 in Kentucky and a decrease in the percentage of tree grade 2 in Tennessee, and a possible, if erratic, increase in the percentage of tree grade 4 in both states, the quality and repeatability of the tree grade data themselves have been called into question. Sudden increases and decreases in the percentages of saw-log volume found in different tree grades over only a few years do not make biological sense.

Zarnoch and Turner (2005) questioned the validity of the 2001 tree grade data from Kentucky based on values observed in the preceding periodic forest inventories. They cited volumes of tree grade 1 hardwood saw-logs that were twice as great in 2001 as they were in the last periodic inventory of 1988 (Zarnoch and Turner, 2005). They postulated that there had been changes in the training of Kentucky field crews on tree grading that resulted in their assigning too many trees to tree grade 1 when compared to past inventories. There was further speculation that the bias toward grading trees as grade 1 had continued until as late as 2005 (Turner, personal communication). We were able to see this

Table 5
Numbers of trees graded on plots visited by both field crew and Quality Assurance/Quality Control foresters, with numbers and percentage of tree grade agreements for Kentucky and Tennessee, 2002 to 2013.

Measurement year	Kentucky				Tennessee			
	Total trees graded by either field or QA/QC	Total trees with both field and QA/QC grades	Number with matching grades	Percentage of trees with matching grades	Total trees graded by either field or QA/QC	Total trees with both field and QA/QC grades	Number with matching grades	Percentage of trees with matching grades
2002	9	8	7	87.5	7	7	4	57.1
2003	36	33	23	69.7	9	8	4	50.0
2004	39	38	26	68.4	11	9	5	55.6
2005	104	98	61	62.2	68	61	35	57.4
2006	34	33	18	54.5	28	25	20	80.0
2007	19	19	8	42.1	13	11	4	36.4
2008	15	15	12	80.0	0	0	–	–
2009	11	11	7	63.6	28	28	24	85.7
2010	54	54	33	61.1	10	10	7	70.0
2011	24	24	17	70.8	10	10	8	80.0
2012	25	25	17	68.0	7	7	4	57.1
2013	70	70	45	64.3	33	33	27	81.8
Total	440	428	274	64.0	224	209	142	67.9

unexplained increase in tree grade 1 as a percentage of VOLCSNET since the 1988 periodic inventory and its gradual return to pre-2005 levels. However, there has been no documentation or studies to indicate the possibility of a similar bias in the Tennessee data, where a decrease in tree grade 1 vol was also observed. Those field crews operated and were trained independently of the Kentucky field crews.

Although we can postulate management or biological reasons for steady decreases or increases in certain grades of volume over time, it is harder to do so for the seemingly abrupt spikes and valleys such as those seen in tree grade 4 in Tennessee from 2005 to 2011. There we must consider that the observed trends might be due to training inconsistencies or field crew turnover. Our exploration of the QA/QC data did not provide satisfactory answers to these questions. This was primarily due to the paucity of QA/QC data for specific grades for a given year despite ample numbers of graded trees in the FIADB. Perhaps with a larger QA/QC sample, patterns would have emerged that could have indicated training-induced biases during specific inventory years. These biases could be corrected with interim field crew re-trainings and recalibrations. While the quantification of tree grade on FIA plots has potential value, the subjectivity and inconsistency of the variable limits its usefulness in Tennessee and Kentucky.

Even with the uncertainties observed in the FIA data, the lack of stable or increasing amounts of higher-graded hardwood timber in commercially valuable species when overall sawtimber volumes are gradually increasing should be cause for concern. We expect that carefully implemented forest management and silvicultural interventions would result in a gradual improvement in the quality of the hardwood resource over time within the limits of initial conditions (Leak and Sendak, 2002; Miller et al., 2001, 2008), or at least that the proportions of saw-log volume in each grade would remain relatively constant. The FIA tree grade data fail to provide a definitive answer but do raise serious questions about the resource.

Additional indirect evidence of a change in the resource might be seen in the trends in forest products. The forest products industry has perceived and has been adapting to these conditions for some time. Wood from tree grades 3, 4 and 5 can be used to produce lower-grade hardwood products such as pallets, flooring, frame stock for upholstered furniture and railroad ties (Cumbo et al., 2003; Luppold and Bumgardner, 2003). The forest products industry has been responding by making greater use of lower quality logs to produce more low-grade lumber and using new production technologies that allow the use of lower-grade material for products that would normally require higher-grade lumber (Alderman et al., 2005; Cumbo et al., 2003). These adaptations could be in response to the abundance of lower grade timber, the lack of higher grade timber across the landscape, or a combination thereof.

Changes in overall timber availability due to socioeconomic conditions, evolving landowner management goals, reduction in average tract size, and proximity to urban areas—factors that all might affect the probability of harvest—could be the cause for some of the concerns voiced about the lack of higher quality trees. Even the suggestion that the resource has been degraded over time calls for in-depth study of factors that might impede the retention and development of trees that would receive better grades—larger trees with clearer stems and fewer defects. Factors to explore include trends in land use, ownership and harvesting, as well as biological causes such as forest pests, diseases and disturbances like wildfire and extreme weather events. For example, modeling to estimate tree grade on hardwoods in the Southern Appalachian Mountains using FIA data found that a dummy variable indicating a tree's presence in non-industrial private forests was negatively correlated with the probability of finding better grades of trees; a result possibly explained by a history of high-grading on those lands (Prestemon, 1998). Natural successional processes might also be influencing the distribution of volume by tree grades. The increase in red maple (*Acer rubrum*) in the northeastern U.S. has led to an increase in stems that were tree grade 3 or lower (Alderman et al., 2005).

5. Conclusions

The finding that hardwood tree grade fluctuates widely over time illustrates the need for robust QA/QC procedures in national forest inventories. More frequent QA/QC data collection and analysis could provide more clarity and confidence when assessing the condition of forest resources. In this example, the FIA program's forest industry stakeholders in Kentucky and Tennessee have a growing need for accurate, reliable estimates of high-quality wood volume. While lower-graded timber has an increasingly wide array of uses, the forest products sector in those states would be negatively affected if there is ongoing forest degradation due to the relative loss of higher graded timber.

One way of making tree quality information in these states more accurate and consistent is to improve training and data collection protocols for grading trees. Steps need to be taken to improve training consistency across states and over time to combat tendencies toward data collection drift, which may cause between-state differences. We also recommend that the FIA program consider modifying the way in which tree grade is noted during field data collection, either by more in-depth, intensive, and frequent training on tree grading or by moving in the other direction, toward more simplified methods for quantifying tree stem quality for producing sawn lumber. FIA field data collection is done on a portable data recorder (PDR). As an example of simplifying tree grading, the PDR could be programmed to ask a series of questions (as in a decision tree) about tree stem characteristics, which would lead to assigning the tree the correct tree grade, rather than have field crew personnel directly enter a tree grade into the PDR. These step-by-step questions could be linked to tree class, d.b.h. and other variables for additional logic checks, thereby reducing the possibility of some of the more egregious grading errors.

This study also highlighted the need to take into account the partial lack of independence within forest inventory and monitoring datasets with repeated measurements on the same permanent plots and the trees within them. Statistical techniques exist to correctly account for this lack of independence, allowing researchers to track long-term trends over time. But further research is needed into the best covariance structures to use with remeasured panels of data such as those implemented by the FIA program.

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References

Alderman Jr., D.R., Baumgardner, M.S., Baumgras, J.E., 2005. An assessment of the red maple resource in the northeastern United States. Northern J. Appl. For. 22 (3), 181–189.

Bailey, R.G., 1983. Delineation of ecosystem regions. Environ. Manage. 7, 365–373.

Bechtold, W.A., Patterson, P.L., 2005. The enhanced forest inventory and analysis program – national sampling design and estimation procedures. Gen. Tech. Rep. SRS-80, U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC. 85 p.

Bentley, J.W., Cooper, J.A., Howell, M., 2014a. Kentucky's timber industry – timber product output and use, 2011. E-Science Update SRS-091. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, p. 4.

Bentley, J.W., Cooper, J.A., Howell, M., 2014b. Tennessee's Timber Industry - Timber Product Output and Use, 2011. E-Science Update SRS-097. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC, p. 4.

Brandeis, T.J., Hartsell, A.J., Bentley, J.W., Brandeis, C., 2012. Economic dynamics of forests and forest industries in the Southern United States. e-Gen. Tech. Rep. SRS-152, U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC. 77 p.

Cumbo, D., Smith, R., Araman, P., 2003. Low-grade hardwood lumber production, markets and issues. For. Products J. 53 (9), 17–24.

Kelly, J.F., Sims, M., 1989. Forest resources of Mississippi – 1989. Res. Bull. SO-147. U.S. Department of agriculture, forest service, southern forest experiment station, New Orleans, Louisiana, p. 69.

Leak, W.B., Sendak, P.E., 2002. Changes in species, grade, and structure over 48 years in a managed New England northern hardwood stand. Northern J. Appl. For. 19 (1), 25–27.

Littell, R.C., Pendergast, J., Ranjini, N., 2000. Modelling covariance structure in the analysis of repeated measures data. Stat. Med. 19, 1793–1819.

Luppold, W., Bumgardner, M., 2003. What is low-value and/or low-grade hardwood? For. Products J. 53 (3), 54–59.

Miles, L., Kapos, V., 2008. Reducing greenhouse gas emissions from deforestation and forest degradation. Global land use implications. Science 320, 1454–1455.

Miller, G.W., Gottschalk, K.W., Graves, A.T., Baumgras, J.E., 2001. The effect of silvicultural thinning on tree grade distributions of five hardwood species in West Virginia. in Sustaining natural resources on private lands in the central hardwood region, proceedings of the 29th annual hardwood symposium; National Hardwood Lumber Association, Memphis, TN, pp. 39–48.

Miller, G.W., Graves, A.T., Gottschalk, K.W., Baumgras, J.E., 2008. Accuracy of tree grade projections for five Appalachian hardwood species. Northern J. Appl. For. 25 (1), 45–51.

Oswalt, C.M., 2015. Forests of Kentucky, 2012. Res. Update FS-46. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 4 p.

Oswalt, C.M., Brandeis, C., Cooper, J.A., Oswalt, S.N., Randolph, K.C., 2015. Kentucky's forests, 2009. Res. Bull. SRS-201. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 92 p.

Oswalt, C.M., Conner, R.C., 2011. Southern forest inventory and analysis volume equations user's guide. Gen. Technical Rep. SRS-138, U.S. Department of Agriculture Forest Service, Southern Research Station, Asheville, NC. 22 p.

Oswalt, C.M., King, C.R., 2014. Forests of Tennessee, 2012. Res. Update FS-32. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 4 p.

Oswalt, C.M., Oswalt, S.N., Johnson, T.G., Brandeis, C., Randolph, K.C., King, C.R., 2012. Tennessee's forests, 2009. Res. Bull. RB-SRS-189. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 136 p.

Prestemon, J.P., 1998. Estimating tree grades for southern Appalachian natural forest stands. For. Sci. 44 (1), 73–86.

Rast, E.D., Sonderman, D.L., Gammon, G.L., 1973. A guide to hardwood log grading. Gen. Tech. Rep. NE-1. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 32 p.

SAS Institute Inc., 2011. SAS/STAT 9.3 User's Guide. Cary, NC. On-line resource available at https://support.sas.com/documentation/cdl/en/qcug/63964/PDF/default/qcug.pdf, accessed March 3 to Nov. 10, 2015. 2340 p.

Thompson, I.D., Guariguata, M.R., Okabe, K., Bahamondez, C., Nast, C., Heymell, V., Sabogal, C., 2013. An operational framework for defining and monitoring forest degradation. Ecol. Soc. 18 (2), 20.

U.S. Department of Agriculture Forest Service. 2014. Forest inventory and analysis national core field guide. Volume I: field data collection procedures for phase 2 plots, version 6.11. U.S. Department of Agriculture Forest Service, Forest Inventory and Analysis Program, Knoxville, TN. 305 p.

Westfall, J.A., Pugh, S.A., Coulston, J.W., 2013. Conducting tests for statistically significant differences using forest inventory data. Res. Pap. NRS-22. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 10 p.

Woudenberg, S.W., Conkling, B.L., O'Connell, B.M., LaPoint, E.B., Turner, J.A., Waddell, K.L., 2010. The Forest Inventory and Analysis database: database description and user's manual version 4.0 for Phase 2. Gen. Tech. Rep. RMRS-GTR-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 336 p.

Zarnoch, S.J., Bechtold, W.A., 2000. Estimating mapped-plot forest attributes with ratios of means. Can. J. For. Res. 30, 688–697.

Zarnoch, S.J., Turner, J.A., 2005. Adjustments to forest inventory and analysis estimates of 2001 Saw-Log Volumes for Kentucky. Res. Pap. SRS-38 Asheville. U.S. Department of Agriculture, Forest Service Southern Research Station, NC, p. 4.