Estimates of Storage, Sequestration, Harvest-Related Removals and Transport-Related Emissions of Carbon in the Pisgah State Park, 2008 to 2021

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Published: 2/28/2022
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Preferred Citation:
Forest Ecosystem Monitoring Cooperative. 2022. Estimates of Storage, Sequestration, Harvest-Related Removals and Transport-Related Emissions of Carbon in the Pisgah State Park, 2008 to 2021. https://www.doi.org/10.18125/v31lrj. South Burlington, VT.

Available online at:
https://www.doi.org/10.18125/v31lrj

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Keywords: Forest management, Carbon, Timber resources

Acknowledgements
The Forest Ecosystem Monitoring Cooperative (FEMC) would like to acknowledge the contributions of the FEMC's committees in developing this project. We would like to thank NH Department of Natural and Cultural Resources, Division of Forest and Lands staff for their support in the project, including Susan Francher, for providing project review and direction, William Guinn for the providing data and guidance, Inge Seaboyer for sharing her work and helping guide the analysis, and Jonathan Horton for his review of the final products.

We are appreciative of the long-term funding from the U.S. Department of Agriculture, Forest Service State & Private Forestry, Vermont Agency of Natural Resources, Massachusetts Department of Conservation and Recreation, and the University of Vermont.

Contents

Executive Summary

Forests in the Northeast form the foundation of many valuable ecological, cultural and economic services, such as providing habitat, creating recreational opportunities and producing timber. As efforts to meet the challenges presented by climate change in the Northeast grow, there has been a growing focus on the role of the region's forests in countering the accumulations of greenhouse gases in the atmosphere through sequestration and storage of carbon, and how the harvesting of trees intersects with that role. The Forest Ecosystem Monitoring Cooperative partnered with the New Hampshire Division of Forests and Lands to investigate the relative quantities of carbon storage, removals and emissions using a range of data sources. Specifically, this project analyzed forest inventory and timber harvest data from the Pisgah State Park (PSP) to quantify a) the current carbon storage and, if possible, sequestration rates in the Park, b) the amount of carbon removed from the Park through harvesting operations from 2008 to 2019, and c) the amount of carbon emitted in transporting timber to mills from a single timber sale harvested from 2019 to 2021.

From this analysis, several key questions were answered or explored:

- **What is the best estimate of carbon storage and sequestration for the Pisgah State Park?** Carbon storage on managed areas (45.0 ± 0.4 Mg C/acre) is similar to median carbon storage estimates for similar forest types in the larger landscape 25 miles around the Park (44.5 ± 1.8 Mg C/acre). Based on a look into the biases within each approach, utilizing cruise data may be the best available current data source for the Pisgah State Park, and acquiring inventory data for the unmanaged Criteria 1 lands within the Park would be preferable to using FIA data alone from the larger landscape.
- **Is recent harvesting removing more tree-based carbon than is being sequestered?** Average annual C removals in harvested wood products in the Park were 13.6% of total annual C sequestration by forests in the PSP. Based on the average annual C removal per acre harvested over the last 13 years and the sequestration rates of similar forests within and surrounding the Park, a 7-fold increase in removals would be needed to outstrip sequestration by growth of trees in PSP.
- **Is recent harvesting plus emissions from transport outweighing sequestration?** In evaluating the transport of all material off the site of a single sale, the carbon removed in harvested wood, and the estimated sequestration of the remainder of the Park, removals and emissions are approximately 9.2% of the sequestration over the two years of the harvest (using the final sequestration rate from Table 4). This comparison excludes a variety of important sources of both emissions and sequestration, but harvest activities as quantified here do not exceed sequestration.

While these analyses made the best use of available data, there are limitations including an inability to account for the emissions or storage loss from wood harvested but not moved off the site, emissions from the operation of logging equipment on the site, the final fate of wood products, and a lack of sufficient data to calculate Park-specific sequestration rates. Therefore, these results should be interpreted as general comparisons, and not a full carbon accounting for the Park.

Pisgah State Park provides an interesting case study in how to conceptualize the role of large tracts of publicly managed land in climate change mitigation in the Northeast, especially given the area's unique site history, ecology and cultural significance. There are several potential future steps that could be taken to further improve or refine our understanding of how Pisgah State Park and its various management activities are contributing to carbon storage, sequestration and emissions. These include comparing estimates of storage and sequestration from the Pisgah Tract of the Harvard Forest, exploring the differences and similarities in carbon storage patterns between management regimes, estimating heights during timber cruises, establishing a basic inventory for

Criteria 1 stands, establish permanent continuous forest inventory plots for the entire Park, and/or pursuing opportunities to use Pisgah State Park as a test case in various carbon mapping and assessment efforts.

Key Findings

In comparing various forest inventory data sources, there is no one inventory that is fully sufficient for estimating carbon storage and sequestration for Pisgah State Park as a whole, but useful datasets are available.

Based on data from all harvests in the Park between 2008 and 2020, an average of 54.3 acres are harvested per year and the annual rate of sequestration is seven times the average annual rate of removal of harvested wood products.

Based on the intensity of those harvests, sequestration of carbon in unharvested forests will exceed the carbon removed in wood products if less than ~400 acres per year are harvested at similar levels.

In evaluating detailed information from a single sale over two years, the combination of emissions from transporting harvested wood to mills and the carbon stored in the harvested wood was nine percent of the estimated carbon sequestered on the remainder of the Park.

Introduction

Forests play a significant ecological, economic and social role in the fabric of the northeastern US. Following large scale clearing for grazing and timber through the 1800's, much of the region's forests have regrown. Active forest management, including timber harvesting, has continued on state, federal, tribal and privately-owned lands. As efforts to meet the challenges presented by climate change in the region grow, there has been a growing focus on the role of northeastern forests in countering the accumulations of greenhouse gases in the atmosphere through sequestration and storage of carbon, and how timber harvesting intersects with that role.

The Forest Ecosystem Monitoring Cooperative provides analytical services to participating states upon request, and with the New Hampshire Division of Forests and Lands, initiated an analysis of inventory and harvest data from Pisgah State Park to quantify a) the current carbon storage and, if possible, sequestration rates on the Park, b) the amount of carbon removed from the Park through harvesting operations from 2008 to 2019, and c) the amount of carbon emitted in transporting timber to mills from a single timber sale harvested from 2019 to 2021. This report details the data sources, methodology and results of this analysis. More information about this project can be found online at https://www.uvm.edu/femc/data/archive/project/pisgah-carbon-storage-sequestration-emissions-removals-estimates.

Methodology

This project utilized several sources of data for four specific analyses on Pisgah State Park, summarized in Table 1. Together, these analyses investigate related but distinct portions overall carbon picture on the Park, including the storage and sequestration in standing trees as well as the removals and transport emissions related to harvesting.

Table 1.Summary of analyses performed for this project

Description of Analysis	**Data source(s)**
Carbon storage and sequestration in the landscape encompassing the Park	USDA Forest Inventory and Analysis (FIA 2021)
Carbon storage of managed areas estimated from Pisgah State Park cruise data	New Hampshire Division of Forests and Lands cruise data (NHDFL 2021a)
Estimated carbon removed through harvesting	New Hampshire Division of Forests and Lands harvest reports (NHDFL 2021c)
Estimated emissions from transport of harvested material from 2019-2021 sale	New Hampshire Division of Forests and Lands scale slip data (NHDFL 2021b)

Study Site

Pisgah State Park (PSP) is a 13,361-acre public forest located across the towns of Winchester, Chesterfield and Hinsdale in New Hampshire (Figure 1). The Park was established in 1968 through the purchase of land from several large landowners that had extensively harvested timber on the property, leaving a network of roads and several remnant patches of old growth forest (NHDRED 2011). The forests within the Park boundaries are heterogeneous and contain several forest types: eastern white pine, eastern hemlock, northern red oak, mixed upland hardwoods, sugar maple/beech/yellow birch forest and red maple/upland habitat. The forested areas of the Park are divided into three criteria types: Criteria 1 – undisturbed/unmanaged lands (4,723 acres), Criteria 2 - uneven age management lands (3,677 acres) and Criteria 3 - even aged management (4,961 acres).

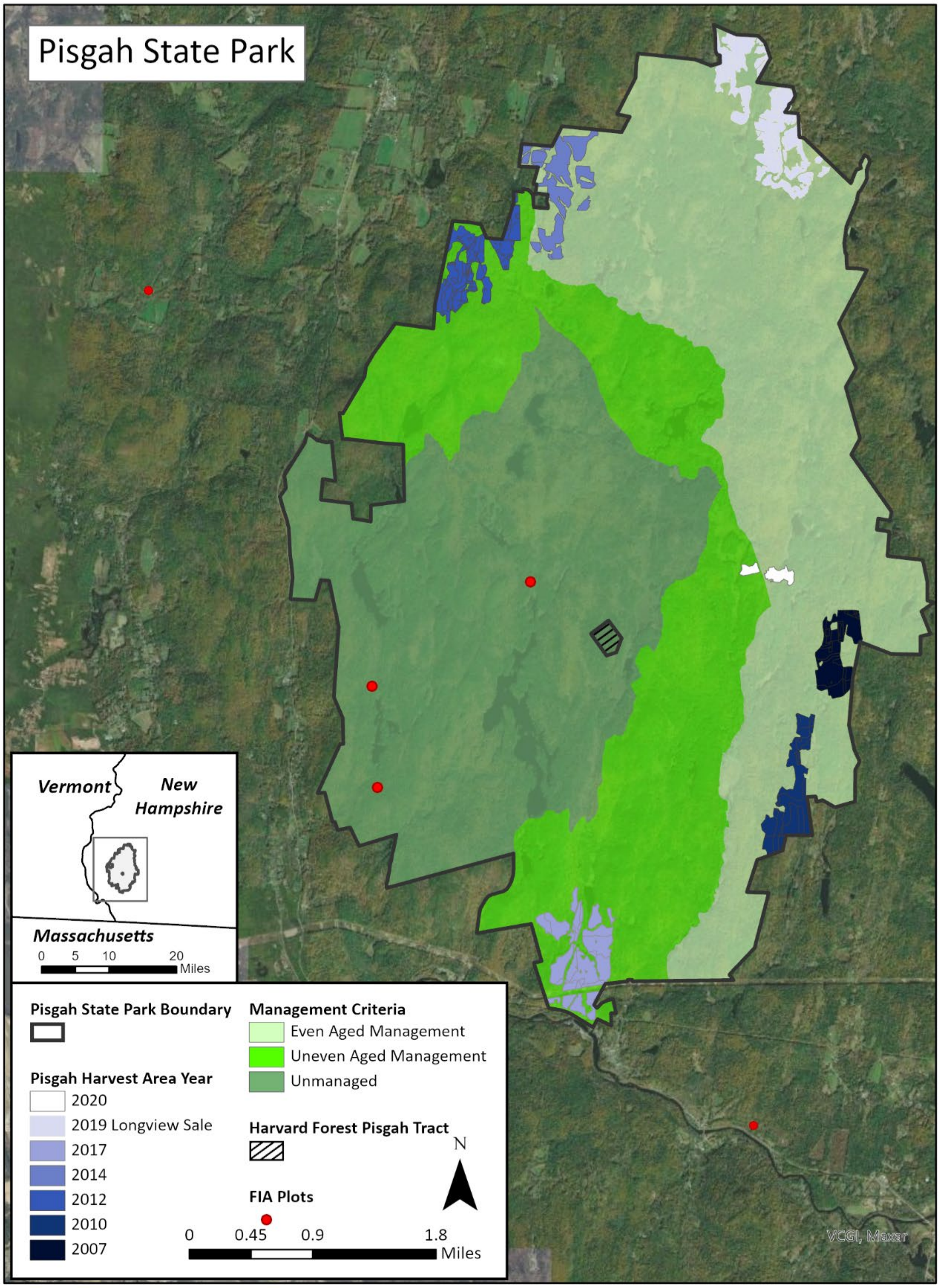

Figure 1. Map of the Pisgah State Park, including management designations and recent areas of timber harvest.

CARBON STORAGE AND SEQUESTRATION ESTIMATES

The forests of Pisgah State Park are unlike surrounding areas because of vastly different management and land use history. Due to the small size of and variability in forest inventory dataset overlapping the PSP, we had to utilize three datasets to estimate carbon storage at two scales – the larger landscape encompassing the Park, and the managed areas (Criteria 2 and 3). Carbon sequestration could only be estimated for the larger landscape encompassing the Park. In addition, we used intensive inventory from the Harvard Forest Pisgah Tract to estimate carbon storage on that particular area to compare to the landscape-level and managed-area level estimates.

Calculating carbon storage and sequestration in the landscape encompassing the Park

USDA Forest Inventory and Analysis (FIA) provides the best forest inventory dataset for assessing the Pisgah State Park as a whole. However, as only three FIA plots fall in the Park boundary (Figure 1), we used the most recent census data from all FIA plots within 25 miles of the center of the PSP (FIA 2021, Figure 2). FIA's EVALidator tool was used to estimate the aboveground carbon storage for all live trees > 1 inch diameter at breast height on forestland based on data from these plots. The queries used to generate these estimates can be found in Appendix 3.

However, these plots encompass a range of forest types, management histories and current land uses that are not entirely representative of the PSP, and we expect that this estimate is lower than that of the PSP. To provide a more refined estimate of carbon storage, we assembled a subset from these plots that had forest types similar to those of the PSP (see above) with the goal of increasing the likelihood of true statistical representation of the PSP forests. Nine plots were selected through this process, with plot IDs 2070, 2075, 2081, 2542, 2547, 2552, 2619, 2624 and 2630. We generated carbon storage and sequestration estimates using the Forest Vegetation Simulator (FVS) with the New England Variant (FVS Staff, 2008) 10-year no harvest scenario, which does not consider the growth factors of those forests that have silvicultural treatment or harvesting.

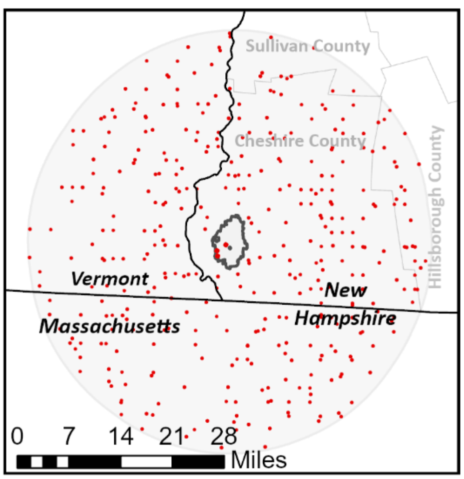

Figure 2. Approximate location of FIA plots within 25 miles of the Park center.

Because of PSP's unique management history and large proportion of unmanaged forest land, these estimates should be considered as a rough approximation for carbon stored in aboveground living trees > 1 inch diameter.

Carbon storage in managed areas of the Park

In addition to the FIA-derived estimates above, which rely on relatively few measurements, we analyzed data collected by NHDFL on timber cruises within demarcated Criteria 2 and 3 stands of the PSP designated for active management (NHDFL 2021a). NHDFL collected large basal area factor cruise data with an 80factor prism and recorded diameter at breast height (1.47m, DBH), species, number of sawlogs and a product rating for each tally tree within the variable-radius plot. There are 10 compartments comprised of 162 stands with 3,999 points where data was collected. Without height measurements, we could not use more recent carbon estimation equations such as the component ratio method (Woodall et al. 2011), so we used equations developed by

Jenkins et al. (2003) combined with species-specific coefficients β_0 and β_1 provided by FIA (Burrill et al. 2018) to compute megagrams of carbon per acre from diameter and species for each tree using the following equation:

$$\text{Carbon} = \exp(\beta_0 + \beta_1 * \ln(\text{DBH}*2.54)) * 2.2046$$

These tree-level estimates were then scaled to the stand, compartment and managed areas based on the number of survey points to produce total estimates at each scale.

ESTIMATED CARBON REMOVED THROUGH HARVESTING

New Hampshire DFL has collected data on removals through harvesting on the PSP from 2008 to 2020, capturing the date, location of sale, species or species group of harvested material, and the harvested volume in either thousands of board feet (MBF) or tons (NHDFL 2021c). In addition, spatial data delineating the sale areas was provided, and this data included the harvestable areas that were not entered during the harvest, allowing us to calculate a per-acre removal value. Note that the year of sale refers to the fiscal year it was sold, not the year(s) it was harvested, and for ease of presentation, we use the year of sale for reporting data over time.

Carbon content of all harvested material reported in MBF was estimated using conversion factors developed by Birdsey (1996) for estimating the carbon content from volume for northeastern forest types. Carbon content of harvested hardwood and softwood material reported in tons was estimated using the ratio of carbon to mass (Birdsey 1992). To utilize these conversion ratios, species were grouped into the forest types in which they generally occur, and the corresponding conversion factor used (Table 2). For the general “hardwood” category, the average of the maple-beech-birch and oak-hickory hardwood conversion factors were used, as these are the predominant hardwood forest types. For hemlock, we used the average of the maple-beech-birch softwoods, oak-hickory softwoods, and pine conversion factors, as there was no forest type available for hemlock in Birdsey (1996).

Table 2. Conversion factors to estimate carbon from harvested wood based on species and either volume or mass of the harvested product. When harvests were reported in millions of board feet, these were converted to carbon using volume conversion factors. When harvests were reported in tons, these were converted to carbon using mass-to-carbon conversion factors.

Wood species as recorded in data	Forest type	Volume to carbon conversion factor	Carbon as percent of total mass [e]
Paper Birch Red Maple White Ash Sugar Maple Black & Yellow Birch Black Cherry B&W Oak Black birch Beech Yellow Birch Y&B Birch	Maple-Beech-Birch	12.48 [a]	0.498
Hardwood Aspen Other Hardwood	Hardwood	12.32 [b]	0.498
Red Oak Black Oak	Oak-Hickory	12.16 [a]	0.498
White Pine Red Pine	Pine	16.87 [a]	0.521
Hemlock	Softwood	18.43 [c]	0.521
Mixedwood	Mixedwood	15.37 [d]	0.510

[a] Birdsey 1996.
[b] Average of maple-beech-birch and oak-hickory hardwood component conversion factors for hardwoods.
[c] Average of the conversion factors for maple-beech-birch softwoods, oak-hickory softwoods, and pine forest types.
[d] Average of hardwood and softwood averages
[e] Birdsey 1992.

Estimated Emissions from Transport of Harvested Material from Sale in 2020-2021

NHDFL provided detailed scale slip data for a single timber sale, including the origin and destination for each load of material removed from the site (NHDFL 2021b). The sale was harvested between 2019 and 2021, and the area of harvest totaled 138 ac. With this data, we estimated the carbon removed in harvested material using the same methods as above, as well as the carbon emissions resulting from transportation of the harvested material to processing facilities.

The primary methodology employed in calculating the relative carbon cost of transportation from mileage followed the standards put forward by the US Environmental Protection Agency (EPA). Each trip's emissions were estimated based on individual scale slip data. The primary calculation is an adaptation of carbon dioxide emissions from trucking (EPA 2003, see also Mathers et al. 2015) to the chemical carbon component weight:

$$Transportation\ C\ (grams) = Distance\ (Miles) \times Weight\ (Short\ Tons) \times Emissions\ Factor \times \frac{Molecular\ weight\ C}{Molecular\ weight\ CO2}$$

Distance was derived using Google's Distance Matrix API[1], using estimated location coordinates from loading, and unloading locations. Location coordinates were estimated using information provided about the mill (the mill code) and publicly available information on the business location. Where possible satellite imagery was used to identify the coordinates of the likely mill yard. When this wasn't available, the geographic center of the town in which the mill operates was used.

Harvested material weights were provided for all transported products from 09/16/19 to 04/08/21. Using species level average weight (Miles 2009) and standard conversion methodology (NHDRA 2011) short tons were estimated for each haul recorded in MBF. This conversion was not necessary for pulp transportations, as they are already in short ton units.

The emissions factor is derived from EPA SmartWay: Shipper Partner Tool's technical documentation (EPA 2013), and is the same methodology employed by the Environmental Defense Fund as described in their Green Freight Handbook (Mathers et al. 2015). We utilized an emissions factor of 161.8, which is the average emissions factor for truck models, as the models of trucks used in hauling were not specified in the scale data.

For example, for a logging truck that travels from the 2019 Pisgah Harvesting area to Durgin & Crowel Lumber Co. Inc in Springfield NH (~54.95 miles) hauling 29.5 short tons of white pine. With the emissions factor or 161.8, there is a transportation carbon cost of roughly 262,684 grams or 0.26 Mg of CO_2 associated with that haul. Converting CO_2 to C using the ratio between their molecular weights (~0.2727), this yields 0.07 Mg C.

[1] https://developers.google.com/maps/documentation/distance-matrix/overview

Results

The results of the analysis at various scales and from various data sources are summarized in the table below (Table 3).

Table 3. Summary of results for carbon sequestration, storage and removals using various data sources and methods.

Geographic scope of assessment	Method of Assessment	Result
Carbon storage based on the larger landscape	FIA EVALidator estimation of all plots within 25 miles of PSP center	35.66 ± 1.91 Mg C/acre 476,417 ± 9,029 Mg C total
Carbon storage based on like forests in the larger landscape	Median of FVS analysis of nine FIA plots within 25 miles of PSP center with similar forest types to PSP	44.5 ± 1.8 Mg C/acre 535,776 ± 33,403 Mg C total
Carbon storage in managed areas of Pisgah State Park	Biomass estimation and subsequent conversion to carbon using species and diameter data from stand cruises	45.0 ± 0.4 Mg C/acre 388,710 ± 3,455 Mg C total
Carbon sequestration on the larger landscape	FVS analysis of nine FIA plots within 25 miles of PSP center with similar forest types to PSP	0.76 ± 0.03 Mg C/acre/year 9,695 ± 383 Mg C/year
Carbon removed from Pisgah State Park by harvesting	Estimation of carbon removed in reported wood products for sales from 2008 to 2020	1,273 Mg C/year 17,163 Mg C total
Estimated carbon removals and carbon emissions from transport of harvested materials	Total lifecycle analysis of emissions from a single sale to the point of processing	25.68 Mg C in emissions 2,323 Mg C in removals

CARBON STORAGE AND SEQUESTRATION ESTIMATES

Carbon storage and sequestration in the landscape surrounding the Park

Using FIA's EVALidator tool for all plots within 25 miles of the PSP center, carbon storage was calculated to be 35.66 ± 1.91 Mg C per acre. This translates into an estimate of 378,116 Mg C stored in the entire PSP. Utilizing the subset of nine similar forest type plots within 25 miles of the PSP center yielded a mean estimate of 40.1 ± 2.5 Mg of carbon per acre for PSP, with total carbon stored in above ground live trees estimated to be roughly 535,776 Mg C for the entire site. However, due to the skewed nature of these already conservative estimates, the median storage per acre may be more appropriate, and was estimated to be roughly 44.5 ± 1.8 Mg C per acre. The inter quartile estimate ranges between 38.9 and 51.1 Mg C per acre.

Examining sequestration, the average predicted annual growth from FVS carbon estimate modeling of these plots is 0.76 ± 0.03 Mg C per acre per year. These growth estimates are likely not representative of the areas having been harvested within the last 10 years, which have a higher growth rate and, consequently, sequestration rates. For this reason, we applied this estimated sequestration rate to the portion of the Park that was not part of a sale in the last 10 years (623 acres). This area encompasses roughly 12,738 acres, and an estimated carbon sequestration total of 9,681 ± 382 Mg C per year. We cannot provide carbon sequestration estimates for the roughly 623 acres of land that has been harvested in the last 10 years, due to modeling constraints.

We can apply this yearly rate of sequestration to the areas that have not been harvested in the last 10 years on a yearly basis using information about when timber sales and the amount soled for harvest. This analysis shows that yearly sequestration across the park drops from 10,154 ± 401 Mg C to 9,681 ± 382 Mg C (Table 4). However, this does not capture the sequestration occurring on harvested sites post-harvest, which can be much higher than older stands.

Table 4. Estimated total carbon sequestration per year based on the year of sale for harvested areas. The carbon sequestration rate estimated from the larger landscape is only applicable to those areas harvested more than 10 years ago, excluding areas that have been harvested over the past 10 years thus affects total yearly sequestration.

Year	Area Park not harvested 2010 -2020 (acres)	Yearly total sequestration excluding recent harvest areas (Mg C)
2010	13,361	10,154 ± 401
2011	13,270	10,085 ± 398
2012	13,270	10,085 ± 398
2013	13,149	9,994 ± 394
2014	13,149	9,994 ± 394
2015	13,037	9,908 ± 391
2016	13,037	9,908 ± 391
2017	13,037	9,908 ± 391
2018	12,894	9,800 ± 387
2019	12,756	9,695 ± 383
2020	12,738	9,681 ± 382

Carbon storage in managed areas of the Park

Based on the timber cruise data provided, carbon storage in trees in the managed areas (Criteria 2 and 3) of the Park is estimated to be 45.0 ± 0.4 Mg C per acre. Scaling up to the corresponding landscape, we estimate there are 388,710 Mg C stored in the 8,638 acres of managed area on the PSP. As heights were not available and carbon content was estimated from diameter, these figures are likely overestimating the carbon storage slightly, but are in line with estimates found from more precise estimation methods above. A breakdown of carbon storage by compartment is available in Appendix 1.

ESTIMATED CARBON REMOVED THROUGH HARVESTING

Utilizing data from 2008 to 2020, an estimated total of 17,163 Mg C was removed through timber harvests during this period. This equates to 3.2% of the carbon stored in the entire Park and 4.4% of the carbon stored in the Criteria 2 and 3 portions of the Park. Of the 765.6 acres of sales, 59.3 acres were marked as leave areas, yielding 706.3 acres of harvested area. This corresponds to an average yearly removal of 1,320 Mg C per year from harvesting, and an average of 24.3 Mg C removed per acre harvested during that time-period. These are likely conservative estimates because they do not include material or by-products left on the site. Combining the annual harvest removal rate with the sequestration rates estimated above for the Park as a whole, the Park is sequestering 7.3 times more carbon per year than is being removed through harvesting. A detailed breakdown of carbon removals by sale is provided in Appendix 2.

ESTIMATED EMISSIONS FROM TRANSPORT OF HARVESTED MATERIAL FROM SALE IN 2020-2021

The relative carbon emissions of transportation associated to harvesting in PSP over the two years of harvest is estimated to be 25.68 Mg C (Table 5). A total of approximately 20,745 miles were traveled by vehicles with loads, averaging 84.3 miles per trip, with a median of 52.83 miles per trip, with most trips occurring relatively close to the harvest site (Figure 4). Each year's relative carbon emissions varies widely depending on the distance traveled, the load weight, and the number of loads. The carbon stored in the material removed from the site totaled 2,323 Mg C, equivalent to 16.8 Mg C per acre of harvest. Combined, this sale removed and emitted a total of 2,349 Mg C, with emissions representing 1.09% of that total.

Table 5. Summary of transportation carbon cost statistics by year for a single timer sale on the Pisgah State Park

Year	Total Distance (miles)	Mean Distance (miles)	Median Distance (miles)	# of loads	Total C Emitted (Mg)
2020	6,801	69.39	21.29	98	9.24
2021	13,944	94.22	110.65	148	16.44
Combined	**20,745**	**84.33**	**52.83**	**246**	**25.68**

Based on the acreage of the sale and the harvested volume, we estimate 0.18 Mg C is emmitted per acre harvested, and for this particular sale, 11.05 kg C (0.001105 Mg C) were emitted for every Mg C of harvested material removed from the site. It should be noted that these estimates are very specific to the geographic location, type of material being harvested, and the proximity of mills to this particular sale, and thus cannot and should not be extrapolated to harvests in other areas of the PSP. However, it is possible to compare the removals and emissions against the estimated sequestration rate of the rest of the Park, based on estimates from prior sections, to see that 8.2 times more carbon is sequestered in this time range than is emitted or removed during this harvest (Figure 4).

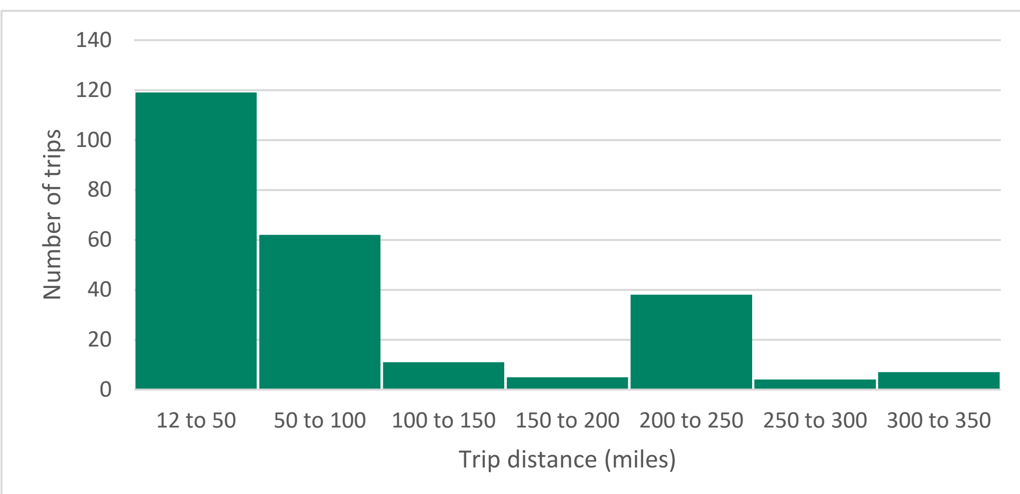

Figure 3. Histogram of trip distances. The large majority of trips were between 12 and 620 miles from the harvest site.

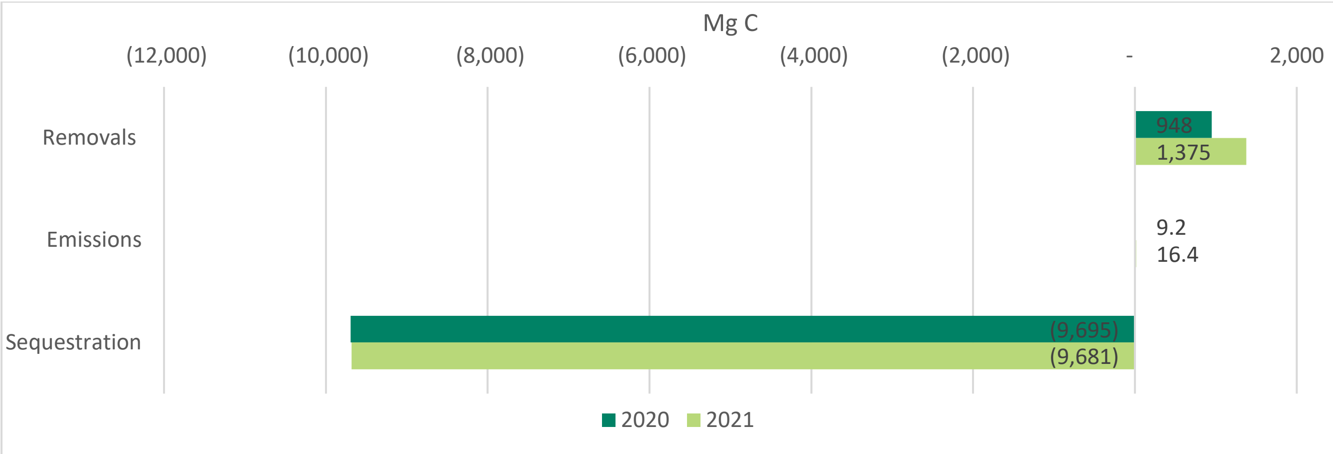

Figure 4. Comparison of carbon removed from harvesting, emissions of carbon from transportation of harvested material, and sequestration by the remaining areas of the Park not harvested in the last 10 years.

Outcomes and Findings

Based on the data and analyses presented here, we can consider several questions posed by FEMC partners about carbon on the Pisgah State Park. However, while these analyses made the best use of available data, there are limitations including an inability to account for the emissions or storage loss from material harvested but not moved off the site, emissions from the operation of logging equipment on the site, the final fate of wood products, and a lack of sufficient data to calculate Park-specific sequestration rates. Therefore, these results should be interpreted as general comparisons, and not a full carbon accounting for the Park, and specific limitations are noted below.

What is the best estimate of carbon storage and sequestration for the Pisgah State Park? Carbon storage on managed areas (45.0 ± 0.4 Mg C/acre) is similar to median carbon storage estimates for similar forest types in the larger landscape 25 miles around the PSP (44.5 ± 1.8 Mg C/acre), especially when taking into account that the allometric equations used to estimate carbon in managed areas from only diameter and species likely overestimate carbon storage. Both estimates exceed the storage in the larger landscape when including all forest types (35.66 ± 1.91 Mg C/acre).

Based on our comparison of various data sources, there is not one inventory that is sufficient for estimating carbon storage and sequestration for PSP as a whole. The carbon storage estimates for managed stands estimated from timber cruise data have very low standard error, and thus may be more precise, but the lack of height data means we must rely on coarser modeling of carbon by species (Jenkins et al. 2003). The carbon storage estimates for all FIA plots in forests in the vicinity of similar type to those on the PSP produces a similar estimate to managed stands and are likely more accurate, but the low number of samples yields a high standard error, and thus low precision. In addition, the PSP has a somewhat unique management history compared to surrounding areas, and thus the plots outside the PSP are not necessarily the best representation of what is happening within the PSP. Including all FIA points in the vicinity, we estimate a lower total carbon storage, but this is almost certainly due to the fact that the forests in the surrounding area include much greater ranges in stand age, species composition, current land use and land use history. This approach does serve as a good comparator for the region, in showing how PSP is a relatively large carbon sink that holds above average carbon storage when compared to the forests of the larger area.

Based on all this, utilizing cruise data may be the best available current data source for the Pisgah State Park, and acquiring inventory data for the unmanaged Criteria 1 lands within the PSP would be preferable to using FIA data from the larger landscape as it would yield more precise and supportable estimates.

Is recent harvesting removing more tree-based carbon than is being sequestered? Average annual C removals from harvesting within PSP were 13.6% of total annual C sequestration by forests in the PSP. Based on the average annual C removal per acre harvested over the last 13 years (24.3 Mg C/acre/year) and the general sequestration rates of similar forests within and surrounding the Park (9,681 ± 382 Mg C/year), sequestration of unharvested forests will exceed the C removed by harvesting if less than 398 acres per year are harvested at intensity levels similar to the past. When compared to the actual realized average harvest rate of 54.3 acres per year from 2008 to 2020, a significant increase in harvesting would be needed for removals to outstrip sequestration by growth of trees in PSP. This comparison doesn't take into account subsequent per-acre sequestration rates for stands regenerating after harvest, the release of carbon by equipment used during harvest, post-harvest soil carbon emissions, or the fate of harvested material left on site.

Is recent harvesting plus emissions from transport outweighing sequestration? In evaluating the transport of all material off the site of a single sale, the carbon removed from the site in harvested material, and the estimated sequestration of the remainder of the Pisgah State Park, removals and emissions are approximately 9.2% of the sequestration over the two years of the harvest (using the final sequestration rate from Table 4). This comparison excludes a variety of important sources of both emissions (decomposition of material left on site, soils, processing at the mill, subsequent transport of products) and sequestration (regenerating vegetation). Acknowledging these limitations, harvesting as quantified here, while certainly non-trivial, is not close to exceeding sequestration.

Future Considerations

Pisgah State Park's unique site history, ecology and cultural significance make it a useful lens for examining the role of sustainable forestry in the global effort to tackle climate change issues. Based on the information reported here, the Park provides an interesting case study in how to evaluate the role of large tracts of publicly managed land in climate change mitigation in the Northeast. The area's There are several potential future steps that could be taken to further improve or refine our understanding of how the Pisgah State Park and its various management activities are contributing to carbon storage, sequestration and emissions. These potential future directions are given in rough order of the level of effort and resources required.

Compare estimates of storage and sequestration from the Pisgah Tract of the Harvard Forest. The Harvard Forest's inholding on the Pisgah State Park in an area severely affected by a hurricane could provide some useful comparison to the Criteria 1 lands, but with limited utility due to its unique site history.

Further explore the differences and similarities in carbon storage patterns between management regimes. The cruise data for Criteria 2 (uneven-aged management) and Criteria 3 (even-aged management) and the harvest removals from the last 13 years provide an opportunity to consider the effects these two management strategies have on carbon storage. If this were coupled with at least an initial inventory of the Criteria 1 stands (see below), the Pisgah State Park could be used as a model or case study of three different strategies used in a single ownership with potentially useful lessons for the larger landscape and forestry profession.

Estimate heights during timber cruises. The estimates of carbon storage in managed areas provides a precise estimate, but the lack of height data forces a reliance on less accurate biomass estimation equations. Adding height could allow a more accurate estimation using the component ratio method (Woodall et al. 2011).

Establish and maintain a basic inventory for Criteria 1 stands. There are not enough sample points in the USDA Forest Service's Forest Inventory and Analysis program to represent the current carbon storage or the carbon dynamics over time on the Criteria 1 (unmanaged) lands in the Park. Truly understanding the carbon profile of the Park is not possible without such an inventory.

Establish permanent continuous forest inventory plots for the entire Park. The timber cruise data in the Criteria 2 (uneven-aged management) and Criteria 3 (even-aged management) provide a reasonable snapshot of carbon storage in the managed areas of the Park, but the lack of permanent plots with remeasurements prevents an estimate of sequestration specific to the Park, forcing us to rely on data from the larger region as a best approximation. In addition, such a permanent plot network with remeasurements would enable assessment of sequestration in the Criteria 1 stands as well.

Pursue opportunities to use Pisgah State Park as a test case in various carbon mapping and assessment efforts. There are a range of ongoing efforts to quantify and monitor the role forests in the Northeast play in climate change mitigation strategies. The data and information collected here could leverage some of these efforts by providing easier access to key information needed to validate or enrich existing models.

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Appendix 1. Carbon storage summaries for managed areas

Data from on timber cruises within demarcated stands of the PSP designated for active management (Criteria 2 and Criteria 3) was providing by New Hampshire Division of Forest and Lands. Large basal area factor cruise data were collected with an 80-factor prism and recorded diameter at breast height (1.47m, DBH), species, number of sawlogs and a product rating for each tally tree within the variable-radius plot. There are 10 compartments comprised of 162 stands with 3,999 points where data was collected. From this, we estimated carbon at various scales, including the compartment scale (Table 6).

Table 6. Summary of biomass and carbon for compartments with Criteria 2 (uneven-aged) and Criteria 3 (even-aged) management areas on the Pisgah State Park.

Criteria	Compartment	# of stems	# of points	Total biomass (kg)	Total carbon (kg)	Biomass by area (kg/ac)	Carbon by area (kg/ac)
2	3	1341	870	1,159,290	579,645	77,353	38,676
2	5	377	164	387,599	193,800	110,205	55,102
2	12	387	190	298,784	149,392	87,433	43,716
2	13	545	263	536,109	268,055	93,904	46,952
3	1	1141	543	877,049	438,524	98,537	49,269
3	2	1204	417	1,262,380	631,190	134,671	67,336
3	6	400	211	600,108	300,054	87,273	43,636
3	10	726	454	722,245	361,123	77,054	38,527
3	14	1241	755	1,339,391	669,696	82,632	41,316
3	15	457	285	559,567	279,783	75,813	37,907

Appendix 2. Carbon removals by sale

Data on removals through harvesting were collected on the PSP from 2008 to 2020, capturing the date, location of sale, species or species group of harvested material, and the harvested volume in either thousands of board feet (MBF) or tons (NH DFL 2021). This data was used to compute the carbon content of harvested material removed from the sale for each sale (Table 7), and can be compared to sale acreage to estimate per acre removal rates (Table 8).

Table 7. Carbon content of material removed from the site from sales between 2008 and 2020.

Project Number	Fiscal Year of Sale	Carbon Removal from sawlogs (Mg)	Carbon Removal from tonnage (Mg)	Total Carbon (Mg)
1.495	2008	232	1,486	1,718
1.547	2011	339	3,003	3,343
1.574	2013	113	1,370	1,482
1.597*	2015	192	1,128	1,320
1.5971*	2016	463	3,246	3,709
1.625	2018	886	1,771	2,657
1.637	2019	898	1,425	2,323
1.653	2020	173	437	610
TOTAL	**All**	**3,296**	**13,867**	**17,163**
			Annualized removal rate	**1,320.23 Mg C/yr**
			SE of Annualized removal rate	**350 Mg C/yr**
			# of acres harvested from sale polygon area minus leave area	**706.3 ac**
			Average removal per acre cut	**24.30 Mg C**

Table 8. Sale area and carbon removed per acre from harvesting for each sale and across all sales

Project Number	Fiscal Year of Sale	Area Cut (ac)	Carbon removal by area harvested (Mg C/ac)
1.495	2008	83.3	20.64
1.547	2011	90.6	36.88
1.574	2013	121.0	12.26
1.597*	2015	112.5	44.72
1.625	2018	142.8	18.61
1.637	2019	138.2	16.81
1.653	2020	18.0	33.87
Across all sales		706.3	24.30
*** Note that 1.597 has two reported harvest amounts, but one sale boundary, because the first buyer defaulted and it was resold, so there are not separate sale acreages for those two project numbers. Thus, they are combined here.**			

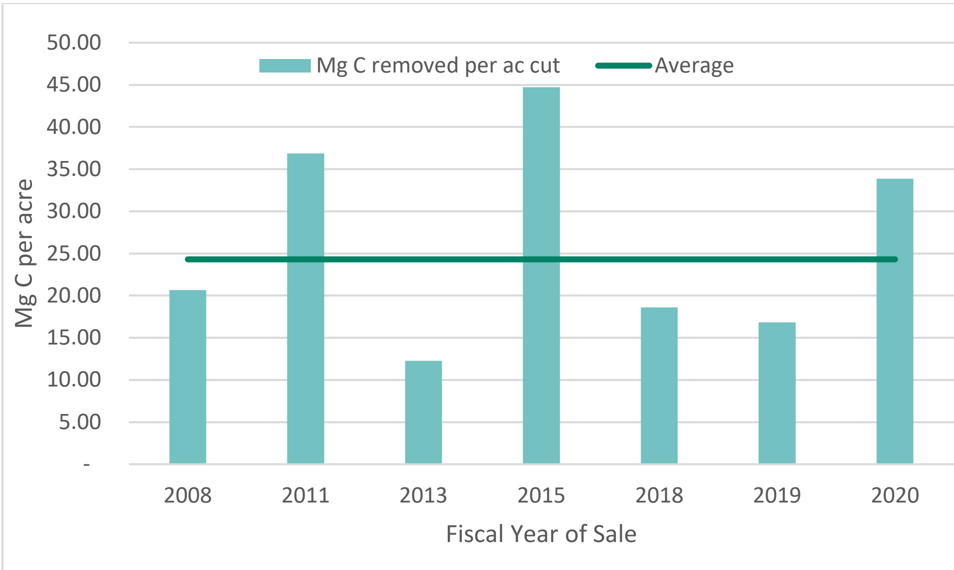

Figure 5. Carbon removal rates per acre for sales between 2008 and 2020 on the Pisgah State Park, as well as the average removal rate across all sales.

Appendix 3. FIA EVALidator queries

The USDA Forest Inventory and Analysis EVALidator service was used to generate carbon storage estimates for the area 25 miles surrounding the Pisgah State Park's geographic center (42.839793 -72.436584)

The REST endpoint to access this query is:

> https://apps.fs.usda.gov/Evalidator/rest/Evalidator/fullreport?reptype=Circle&lat=42.839793&lon=-72.436584&radius=25&snum=Aboveground carbon in live trees (at least 1 inch d.b.h./d.r.c), in short tons, on forest land&sdenom=Area of forest land, in acres&wc=252019,332019,502019&pselected=None&rselected=All live stocking&cselected=All live stocking&ptime=Current&rtime=Current&ctime=Current&wf=&wnum=&wnumdenom=&FIAorRPA=FIADEF&outputFormat=HTML&estOnly=N&schemaName=FS_FIADB.

The SQL version of this same query is:

> *SELECT pagestr, rowstr, colstr, sum(case den when 0 then 0 else num / den end) ratio,sum(num),sum(den) From (SELECT pagestr, rowstr, colstr, sum(ESTIMATED_VALUE) num, sum(Denom) den From (select coalesce(pagestr,'`0000 Total') pagestr, coalesce(rowstr,'`0000 Total') rowstr, coalesce(colstr,'`0000 Total') colstr, sum(estimated_value) estimated_value,sum(denom) denom from (SELECT case 1 when 1 then '`0001 None`' end as pagestr, case coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then '`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked' when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end as rowstr, case coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then '`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked' when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end as colstr, SUM((TREE.TPA_UNADJ * CASE WHEN TREE.DIA IS NULL THEN POP_STRATUM.ADJ_FACTOR_SUBP ELSE CASE LEAST(TREE.DIA, 5 - 0.001) WHEN TREE.DIA THEN POP_STRATUM.ADJ_FACTOR_MICR ELSE CASE LEAST(TREE.DIA, COALESCE(PLOT.MACRO_BREAKPOINT_DIA, 9999) - 0.001) WHEN TREE.DIA THEN POP_STRATUM.ADJ_FACTOR_SUBP ELSE POP_STRATUM.ADJ_FACTOR_MACR END END END * COALESCE(TREE.DRYBIO_AG / 2 / 2000, 0))*POP_STRATUM.EXPNS) AS ESTIMATED_VALUE, 0 as denom FROM FS_FIADB.POP_STRATUM POP_STRATUM JOIN FS_FIADB.POP_PLOT_STRATUM_ASSGN ON (POP_PLOT_STRATUM_ASSGN.STRATUM_CN = POP_STRATUM.CN) JOIN FS_FIADB.PLOT ON (POP_PLOT_STRATUM_ASSGN.PLT_CN = PLOT.CN) JOIN FS_FIADB.PLOTGEOM ON (PLOT.CN = PLOTGEOM.CN) JOIN FS_FIADB.COND ON (COND.PLT_CN = PLOT.CN) JOIN FS_FIADB.TREE ON (TREE.PLT_CN = COND.PLT_CN AND TREE.CONDID = COND.CONDID) WHERE TREE.STATUSCD = 1 AND COND.COND_STATUS_CD = 1 AND ((pop_stratum.rscd=24 and pop_stratum.evalid=251901) or (pop_stratum.rscd=24 and pop_stratum.evalid=331901) or (pop_stratum.rscd=24 and pop_stratum.evalid=501901)) and plot.cn in (select p.cn from FS_FIADB.plot p, FS_FIADB.pop_plot_stratum_assgn q where p.cn=q.plt_cn and q.rscd=pop_stratum.rscd and q.evalid=pop_stratum.evalid and ((pop_stratum.rscd=24 and pop_stratum.evalid=251901) or (pop_stratum.rscd=24 and pop_stratum.evalid=331901) or (pop_stratum.rscd=24 and pop_stratum.evalid=501901)) and*

*p.lat>42.461005121212125 and p.lat<43.218580878787876 and p.lon<-71.2461078095238
and p.lon>-73.62706019047619 and SDO_GEOM.SDO_DISTANCE(SDO_GEOMETRY(2001,
8265,SDO_POINT_TYPE(-
72.436584,42.839793,NULL),NULL,NULL),SDO_GEOMETRY(2001,8265,SDO_POINT_TYPE(p.lo
n,p.lat,NULL),NULL,NULL),0.0001,'unit=mile') <=25) GROUP BY case 1 when 1 then '`0001
None`' end,case coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then
'`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked'
when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end ,case
coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then '`0002 Fully stocked'
when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked' when 5 then '`0005
Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end) tmpxxx group by
cube(pagestr,rowstr,colstr) Union select coalesce(pagestr,'`0000 Total') pagestr,
coalesce(rowstr,'`0000 Total') rowstr, coalesce(colstr,'`0000 Total') colstr,
sum(estimated_value) estimated_value,sum(denom) denom from (SELECT case 1 when 1
then '`0001 None`' end as pagestr, case coalesce(cond.alstkcd,-1) when 1 then '`0001
Overstocked' when 2 then '`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4
then '`0004 Poorly stocked' when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable'
else '`0007 Other' end as rowstr, case coalesce(cond.alstkcd,-1) when 1 then '`0001
Overstocked' when 2 then '`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4
then '`0004 Poorly stocked' when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable'
else '`0007 Other' end as colstr, SUM(0) AS ESTIMATED_VALUE,
SUM(POP_STRATUM.EXPNS*COND.CONDPROP_UNADJ * CASE COND.PROP_BASIS WHEN
'MACR' THEN POP_STRATUM.ADJ_FACTOR_MACR ELSE POP_STRATUM.ADJ_FACTOR_SUBP
END) AS DENOM FROM FS_FIADB.POP_STRATUM POP_STRATUM JOIN
FS_FIADB.POP_PLOT_STRATUM_ASSGN ON (POP_PLOT_STRATUM_ASSGN.STRATUM_CN =
POP_STRATUM.CN) JOIN FS_FIADB.PLOT ON (POP_PLOT_STRATUM_ASSGN.PLT_CN =
PLOT.CN) JOIN FS_FIADB.PLOTGEOM ON (PLOT.CN = PLOTGEOM.CN) JOIN FS_FIADB.COND
ON (COND.PLT_CN = PLOT.CN) WHERE COND.COND_STATUS_CD = 1 AND
COND.CONDPROP_UNADJ IS NOT NULL AND ((pop_stratum.rscd=24 and
pop_stratum.evalid=251901) or (pop_stratum.rscd=24 and pop_stratum.evalid=331901) or
(pop_stratum.rscd=24 and pop_stratum.evalid=501901)) and plot.cn in (select p.cn from
FS_FIADB.plot p, FS_FIADB.pop_plot_stratum_assgn q where p.cn=q.plt_cn and
q.rscd=pop_stratum.rscd and q.evalid=pop_stratum.evalid and ((pop_stratum.rscd=24 and
pop_stratum.evalid=251901) or (pop_stratum.rscd=24 and pop_stratum.evalid=331901) or
(pop_stratum.rscd=24 and pop_stratum.evalid=501901)) and p.lat>42.461005121212125
and p.lat<43.218580878787876 and p.lon<-71.2461078095238 and p.lon>-
73.62706019047619 and SDO_GEOM.SDO_DISTANCE(SDO_GEOMETRY(2001,
8265,SDO_POINT_TYPE(-
72.436584,42.839793,NULL),NULL,NULL),SDO_GEOMETRY(2001,8265,SDO_POINT_TYPE(p.lo
n,p.lat,NULL),NULL,NULL),0.0001,'unit=mile') <=25) GROUP BY case 1 when 1 then '`0001
None`' end,case coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then
'`0002 Fully stocked' when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked'
when 5 then '`0005 Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end ,case
coalesce(cond.alstkcd,-1) when 1 then '`0001 Overstocked' when 2 then '`0002 Fully stocked'
when 3 then '`0003 Medium stocked' when 4 then '`0004 Poorly stocked' when 5 then '`0005*

Nonstocked' when -1 then '`0006 Unavailable' else '`0007 Other' end) tmpyyy group by cube(pagestr,rowstr,colstr)) tmptable GROUP BY pagestr, rowstr, colstr) tmp2table group by pagestr, rowstr, colstr order by pagestr, rowstr, colstr

Providing the information needed to understand, manage, and protect the region's forested ecosystems in a changing global environment