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Managing Carbon on Federal Public Lands: Opportunities and Challenges in Southwestern Colorado

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Abstract Federal lands in the United States have been identified as important areas where forests could be managed to enhance carbon storage and help mitigate climate change. However, there has been little work examining the context for decision making for carbon in a multiple-use public land environment, and how science can support decision making. This case study of the San Juan National Forest and the Bureau of Land Management Tres Rios Field Office in southwestern Colorado examines whether land managers in these offices have adequate tools, information, and management flexibility to practice effective carbon stewardship. To understand how carbon was distributed on the management landscape we added a newly developed carbon map for the SJNF–TRFO area based on Landsat TM texture information (Kelsey and Neff in Remote Sens 6:6407–6422. doi:10.3390/rs6076407, 2014). We estimate that only about 22 % of the aboveground carbon in the SJNF–TRFO is in areas designated for active management, whereas about 38 % is in areas with limited management opportunities, and 29 % is in areas where natural processes should dominate. To project the effects of forest management actions on carbon storage, staff of the SJNF are expected to use the Forest Vegetation Simulator (FVS) and extensions. While identifying FVS as the best tool generally available for this purpose, the users and developers we interviewed highlighted the limitations of applying an empirically based model over long time horizons. Future research to improve information on carbon storage should focus on locations and types of vegetation where carbon management is feasible and aligns with other management priorities.

Keywords Carbon management · Sequestration · Public lands · Decision making · Modeling · Climate change

Introduction

Management of forests and agricultural lands to increase carbon storage has been advanced as a relatively low-cost strategy to mitigate climate change (McCarl and Sands 2007; McKinley et al. 2011; Zheng et al. 2013). Roughly half of forest carbon stocks in the United States are estimated to be on federal public lands (Heath et al. 2011; Dilling et al. 2013). In 2011, to assist national forest managers in assessing the potential for future carbon management activities, the US. Forest Service (USFS) began asking its units to track "carbon assessment and stewardship" as part of its Climate Change Performance Scorecard.[1] The carbon assessment and stewardship metric asks (a) Does the unit have a baseline assessment of carbon stocks and the influence of disturbance and management

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[1] www.fs.fed.us/climatechange/advisor/scorecard.html.

activities on these stocks?, and (b) Is the unit integrating carbon stewardship with the management of other benefits being provided by the unit?

This raises the question of how public land resource managers are positioned to integrate carbon stewardship into their practices, and whether they have adequate tools and data to support their decision making in that arena. Studies on the use of climate information in applied settings have found that both the *context* of decision making and factors intrinsic to the *characteristics of the science or the process of producing science* themselves affect the usability of information (Dilling and Lemos 2011). The requirement to respond to the Performance Scorecard presents an opportunity to examine whether managers have the tools to effectively consider how carbon goals map to existing decision contexts—in other words, how decision context and the usability and applicability of scientific information and tools set the stage for managers to begin to consider carbon in their decision making.

The decision context for public land managers is strongly guided by existing policy priorities, management plans, and decision drivers and will thus represent a strong constraint on how new policy priorities like carbon management are integrated into public land management (Ellenwood et al. 2012; Dilling and Failey 2013). Carbon management goals are being overlain onto a complicated federal land management structure that must be responsive to multiple intended users (Failey and Dilling 2010; Olander et al. 2012; Dilling and Failey 2013; Dilling et al. 2013). Carbon management is therefore rarely the primary goal for land management decision making, and can be subordinate to a host of other driving factors (Ellenwood et al. 2012). The potential for large amounts of carbon to be managed on public lands is tempered by the fact that large areas such as designated wilderness may be effectively off-limits for active management, for example (Olander et al. 2012).

Several factors influence the usability of data and tools to support the management of carbon. Carbon accounting in practice is regionally and locally specific, and depends heavily on the availability of appropriate datasets and tools to establish baselines and to project changes in stocks over time (Galik et al. 2009). Many of the recommended datasets and tools have been developed and calibrated at the national scale, however, it is important to consider whether they are adequate at the scale of an individual forest. Related questions, therefore, are how much of the carbon stocks present on public lands are actually available for the active management of carbon, given multiple-use mandates, physical landscape constraints, and staffing requirements; and whether opportunities for management could be more clearly identified by considering these constraints.

In this paper we present a case study looking at how these two factors, decision context and usability of scientific tools, can be applied to carbon management decision making in the San Juan National Forest/Tres Rios Field Office (SJNF–TRFO) areas of federal public land in southwestern Colorado. First, we examine the degree to which existing carbon stocks in the SJNF–TRFO overlap with management designations that allow for interventions to increase carbon, given the constraints in a multiple-use policy environment. Second, we examine the suitability of existing tools and methods for performing carbon analyses in support of decision making in the federal public land context. To understand the specific elements of our study and the methodology involved we first present some additional background and terminology.

Estimating Carbon Stocks and Changes

Estimates of forest carbon stocks are based on ground-based observations of forest carbon that are extended to the landscape using a variety of approaches (Goetz et al. 2009). For example, some carbon maps are developed by assigning a single carbon value to a categorical landscape unit, whereas others extend ground-based carbon estimates to the landscape scale with the use of spatially continuous data generally derived from remotely sensed imagery. A primary source of ground-based forest carbon information in the US is the Forest Inventory Analysis (FIA) dataset that estimates biomass at a series of plot locations across the continental US. These data have been used to estimate and create national maps of carbon inventories on federal public lands over the US (e.g., Smith and Heath 2004). However, there are many limitations in the accuracy of carbon maps developed from these methods. First, ground-based estimates of forest carbon derived from the measurements of tree dimensions and forest density can include errors as a result of the measurement protocols used and the allometric equations used to convert tree dimensions to estimates of forest carbon (Chave et al. 2004). Second, estimates of carbon stocks produced by assigning one carbon value to each spatial unit of the landscape have limited accuracy due to the heterogeneity present within each unit (Goetz et al. 2009). Those constructed from continuous data derived from remotely sensed imagery also have limitations, including issues with sensor saturation or saturation of vegetation indices used to estimate carbon (Dubayah and Drake 2000; Huete and van Leeuwen 1997; Kasischke et al. 1997), and the mismatch in spatial scale between the size of measurement plots and the spatial resolution of remotely sensed imagery. Furthermore, the relationship between remotely sensed information and forest carbon can vary between regions (Cutler et al. 2012; Woodcock et al. 2001, Nowak and Greenfield 2010), creating challenges regarding the transferability of carbon estimation methods. All of these issues contribute to the limitations on the accuracy of forest carbon estimates at fine spatial resolution and local to regional spatial extents.

For carbon accounting, a key concern is additionality—whether or not the carbon sequestered by a project would have been stored even if the project never took place. Developing a project baseline, that is, an agreed-upon narrative of how carbon stocks would have evolved in the absence of deliberate management actions, is a necessary first step to estimate how management affects carbon stocks. In one study, creditable carbon varied by up to a factor of three depending on the baseline assumptions and carbon stocks included in the analysis (Galik et al. 2009). Estimating changes in carbon stocks in the future and the impact of various management regimes on those stocks relies on the use of models. In recent years, the USFS has been adapting the Forest Vegetation Simulator (FVS) for use in projecting carbon storage implications of management actions, including under changing climate conditions (Crookston et al. 2010). FVS is a forest growth and yield model that was developed for timber management applications (Crookston and Dixon 2005; Dixon 2002). The USFS plans to use FVS to model forest carbon dynamics in the Forest Carbon Management Framework (ForCaMF) that it is developing for use in Performance Scorecard assessments (http://www.fs.fed.us/climatechange/advisor/scorecard/carbon-assessment-stewardship.html, last accessed Jan. 6, 2015).

Roadmap for the Case Study

To examine the management context and the adequacy of nationally available datasets and tools for carbon management in the SJNF–TRFO, we first present an updated map of aboveground live carbon stocks that was created specifically for this region by adding estimates for the grass and shrublands to those published recently by Kelsey and Neff (2014) for forested portions of the SJNF. Errors in Kelsey and Neff's local-scale map for the SJNF are compared to errors found for the same area in two different national maps of forest carbon stocks. Next, we present the results of a GIS analysis to quantify how carbon stock estimates, management objectives, and biophysical characteristics of the land can be combined to provide a more specific estimate of the areas most likely to represent opportunities for carbon management. This analysis helps to identify areas and types of vegetation that warrant priority for research to better understand current stocks and effects of potential carbon management strategies. To examine the usability and appropriateness of available tools for carbon decision support, we present the results of interviews we conducted with technical specialists to better understand their perspective on the benefits and limitations of FVS for use in projecting changes in carbon storage at the forest/field office level. Finally we use carbon storage projections from FVS to illustrate the challenge local forest managers face in evaluating possible management activities when the resulting changes in carbon storage are modest in comparison to errors in the baseline.

Methods

Case Background

This paper reports the results of a case study of the SJNF–TRFO area in southwestern Colorado. The San Juan National Forest (SJNF) is a part of the US Forest Service under the Department of Agriculture, while the Tres Rios Field Office (TRFO) is a part of the Bureau of Land Management, within the US Department of the Interior. Because of the proximity of lands managed by the two agencies, the SJNF–TRFO was managed together for a period of time in a jointly administered Public Lands Office at the beginning of our study. The lands have returned to being managed separately as of 2014 but they are still tightly coordinated and share a common headquarters space. We discuss them together for much of this paper, except for some analyses as noted when we focus on the SJNF portion exclusively. The SJNF and TRFO together manage about 9600 km^2 of land within the boundaries of a 16,300 km^2 area that also includes significant private land. The SJNF–TRFO area extends from grass and shrublands to alpine tundra, with elevations ranging from 1500 m to over 4200 m. The SJNF–TRFO area has been actively engaging with the issue of carbon management for the past several years, and provides a valuable context for more deeply investigating how the issues of decision context and the use of scientific information in decision making affect the potential for usable science to support carbon management. The San Juan National Forest within the SJNF–TRFO area is one of a handful of FS units that have pursued carbon demonstration projects through the National Forest Foundation. For example, the San Juan National Forest has participated in an ongoing partnership program for carbon offsetting through the National Forest Foundation (https://www.nationalforests.org/corporate-partnerships last accessed March 27, 2016).

Overview of Approach

Our case study of tools and limitations for carbon reporting and management in the SJNF–TRFO centers on an improved map of aboveground carbon stocks developed for the SJNF by Kelsey and Neff (2014). The information in this map was supplemented with aboveground carbon estimates for the grass and shrublands to provide complete coverage of how aboveground carbon stocks vary across the SJNF–TRFO area. We used existing FIA data and new aboveground forest carbon survey data collected for this study to assess errors in the new carbon map for the SJNF specifically and in previously published maps that are widely used to assess carbon stocks. We examined the change in carbon stocks that might be achieved in forest stands within the SJNF through two illustrative management activities—thinning to improve forest health and replanting after a fire. Finally, the new carbon map was combined with GIS-based information about management aims and physical restrictions within the SJNF–TRFO domain to understand how they might limit options for active carbon management.

SJNF–TRFO Carbon Calculations

Maps of aboveground live carbon stocks for the SJNF and TRFO were derived from two different sources. Carbon estimates from the forested regions within SJNF–TRFO were taken from the carbon map produced by Kelsey and Neff (2014). Carbon estimates for the non-forested regions within SJNF–TRFO were created for the purpose of this study. These two different maps were combined into a single carbon map for the SJNF–TRFO area.

The forest carbon estimates from Kelsey and Neff (2014) were based on field-sampled aboveground carbon data from the Forest Inventory and Analysis (FIA) program. The field-sampled data were used to train a model that predicts forest carbon based on image texture information derived from Landsat TM imagery. This texture-based model was used to create a continuous map of forest carbon stocks for all forest vegetation types within SJNF including Ponderosa Pine (*Pinus ponderosa*) woodlands, Warm–Dry Mixed Conifer forests, Cool–Moist Mixed Conifer forests, and Spruce–Fir (*Picea engelmannii* and *Abies lasiocarpa*) forests (Kelsey and Neff 2014). Kelsey and Neff compared models estimated using texture metrics, physical variables (elevation, slope, aspect, and precipitation), and spectral variables (NDVI and EVI). The best performing model, which was used to prepare the map presented here, included texture metrics along with slope.

The method used to calculate carbon in non-forest landscapes used a combination of the Forest Service R2 vegetation spatial database (R2 is the USFS vegetation layer designation),[2] remotely sensed cover data derived from Landsat imagery by the Multi-Resolution Land Characteristics Consortium,[3] and biomass regression equations that were either found in the literature or derived from literature data, in order to calculate carbon in Pinyon–Juniper (various species, *Juniperus* spp.–*Pinus* spp.) landscapes, shrublands, and grasslands (Branson et al. 1976; Rickard 1985; Gallardo and Schlesinger 1992; Havstad and Schlesinger 1996; Dwire et al. 2004; Reiner 2004; Nafus et al. 2009; Bradley et al. 2006; Fernandez et al. 2013). In this process 30 m × 30 m Landsat pixels within an R2 vegetation polygon were averaged using a one-to-one join in order to come up with a single percent cover value for the R2 vegetation polygon. Regression equations predicting understory biomass as a function of percent cover were then used to estimate understory carbon storage.

Errors in Carbon Estimates

To examine accuracy in baseline estimates of carbon stocks, we conducted an error analysis of the representation of aboveground live tree forest carbon within the SJNF for two of the few publicly available biomass maps that would be used in carbon stock assessments. The first is produced by Blackard et al. (2008), referred to hereinafter as ‘Blackard 2008.’ The Blackard 2008 dataset was produced with ground-based FIA plot biomass data and a series of geospatial predictor layers including digital elevation model (DEM)-derived variables, vegetation indices from MODIS and Landsat TM, and adapted PRISM climate data that were used to predict biomass using boosted regression trees (Blackard 2008). The second map referred to herein as the Kellndorfer 2000 was produced by the Woods Hole Research Center (Kellndorfer et al. 2000). The Kellndorfer 2000 map is produced using a combination of FIA ground-based plot data, InSAR data, and information from Landsat ETM+ images. Both of these maps were developed in units of aboveground biomass (Mg ha^{-1}); we have converted aboveground biomass to carbon for the purpose of this work using a conversion factor of 50 % (Penman et al. 2003; Rebain 2010). Errors in these maps for the SJNF are compared to those in the new map developed specifically for the SJNF by Kelsey and Neff (2014). The latter map is used as the basis for the other analyses in this study.

We used two sets of field-measured data to evaluate error in the Blackard 2008 and Kellndorfer 2000: (1) ground-based FIA plot aboveground live tree carbon data surveyed between 2002 and 2009, and (2) data from independent plots surveyed for aboveground live tree carbon in 2012 for the purpose of this study. The 164 FIA ground-based plots provide the most numerous and most evenly spatially distributed set of aboveground carbon measurements within SJNF, and are therefore useful in describing spatial distribution of error in Blackard 2008 and Kellndorfer 2000. However, the FIA plots were also used in the construction of both maps, and consequently do not provide an independent measure of error. Therefore, we

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[2] http://www.fs.usda.gov/detail/sanjuan/landmanagement/gis/?cid=fsbdev3_002263.

[3] www.mrlc.gov.

also evaluate error using a set of 25 independent ground-based carbon measurements collected for the purpose of this study. Error was evaluated by comparing the aboveground carbon value predicted by the map to the measured carbon value for each inventory plot location.

Absolute and relative error was calculated for both the ground-based FIA plot data and the independent plots. The absolute error in carbon storage was calculated as the difference between predicted and observed aboveground carbon, and is reported in Mg C ha^{-1}. An analysis of variance (ANOVA) was used to test for differences in the mean absolute and relative error between vegetation types in the Blackard 2008 and Kellndorfer 2000 maps.

Errors in the carbon map produced by Kelsey and Neff were determined by withholding 30 % of the inventory plots during the model training process to serve as validation plots. The measured carbon value of each validation plot was then compared to the predicted carbon values for that location in order to derive an estimate of map error.

SJPL Management Zones Carbon Calculations

To characterize the decision context in the SJNF–TRFO, we examined how existing features of the landscape and vegetation patterns intersected with management objectives to define where active carbon management was likely to be an option. For this we superimposed GIS-based aboveground carbon estimates with boundaries of areas where certain activities are restricted by law, restrictive features of the landscape such as steepness and access to roads, and management zones that are designated in the area's forest and land management plan. GIS data defining management area categories and plan criteria are available at http://www.fs.usda.gov/detail/sanjuan/landmanagement/planning/?cid=stelprdb5432707.

Interviews and Other Supporting Information

Qualitative interviews were conducted as supplementary background to our analysis. In 2012 we conducted six semi-structured interviews of land managers and technical specialists of the SJNF–TRFO area including those who make permitting decisions and those who support decisions through technical analysis. We asked questions about the key decisions made by the individuals, the tools used to support those decisions, and whether carbon management was considered. In order to investigate the use of FVS as a tool for managing for carbon, in 2013 we also conducted informal, semi-structured, interviews of 20 FVS users and developers from both in and outside of the USFS. We asked questions on how FVS is being used within the organization, what users' experience has been like in applying FVS to estimate carbon balances on a regional level, and what the limitations and opportunities for FVS and other tools for carbon management were going to be. These individuals were identified by their authorship of papers in technical conferences focusing on the use of FVS, with additional individuals identified through snowball sampling (meaning that we asked each interviewee whether there were additional experts on the use of FVS that we should talk with). We relied on these interviews for supplementary information on the context of the use of FVS. We also reviewed documents for the region such as the Forest Management Plans, FVS user guides, and technical papers on the application of FVS.

Estimating Results of Example Management Actions

We used two hypothetical scenarios to estimate the magnitude of changes in carbon stocks from management actions that might typically be contemplated for forested ecosystems within the SJNF–TRFO area. Changes are projected for a 100-year time horizon. Both scenarios were run using FVS, which is the tool most likely to be used for such projections. Forest growth and the effects of wildfire and management were modeled using the Central Rockies variant of FVS (Dixon 2002) and the Fire and Fuels Extension (FFE; Rebain 2010). The scenarios were constructed using default growth equations, as might be done for a preliminary screening assessment. More adjustments to the model would likely be made if FVS was used to help secure credits for carbon sequestration.

Scenario 1 examined the effects of varying scenarios of forest thinning on the forest carbon stocks of 18 stands within Ponderosa Pine and Warm–Dry Mixed Conifer vegetation types in the Fossett Gulch area, which is in the southern part of the SJNF. Projected carbon stocks were evaluated under four management options: (1) all stands are thinned to a basal area of 60 ft^2 per acre (13.77 m^2 ha^{-1}) in 2015, (2) all stands are thinned to a basal area of 70 ft^2 per acre (16.07 m^2 ha^{-1}) in 2015, (3) all stands are thinned to a basal area of 80 ft^2 per acre (18.37 m^2 ha^{-1}) in 2015, and (4) a scenario of no thinning. The initial forest condition for Scenario 1 was determined using Forest Service Common Stand Exam plots obtained from SJNF staff. Effects of forest thinning were modeled using the 'thin from below' function in FVS, which will remove trees from the stand starting with the smallest diameter trees, until the stand reaches the desired basal area. Scenario 2 investigated the carbon balance of a spruce–fir forest following a wildfire in 2010 with two scenarios of post-fire regeneration—one scenario with only natural regeneration of conifers following the fire, and a second with a planting of 300 spruce trees per acre (approximately 742 per hectare) 5 years after the fire. For the wildfire scenario, we modeled the effect of fire under hazardous fire conditions including 35 mph (56 km h^{-1}) wind, 85 °F (29.4 °C) air temperature, and the 'very dry' default fuel moisture content level within FVS–FFE. FVS–FFE was used to predict mortality following this fire.

Results

Estimating Aboveground Carbon Stocks in SJNF–TRFO

Figure 1 shows aboveground carbon (Mg C ha^{-1}) on public lands in the SJNF and TRFO units. Ninety-seven percent of the carbon is on forested units, with the remainder on non-forested grass and shrublands. As discussed in more detail by Kelsey and Neff (2014), aboveground carbon in the SJNF unit generally increases with elevation. Kelsey and Neff (2014) estimate the correlation of predicted versus observed carbon values for the SJNF portion of the map which is $r = 0.86$ and the RMSE is 22.8 Mg C ha^{-1}. For comparison, the mean aboveground carbon observed in FIA plots within the SJNF is 67.4 Mg C ha^{-1}. Kelsey and Neff found that incorporation of Landsat TM-derived texture information improved the ability of their model to capture changes in aboveground forest carbon after disturbance.

Figure 2 shows observed versus predicted aboveground live tree carbon from two national maps: Blackard 2008, created with the goal of making US forest resource data accessible to land managers and researchers Blackard et al. (2008) and Kellndorfer et al. (2000), produced to establish a year-2000 baseline for the coterminous US (http://www.whrc.org/mapping/nbcd/). Although not designed for use at small spatial scales due to constraints related to their construction, these maps are some of the only maps available for regional carbon estimates.

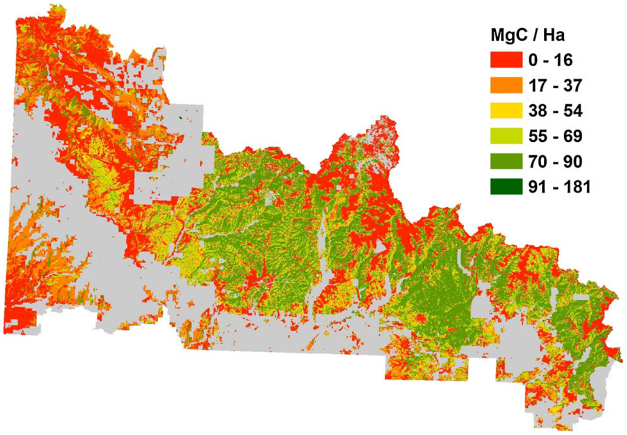


Fig. 1 Estimated aboveground carbon for the SJNF–TRFO area for 2011. Total area shown is 1.03 million ha; total aboveground carbon is 39.1 million MgC. Areas *shaded gray* are outside the jurisdiction of the USFS and BLM. The largest areal carbon values are in forested areas, primarily shown in *shades* of *green*

The national maps were relatively poor predictors of plot scale carbon within SJNF. Our comparisons of Blackard 2008 and Kellndorfer 2000 carbon estimates to the FIA ground-based data yielded relatively low correlation values of $r = 0.49$ and 0.64, respectively, despite the use of FIA data in the construction of these datasets. When we compared the national maps to the carbon data from the independent study plots, the observed versus expected carbon for Blackard 2008 and Kellndorfer 2000 yielded correlations of $r = -0.0710$ and $r = 0.3907$, respectively. The RMSE for comparison of Blackard 2008 to the FIA plots was 48.3 Mg C ha^{-1}; for Kellndorfer 2000 it was 34.8 Mg C ha^{-1}. The comparison of our independent study plots to Blackard 2008 and Kellndorfer 2000 yielded errors of RMSE = 26.8 and 35.5 Mg C ha^{-1}, respectively. As shown in Fig. 2, both maps underrepresent the carbon present in the SJNF, especially in regions with observed forest carbon stocks above 125 Mg C ha^{-1}. Figure 3 shows that the underestimation is especially pronounced for the cool–moist and warm–dry mixed conifer classes.

Decision Context: Juxtaposition of Carbon and Management Restrictions in SJNF–TRFO

Within the SJNF and TRFO, land-use and management options are constrained by a large range of competing aims, including legal mandates as well as internally developed priorities. Protected areas include wilderness areas, areas with sensitive wildlife habitat, cultural and archaeological sites, wetlands, and riparian areas. In wilderness areas and wilderness study areas, the ability of the SJPL–TRFO to change management directions or impose new priorities is very limited because of the legal nature of these designations. Intersecting with the legal designations, SJNF–TRFO has several different types of management zones that correspond to the resources present and the activities allowed upon the land that are updated with each planning cycle. In this section we use the 2013 DOI/USFS combined management zone designations (which include the legally protected areas) to understand where there is opportunity to manage carbon more deliberately (Figs. 4, 5, and 6). Management zone descriptions can vary between the two management agencies and are updated periodically, so these figures should only be understood as illustrating one particular representation of carbon management potential at a point in time.

Using 2013 Resource Management Plan management zones that adopted the FS Management Area categorizations across the SJNF–TRFO, approximately 21 % of area and 22 % of aboveground carbon are in areas with active management; 39 % of area and 38 % of aboveground

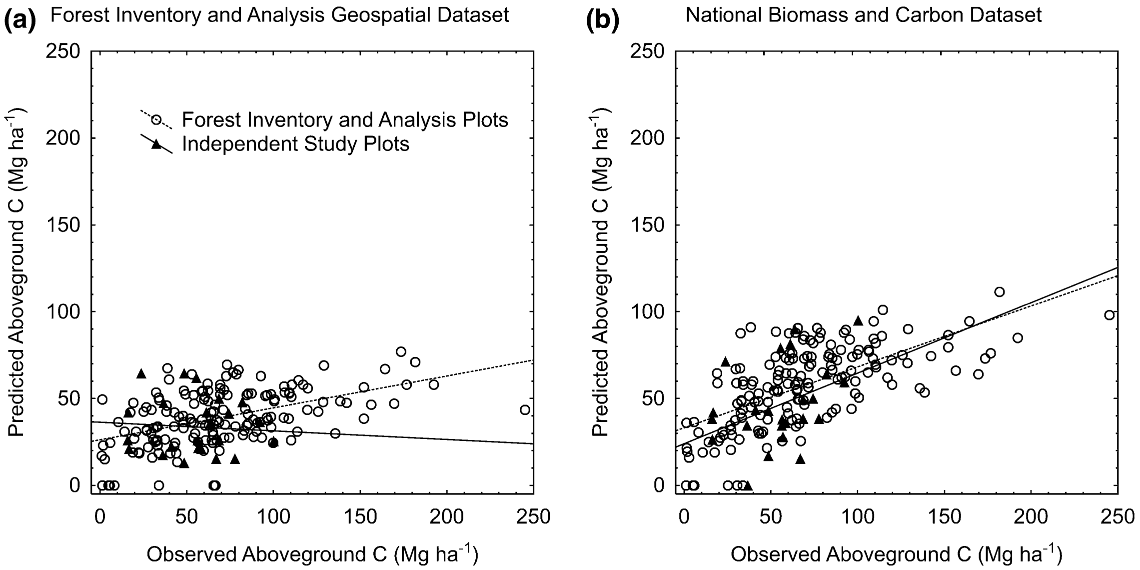
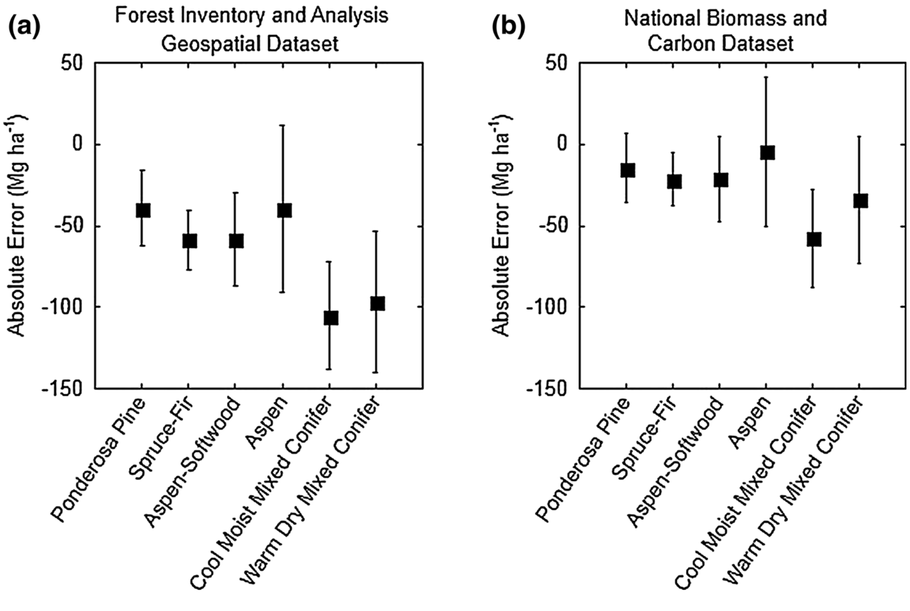


Fig. 2 **a** Observed versus predicted aboveground live tree carbon values for the Forest Inventory and Analysis Geospatial Dataset; **b** Observed versus predicted aboveground live tree carbon values for the National Biomass and Carbon Dataset

Fig. 3 Absolute error in observed versus predicted aboveground live tree carbon values by vegetation class, for **a** the Forest Inventory and Analysis Geospatial Dataset; **b** the National Biomass and Carbon Dataset. *Error bars* show the 95 % confidence intervals around the mean



carbon are in areas with natural landscapes and limited management; and 26 % of area and 29 % of aboveground carbon are in areas where natural processes dominate (Fig. 4). As defined in the plan, areas with active management are relatively easily accessible and open to a range of uses and activities, including timber production (DOI/USFS 2013, p. 188). These would be generally compatible with carbon management activities that would require equipment or access using roads. Areas that encompass natural landscapes with limited management prohibit timber production but allow mechanical fuel treatment and timber harvesting as a management tool (Ibid. p. 186)—these latter activities are also consistent with more active carbon management possibilities. The most restricted category is where natural processes dominate; these areas include designated wilderness, the Piedra Special Management Area, and wilderness study areas. Timber harvest and motorized travel are prohibited in these areas even as a management tool, and mechanized fuel treatment is restricted (p. 185). On the other hand, in these areas the agencies can still use prescribed burns and manage wildland fires for resource benefit. Grazing is allowed in all

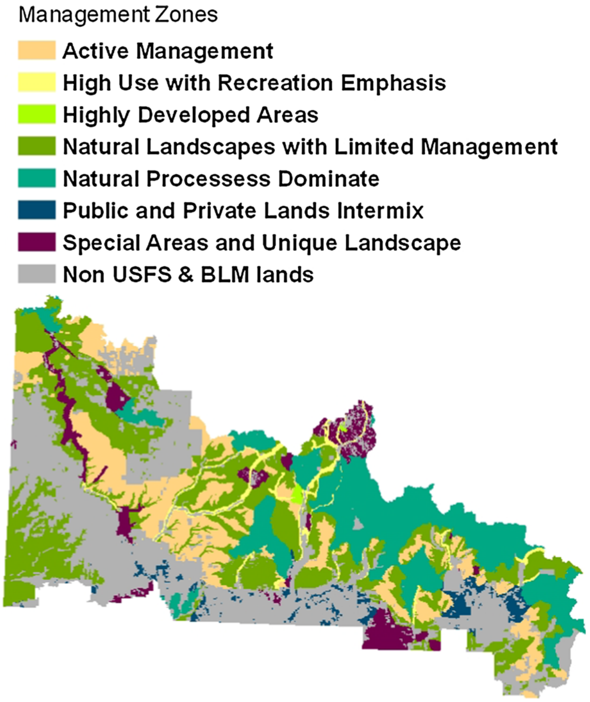


Fig. 4 Management zones for the SJNF–TRFO area, with area and aboveground carbon in each zone. Non-USFS/BLM lands not included in area or carbon totals

Zone	Area (ha)	Percent area	Carbon (MgC)	Percent Carbon
Active Management	214,432	20.8	8,678,560	22.2
High-Use with Recreation	32,209	3.1	1,422,700	3.6
Highly Developed	2,897	0.3	140,115	0.4
Natural Landscapes w/ Ltd Management	404,436	39.3	14,702,564	37.6
Natural Processes Dominate	264,552	25.7	11,136,862	28.5
Public and Private Lands Intermix	33,133	3.2	1,066,408	2.7
Special Areas and Unique Landscape	78,235	7.6	1,965,539	5.0
Total	1,029,894		39,112,748	

three of these management categories. In addition, in its inventory, the SJNF identified nearly 229,000 ha as having roadless character. Of the overall area managed by SJNF–TRFO, about 22 % of the area and 31 % of the aboveground carbon is estimated to be in roadless areas (not shown).

We can further understand the opportunities and limitations on carbon management by examining some of the major carbon-dense species and their distribution into various management designations. Overall, we estimate the spruce/fir type accounts for about one-third of the aboveground carbon in the SJNF–TRFO, followed by aspen

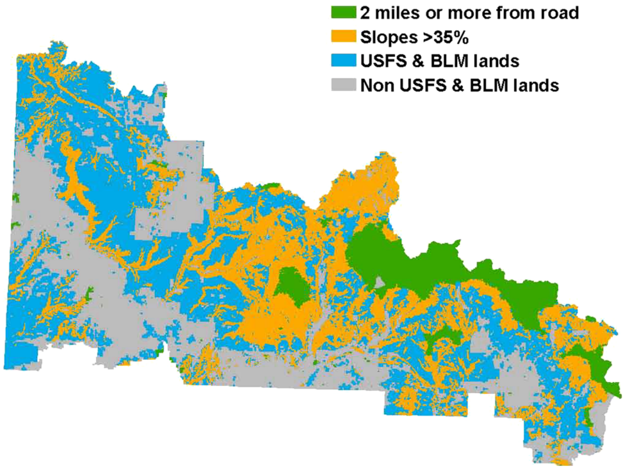


Fig. 5 Portions of the SJ/TR area with physical constraints on carbon management activities. Total area with slopes >35 % is 386,199 ha; that >2 miles (3.2 km) from an established road is 119,628 ha. Aboveground carbon in areas with slopes >35 % is 16,565,761 MgC; that in areas >2 miles (3.2 km) from a road is 4,397,265 MgC

(*Populus tremuloides*)/conifer, ponderosa pine, cool–moist mixed forest, and pinyon/juniper at 13–14 % each. However, much of the spruce/fir forest is in areas where natural processes are to dominate. For the active management zones, ponderosa pine accounts for the largest share of aboveground carbon at about 29 %, followed by spruce/fir at 26 %, and aspen/conifer at 15 % (not shown).

Beyond those areas where specified activities are either prohibited or restricted by law or under the management plan, activities may also be restricted in areas with physical attributes that impede access or use of certain types of equipment (Fig. 5). Access is limited in a significant portion of the SJNF–TRFO with excessive slopes, which are shown in the map as areas with slopes over 35 %. About 38 % of the area and 42 % of the aboveground carbon is in areas with slopes over 35 %, while about 12 % of the area and 11 % of the aboveground carbon is in areas that are more than 2 miles (3.2 km) from a road.

In contrast to the restricted areas, some areas within the SJNF and TRFO may present especially favorable opportunities for action to enhance carbon sequestration, because that goal aligns with other management aims (Fig. 6). These areas include the wildland/urban interface, where fuel management activities receive priority; areas suitable for timber production (a fraction of the area mapped in Fig. 6b); areas where there is interest in improving wildlife habitat through enhanced forage or cover (e.g., Elk, *Cervus canadensis nelsoni*, Fig. 6d); and clear cut and severe burn areas where re-vegetation efforts could be supported (Fig. 6a, c). In total, the unique areas of these categories encompass about 39 % of the aboveground carbon in the SJNF–TRFO area, although the physical limitations already mentioned restrict access in some of this terrain. As noted above, the SJNF has attracted private funding as part of a national voluntary carbon offset program to plant trees in severely burned areas that have high potential for enhanced sequestration, although the area covered by these projects is small.

Fig. 6 Areas within the SJNF–TRFO where other management goals might align with carbon management activities, showing area covered and aboveground carbon. For clear cut and previously burned areas, aboveground carbon potential is shown based on averages for similar areas without these disturbances

(a) Clear Cut: 27,187 ha, 1,166,318 MgC

(c) Past Fire: 45,251 ha, 1,292,419 MgC

(b) Suitable for timber production or where timber management may occur secondarily: 304,308 ha, 17,097,107 MgC

(d) Elk Habitat: 139,076 ha, 6,175,438 MgC

Budget limitations and staff availability impact the ability of the SJNF–TRFO to take on management tasks. Some management options such as planting seedlings after a fire are positive for carbon sequestration, but are difficult unless the Forest Service receives help from outside partners (Gretchen Fitzgerald, forester, San Juan National Forest, personal communication with J. Milford, May 15, 2012). Indeed as mentioned above, the SJNF–TRFO area has participated in a voluntary offset project through the National Forest Foundation. In its first demonstration project, the SJNF secured funding to plant Engelmann spruce trees on 250 acres in an area that was burned in 2003 (National Forest Foundation 2016). Because of the fire severity, the FS had deemed it unlikely that natural regeneration would occur. The project was certified as an afforestation/reforestation project with the American Carbon Registry, so the carbon sequestered over the project's 100-year lifetime can be sold and traded in the form of Verified Carbon Units. The SJNF is now pursuing a second reforestation project on 760 acres. These projects would not have been possible without the funding from the offset project. Moreover, even though funding makes a difference, staffing can also be a limitation, as most field offices do not have enough staff to take on these projects in addition to other existing duties (Gretchen Fitzgerald, forester, San Juan National Forest, personal communication with J. Milford, May 15, 2012).

Use of FVS and Tools

Achieving effective carbon stewardship will also depend on reliable tools and models used to estimate carbon and the changes in stocks with carbon management. Lack of credibility can compromise the estimates that ultimately decision makers rely on. FVS is widely used as a tool for estimating timber stocks on FS lands in the US. The Forest Service annually trains about 150–200 people in using FVS (Lance David, FVS Training Coordinator, personal communication with Y. Huang, May 31, 2013). Many of these users apply FVS for its traditional timber management applications. However, about half of the 20 individuals we interviewed described applications related to carbon, including examining carbon dynamics after beetle outbreaks and timber harvesting, landscape modeling of carbon, and projection of stocks for securing carbon credits. Outside of the US. Forest Service, the state of California, the only state to have incorporated carbon offsets from forests into formal climate policy, has approved seven models for use in carbon accounting, but of those seven, only FVS is both still available for download and free.[4]

As described in Forest Service publications (Hoover and Rebain 2011) and cited in our interviews with FVS developers and users, limitations of FVS for carbon applications include lack of long-term validation, lack of recent stand calibration data, and lack of an automatic regeneration model for some regions (although the latter is intentional to allow for managers to specify regeneration). One of the model's developers noted she sometimes limits her simulations to 25- or 30-year time horizons to avoid reliance on less certain projections for longer time periods. Interviewees also cited relatively poor representation of understory vegetation and lack of soil carbon as limitations for carbon accounting purposes. The climate extension to FVS has fundamental limitations because it is an empirical, statistical model that cannot account mechanistically for genetic responses or disturbance effects. According to one researcher and user, as a relatively recent addition to the FVS toolkit, the climate extension still needs to be thoroughly evaluated. Some of our interviewees also indicated that FVS is not very "user-friendly" or intuitive, and tends to be perceived as a "black box" which may limit its uptake to those who are very savvy with modeling frameworks already.

More effort has been put into updating FVS growth and mortality models for some regions than others; the Central Rockies variant is one that has received relatively little attention since its initial development. Edminster et al. (1991) developed the growth equations for major tree species in the Central Rockies variant using site index as a proxy for site characteristics including slope, aspect, and elevation. Data used to develop the regression equations were collected in the 1970s and early 1980s, and thus reflect growth conditions from the first half of the twentieth century.

Interviewees noted that in applying FVS to carbon estimation, the Fire and Fuels extension is used to estimate carbon storage, but can produce unreliable results at the local scale if the model is not initialized and calibrated with local tree data. However, users we interviewed generally did calibrate the FVS–FFE growth, mortality, and allometric equations for local applications. For example, the SJNF used FVS with local mortality rates and allometric equations for Engelmann spruce in the carbon credit application for its 2011 reforestation project (NFF 2016).

The limitations in FVS and its extensions partially stem from the fact that FVS was created to be a growth and yield model to predict stand level data for timber management purposes; its application to other settings and scales such as landscape scale carbon modeling and extension to non-timber-related carbon pools is therefore expected to be problematic. Researchers are developing new methods to overcome these limitations (Healey et al. 2014; Raymond et al. 2015). Despite these limitations, the users we

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[4] http://www.arb.ca.gov/cc/capandtrade/protocols/usforest/usforest-models.htm.

contacted expected the tool to continue to be widely used for the established purposes such as estimation of timber yields and new purposes like assessment of carbon storage dynamics, in part because of its widespread use and acceptance, the model's record of calibration over the past 30 years, and lack of an established alternative that provides better results. The researchers developing the USFS ForCaMF tool considered other models for projecting carbon growth, but concluded that FVS was the best option (Sean Healey and Crystal Raymond, Rocky Mountain Research Station, personal communication with Y. Huang, March 26, 2013). At the SJNF–TRFO office there are only a few individuals who are trained and experienced in running FVS, and it is unlikely given the workload that they would want to take on a completely different tool for carbon assessments when they would still need to run FVS for other purposes.

Illustrative Results of Carbon Management Activities in the SJNF–TRFO

Carbon accounting is accomplished through comparison of proposed activities to a baseline, often generated through a model as described above. It is beyond the knowledge of carbon stocks, therefore, land managers need information on the projected carbon storage effects of alternative actions in order to assess carbon management potential. To illustrate the magnitude of carbon storage changes that might be affected by management alternatives in the SJNF–TRFO area, we applied the FVS model to two scenarios, one involving thinning in stands of ponderosa pine and warm–dry mixed conifer; and one involving replanting of Engelmann spruce trees after a fire.

As shown in Fig. 7, total stand carbon following the four thinning options ranged from 84.3 to 144.2 Mg C ha^{-1} at the end of the century, with live tree stocks ranging from 44.9 to 79.4 Mg C ha^{-1}. The largest carbon stocks were found for the untreated stand, with progressively smaller stocks with more aggressive treatment.

For the post-wildfire scenario, total stand carbon and total live tree carbon were larger in the replanted stands than those with no replanting following wildfire (Fig. 8). Planting resulted in a 11.6 Mg C ha^{-1} increase in total stand carbon stocks over the scenario with no replanting (139.4 and 127.7 Mg C ha^{-1}, respectively), and a 11.4 Mg C ha^{-1} increase in live tree carbon stocks between the planted stands and those with no replanting (64.8 and 53.4 Mg C ha^{-1}, respectively.)

In both scenarios, the differences in carbon stocks in 2100 from alternative management actions are relatively small; for example, they are smaller than the errors in the carbon maps that might be used to provide estimates of the original or anticipated carbon stocks.

Discussion

The large area occupied by federal public lands in the US suggests that they could be an important contributor to mitigating climate change through deliberate management of land for carbon sequestration (Heath et al. 2011; Zheng et al. 2013). In terms of implementing carbon stewardship actions on public lands there are certainly some areas of potential overlap where management is possible and carbon stocks are high enough to merit consideration for deliberate management. However, our study suggests that only management actions that accomplish high priority goals in addition to carbon sequestration are likely to be undertaken, such as timber production, fuel management, and wildlife habitat enhancement, especially as other benefits and management goals must be considered. Most actions to enhance carbon sequestration will likely need to

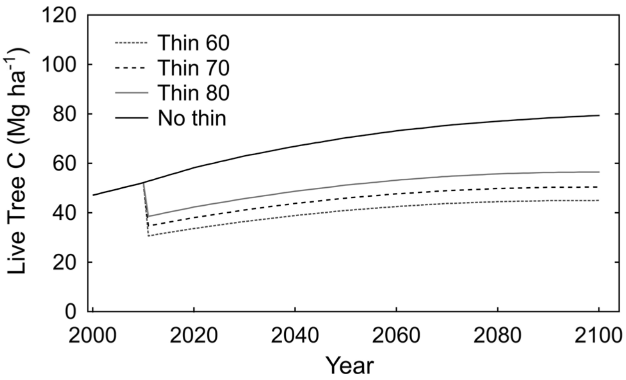

Fig. 7 Results of scenario 1, for live tree carbon through time for thinning treatments to basal area of 60, 70, or 80 ft^2 acre^{-1} (13.77, 16.07, and 18.37 m^2 ha^{-1}) compared to projections for a forest stand that is not thinned

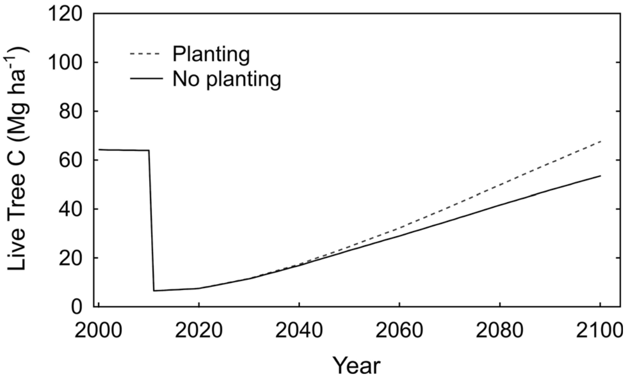

Fig. 8 Results of scenario 2, for live tree carbon through time for two alternatives following wildfire: an alternative where the forest regenerates without a planting treatment, and a second alternative where the forest is replanted

be a part of these existing management foci. Our case study found that even the most effective land management option that is clearly carbon positive, i.e., revegetating after a fire, is also costly in terms of both money and staff time, implies difficult choices for staff considering actions with less well-known outcomes for carbon storage such as prescribed burning or mechanical thinning.

Unless additional resources are allocated, the ability to create a baseline assessment of carbon stocks will likely depend on their existing resources such as staff capacity and access to tools and datasets. Forest Service units may not have unit-specific tools or data to accomplish the Scorecard reporting requirements they are being asked to fulfill. The Forest Carbon Management Framework being developed to support future Scorecard assessments will combine FVS simulations of carbon dynamics with FIA data and remote sensing of land cover changes and disturbances (USFS 2011). It is therefore reasonable to assume that most National Forests will rely on FIA data and FVS to fulfill this requirement at least for now. The Forest Service is actively researching tools and methods to support carbon accounting,[5] and is conducting annual assessments to track participation in the Scorecard across its field offices.[6] Undoubtedly these research projects and assessments will contribute to an evolution of the Scorecard over time.

We find from this case study that using existing national biomass maps based on Blackard et al. (2008) and Kellndorfer et al. (2000) to estimate aboveground carbon stocks in the SJNF–TRFO local area tends to underestimate carbon stocks in the region. This underestimation tendency has been identified previously, due in part to the saturation of reflectance values in regions of high biomass and complex forest canopies (Blackard et al. 2008). As discussed in more detail by Kelsey and Neff (2014), including image texture information appears to be a viable approach for improving aboveground forest carbon estimates. However, most Forest Service units do not have the personnel or computational resources to create these carbon maps on their own.

Our study showed substantial errors for estimating carbon stocks at the Forest and Field Office level. Errors in estimating baseline stocks of the magnitude seen with the national maps could have substantial effects on regional applications, not only in assessing regional carbon stocks but also for informing land management decisions and calculating emissions from past or future disturbance. These errors tend to swamp the differences achieved by alternative management strategies as modeled for the SJNF–TRFO region. These errors contribute another source of uncertainty to estimating the effect of management strategies on carbon in addition to those introduced by vegetation type, age of stand, methods of management, land history, climate, and time frame over which carbon implications are estimated (Hurteau et al. 2008; Hurteau and North 2010; Reinhardt and Holsinger 2010; Kelsey et al. 2014). In addition, because the errors are not evenly distributed across species, and are greater for certain tree ecosystems (in our study, cool–moist mixed conifer and warm–dry mixed conifer), systematic biases in estimation could grow as tree species shift in distribution or numbers with climate change, landscape-changing fires, and pest disturbances. This highlights the importance of accurate, regionally specific data, and tools for estimating both carbon baselines and the impact of management strategies. It also highlights the need for growth projection tools to incorporate future climate change scenarios (Rehfeldt et al. 2012).

As recognized by FVS users and developers, the model's limitations highlight the importance of using local stand measurements to both initialize and *calibrate* FVS (as outlined in Vandendriesche 2010) and other growth projection models in assessing the benefit of proposed management actions. Ongoing efforts to improve FVS and its carbon and climate extensions will enhance the accuracy and usability of these tools over time. Furthermore, the widespread use of FVS and lack of funding for capacity building, training, and maintenance of alternative tools are barriers to adoption of alternative models of carbon and climate dynamics. For the time being, despite the acknowledged deficiencies in FVS, it may be a "good enough" tool for a relative assessment of carbon opportunities, especially if used in conjunction with other GIS layers that can provide targets of opportunity for compatible management objectives. Nevertheless, due to fundamental limitations with FVS and its climate extension, including reliance on empirical relationships that may become obsolete as conditions change, research into more mechanistically based projection models should remain a priority.

In the meantime, estimates of local contributions to national-scale inventories or assessments of carbon management potential should be treated with caution, as nationally available tools have limited accuracy for assessing local carbon stocks or responses. Cash and Moser (2000) have pointed out the difficulty of applying scientific information generated for use at one scale to a different scale—this is often a problem in the application of downscaled climate models to local hydrology for use in decision making, for example (Fowler et al. 2007). Moreover, datasets and tools can be validated at a coarse scale, but

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[5] http://www.fs.fed.us/climatechange/advisor/scorecard/carbon-assessment-stewardship.html.

[6] http://www.fs.fed.us/climatechange/updates/October%202014%20Climate%20Update.pdf.

this may mask errors at the local scale that are not detectable when results are averaged across larger regions. This points to the necessity of testing and evaluating tools at the intended scale of use to ensure that they are robust at that scale.

Because of this region's unique characteristics, the results of this case study may not hold elsewhere although similar categories of questions about the technical and management details needed to implement the Scorecard are likely to be relevant. A case study in the Pacific Northwest, for example, where carbon stocks are much higher per unit area may yield a much different result.

Finally our case study of the SJNF–TRFO suggests that future research should focus on the conditions under which it makes sense to invest in refining measurement strategies to reduce uncertainty in baseline carbon measurements and improve understanding about how management activities affect carbon stocks. In multi-use areas such as the SJNF–TRFO, overlaying maps of management zones, biophysical information, and carbon can help identify locations and types of vegetation where improved information about stocks and dynamics are most likely to influence decisions. The cost of acquiring new information in terms of research expenditures, staff time, and equipment availability will need to be weighed against the value of that information in decision making, and the alternatives available for the same potential climate mitigation benefit.

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