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Refined forest land use classification with implications for United States national carbon accounting

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ABSTRACT

The United States provides annual estimates of carbon sources and sinks as part of its National Greenhouse Gas Inventory (NGHGI). Within this effort, carbon stocks and fluxes are reported for six land use categories that are relevant to economic sectors and land use policy. The goal of this study is to develop methodologies that will allow the US to align with an internationally agreed upon forest land use definition which requires forest to be able to reach 5 m in height at maturity. Models to assess height potential are available for a majority of US forests except for woodland ecosystems. We develop a set of models to assess height potential in these systems. Our results suggest that ∼13.5 million ha of forests are unlikely to meet the international definition of forests due to environmental limitations to maximum attainable height. The incorporation of this height criteria in the NGHGI results in a carbon stock transfer of ∼848 Tg from the forest land use to woodland land use (a sub-category of grasslands) with minimal effect on sequestration rates. The development of a forest land use definition sensitive to climatic factors in this study enables a land use classification system that can be responsive to climate change effects on land uses themselves while being more consistent across a host of international and domestic carbon reporting efforts.

1. Introduction

As signatories to the United Nations Framework Convention on Climate Change (UNFCCC), the United States (US) provides annual estimates of carbon (C) sources and sinks from 1990 to the present following prescribed Intergovernmental Panel on Climate Change (IPCC) good practice guidance (IPCC, 2006; USEPA, 2014) that forms a compendium referred to as the National Greenhouse Gas Inventory (NGHGI) (Woodall et al., 2012). Within the terrestrial components of the NGHGI (as opposed to fossil fuel sources), there resides an important requirement to delineate C stocks and flux by categories of land use, land use change, and forestry. This particular analysis requires the assessment of C by six general land use categories (settlements, grasslands, croplands, wetlands, forests, and other).

In the US, the forest land use category is of critical importance as it accounts for the vast majority (>80%; USEPA, 2014) of the net sequestration of C among all land uses and represents an offset of annual CO_2 emissions from fossil fuel burning in the US (Joyce et al., 2014). The IPCC good practice guidance (IPCC, 2006) does not dictate the definition of forest land use; rather, it instructs signatories to rely upon their domestic definition. However, the IPCC (2006) guidance suggests that the land use classification should not be influenced by 'rotational or cyclical patterns of land use (e.g., the harvest-regrowth cycle in forestry, or managed cycles of tillage intensity in cropland)'. Further, 'forest land includes systems with vegetation that currently fall below, but are expected to exceed, the threshold of the forest land category'. In accordance with IPCC guidelines the US has adopted the forest land use definition used by the US Department of Agriculture's (USDA) Forest Service, Forest Inventory and Analysis (FIA) program (Smith et al., 2013).

As the recognition of the suite of ecosystem services provided by vegetation has increased (e.g., clean air and water in addition to C sequestration) the need to more objectively delineate between land uses has concomitantly increased beyond that of the NGHGI. In the US, a variety of reporting and domestic policy initiatives have provided impetus to more objectively delineate ecosystem services provided by the variety of land uses in order to facilitate their conservation and monitoring. For example, the Montreal Process Criteria and Indicators evaluate a suite of environmental and

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social aspects of US forests (USDA, 2011). The Forest and Rangeland Renewable Resources Planning Act (RPA) of the US requires a comprehensive summary and projection of US forest resources every 10 years (Smith et al., 2009) with updates every 5 years. The US also delineates forest land uses in the Food and Agriculture Organization (FAO) of the United Nations Forest Resource Assessment (FRA, FAO, 2015). Each of these efforts uses a slightly different definition of forest land use which creates inconsistency; however, the FAO forest land use definition is applicable to most of these reporting initiatives.

In regards to domestic US environmental policies, recent executive and legislative guidance has elevated the need to more clearly delineate the ecosystem services provided by woody vegetation among land uses. President Obama's Climate Action plan calls for refining the monitoring of C sequestered among land uses of the US (EOP, 2013). The Agricultural Act of 2014 specifically requires the USDA to identify the capacity and resources needed for refining estimation of forest C and biomass across the US in addition to trees in non-forest land uses such as settlements (US Public Law 113-79). Given the requirement to report ecosystem services such as C sequestration among different land uses for a variety of domestic and international efforts, the likelihood has increased that differing definitions of land uses will result in conflicting estimates of ecosystem services which in turn makes effective rural land policy approaches more difficult to identify. The presence of a variety of estimates has the potential to confound the management, monitoring, and policy development of natural resources. Therefore, the consistent delineation of land uses is needed, especially those that provide the critical function of C sequestration. As an initial step to meet this need, a consistent definition of forest land use should be developed in a fashion that can be implemented across a variety of assessment mechanisms.

Modifying the criteria used to delineate land uses must be done in a consistent fashion for each reporting year as inconsistency may result in misrepresented baselines and unreliable trend information (Grainger, 2008). With the increase in broad-scale forest information the opportunity to draw different inferences regarding status and change in those resources also increases (Coulston et al., 2014; Mather, 1992). Therefore, refined land use criteria must be applicable to the time-series of data that may arise from different sample designs and protocols over time.

The goal of this study is to refine the delineation between forest and non-forest land uses using the FAO forest land use definition for the purpose of improving the consistency of the US' NGHGI estimates with domestic and international reporting instruments with specific objectives being to: (1) develop empirical tree height models as a means to employ an in situ forest land use definition that can be consistently implemented across a range of monitoring mechanisms, across time, and sensitive to climatic attributes (e.g., NGHGI and FRA), and (2) to quantify the implications of this study's refined forest land use definition on forest land use estimates of C stock and C stock change in the US.

2. Methods

As our goal is to employ a forest land use definition that is relevant to a range of national and international reporting efforts, we selected the definition used by FAO (2015). The current US definition (developed by FIA) requires land area to have a minimum of 10% tree cover with an areal extent of at least 0.4047 ha with a minimum width of 36.6 m. Further, if the land has less than 10% tree cover it must have the ability to reach 10% cover in situ and not be subject to any non-forest land use such as agriculture or settlements. The FAO definition is similar but further requires trees to have the capacity to reach 5 m at maturity in situ. To employ the FAO definition models are needed to determine whether the 5 m tree height threshold can be achieved at the maturity of the forest stand.

The FIA program delineates 151 forest community types in the coterminous US and most of these types have associated tree height models (e.g. Carmean et al., 1989) which can be used to apply the FAO definition. However, there is a lack of height models for community types in arid and semi-arid of the coterminous western US (Fig. 1). We focus on these community types and examine their capacity to obtain a 5 m height at maturity. As a means to incorporate an in situ assessment of tree height at forest stand maturity, we develop height models for each of these woodland forest types (Fig. 1).

2.1. Data

For this analysis we used FIA data (USDA 2014a,b), 30 year climate norms 1981–2010 (PRISM Climate Group, 2014), and digital elevation products (USGS, 2011). The FIA program employs a repeated measure rotating panel survey design and the nominal sampling intensity is approximately one 674.5 m^2 ground plot per 2403 ha of land area (Bechtold and Patterson, 2005). Each sample location is classified as either forest land use or non-forest land use (in whole or in part based on FIA's definitions) and those locations meeting the forest land use definition (in whole or in part) have additional measurements taken to quantify percent forest and other salient components of biomass, C, stand structure, community type, and health. Data from the FIA program were the basis for stand height, stand age, community type information, stand physiography, and C stock information. The term stand refers to a contiguous unit of trees of similar species composition (e.g., forest type), age structure, stem density, and other conditions so that it forms a distinguishable unit (Smith, 1986). Carbon stocks included C stored in live trees (above and below ground), C in understory vegetation (above and below ground), C in dead trees (standing and downed), C stored in the litter layer, and C in soil organic matter (see Smith et al., 2013 for background on individual C pool predictions). Total C was the sum of all C pools. Climate norms included average annual maximum temperature, average annual precipitation, degree days above 5 °C, degree days above 5 °C during the growing season. From the climate data a growing season moisture index was also calculated as the ratio of precipitation to potential evapotranspiration (Akin, 1991; Coulston and Riitters, 2005). The Digital elevation data were used to model slope and aspect.

2.2. Height models

We used an empirical height modeling approach (Avery and Burkhart, 1994) to predict which woodland forest stands were likely to have the capacity to meet the 5 m threshold in situ. The modeling was a probabilistic approach where the probability of the stand being at least 5 m tall was a function of stand age, site characteristics, and regional characteristics. The parameterized models could then be used to estimate the probability of each stand to reach 5 m at any age. We parameterized both random forest models (Breiman, 2001) and logistic regression models for each of the woodland forest type in Fig. 1 using stand that had not been recently disturbed stands (i.e., stands without significant cutting, fire, insects and/or diseases, etc.). If disturbed stands were included our model would include the effects of disturbance on height, age, and site relationships which was not desirable. The general form of the random forest models was

$$P(ht \geq 5m) = f(age, elev, Tmax, gmi, lat, physio, eco, dd, gdd, precip, slope, trAspect)$$

where *ht* = maximum tree height, *age* = stand age, *elev* = elevation, *Tmax* = average maximum temperature, *gmi* = the