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Original Articles

An assessment of forest biomass carbon storage and ecological compensation based on surface area: A case study of Hubei Province, China

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ABSTRACT

Area is a basic indicator used in ecological investigations; conventional ellipsoid area describes the earth as a standard ellipsoid without considering undulation of the surface. However, using conventional ellipsoid area in ecological investigations introduces errors in the estimation of forest biomass carbon storage (BCS) in mountainous and hilly areas. In this study, BCS and ecological compensation of the 103 counties in Hubei Province, China, were measured using surface area. Results show that: (1) the surface area of Hubei Province is about 1.97×10^5 km^2, approximately 1.34×10^4 km^2 greater than the calculated ellipsoid area. In terms of forest area, the surface and ellipsoid areas are 6.52×10^4 and 5.92×10^4 km^2, respectively; forest area calculated using surface area is 10.13% greater than that using ellipsoid area. (2) There is a significant difference between the BCS measured in the two areas for mountain landforms, the average difference being 9.13×10^4 t. Plain landforms and hilly landforms have lower average differences, 2.63×10^3 t and 2.95×10^4 t, respectively. (3) The ecological compensation for forest ecosystems in Hubei Province is 33.47 billion Yuan and counties that should be assigned the highest ecological compensation are mainly located in western Hubei. (4) The differences in BCS calculated by the two area methods indicate a typical state of agglomeration in the region, where the western mountainous area belongs to the High–High cluster and the central–southern plain region to the Low–Low cluster. Findings from our investigation show an applied prospective for quantitatively estimating BCS and other resources in a much larger scale. Furthermore, ecological compensation transfer provides a reference for government decision makers to balance the interests of different regions for sustainable development and eco-environmental protection.

1. Introduction

Global carbon emissions were 36 billion t in 2013 (Global Carbon Project, http://www.globalcarbonproject.org/), setting a new emissions record. Increasing trends of emissions can lead to disastrous consequences, such as melting of the polar ice caps, rising sea levels, a reduction of food production and large-scale extinction of species (Farrelly et al., 2013). Several international organizations, including the International Geosphere-Biosphere Program and the World Climate Research Program, view biomass carbon storage (BCS) of the terrestrial ecosystem as an important area of research and claim that forest ecosystems play an important role in regulating the global carbon balance and mitigating global climate change (Piao et al., 2009). At present, sampling and modeling are widely applied in BCS assessment for terrestrial ecosystems. Representative land samples are selected from ecosystems, and the carbon storage in the vegetation litter, soil or other carbon pools in the forest ecosystem are accurately calculated using the harvesting method (Zhang et al., 2009; Nogueira et al., 2008; Wang et al., 2014). On the basis of continuous determination, the exchange fluxes among carbon pools in forest ecosystems can be analyzed through the net ecosystem production of the input system and the carbon emission rates of vegetation litter and soil from the output system. Although sampling is a basic and reliable method, it is generally restricted to small-scale areas. Modeling techniques are important methods to examine the carbon cycle of forest ecosystems on a large scale, in which a mathematical model estimates their productivity and carbon storage. Previous research employed empirical models, including the Thornthwaite Memorial model (Zhao, 2004), the Miami model (Evrendilek et al., 2007), the Biome BGC model (Prentice and Solomon, 1992), the CENTURY model (Parton et al., 1993), the CASA

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model (Defries et al., 1999) and Chave's allometric equation (Chave et al., 2005; Alamgir et al., 2016a,b). However, these methods simplify the complex mechanisms of carbon sequestration in forest ecosystems, besides, the model parameters in these models are mainly obtained on the basis of the characteristics of their own regions, which may not be suitable for China because of the significant differences in geographical features among different regions.

Forestland, by absorbing carbon dioxide and releasing oxygen into the atmosphere through photosynthesis, is one of the main carbon sinks (REFERENCE). This process converts atmospheric carbon dioxide into organic carbon in diverse vegetation; the benefits of carbon sequestration become evident during conversion. Thus, the BCS of forest ecosystems plays an irreplaceable role in balancing the carbon budget, reducing greenhouse effects and responding to global warming. In this context, it is important for regional and central governments to provide compensation for the ecological values created by BCS (Li et al., 2015). Methods to assess this ecological compensation have been proposed by, for example, Li et al. (2015), Gong et al. (2012) and Knoke et al. (2011). However, investigations typically use ellipsoid area rather than actual surface area. In recent years, geo-information techniques (GIS, GPS, etc.) have provided effective ways to assess the BCS of large-scale ecosystems. Vegetation status parameters can be obtained by combining remote sensing with ground surveys, enabling carbon storage of forest ecosystems over large areas, and their spatial distribution and dynamic change to be estimated (Yang and Wu, 2005). However, investigations often neglect to take into account the type of area surveyed in their estimations. Previous investigations have applied the projected area obtained from remote sensing images with Geometric Precision Correction and Ortho-rectification to estimate carbon sequestration in forest ecosystems (Fan et al., 2008; Fang et al., 2011; Jian, 2002; Yang et al., 2010; Jian, 2001). The projected area can be described as the area of land cover projection on the horizontal plane. However, the earth's surface is not absolutely flat, but rather distributed over the 3D space, with various hills and troughs, especially in mountainous regions. Land and living beings are also distributed in the undulant terrain rather than the imagined ellipsoid space (Zhou et al., 2015; Eisenlohr et al., 2013). Moreover, land area is not only determined by the spatial distribution of the 2D space, it is also closely related to the change in elevation; that is, the real area is not completely equal to the area obtained from remote sensing images. Therefore, utilization of the area acquired from remote sensing images in quantitative analyses based on the estimated value could lead to errors or even incorrect conclusions (Jenness et al., 2004; Tian et al., 2007; Ni, 2002). However, the surface area has yet to be applied for the estimation of BCS and ecological compensation in large-scale ecosystems. China, as the largest developing country in the world, has experienced rapid industrialization and urbanization over the past 30 years, and its carbon emissions account for 29% of the total global emissions. At present, China has established several methods for assessing carbon in different regions of forest, grassland and other terrestrial ecosystems. Several parameters affect the assessment of carbon sequestration (Fang et al., 2011; Lu et al., 2009; Bai et al., 2011; Guo et al., 2008; Zhou et al., 2000). Furthermore, the accuracy of BCS assessments has continuously improved through the long-term observation of terrestrial ecosystems and the development of assessment models (Piao et al., 2009; Houghton, 2007).

In this study, Hubei Province in Central China was selected as a case study area to test the influence of area estimation on carbon storage and ecological compensation. Given its various mountains, hills, plains and other types of landforms, as well as its rich forest resources, Hubei Province characterizes the different types of landforms using different area measurement methods to compare carbon storage. The main objectives of this study are: (1) to quantitatively compare the difference between BCS estimated by surface area and ellipsoid area for different terrain environments. It is hoped that this study will highlight the importance of surface area as a basic area parameter for forests and other resource censuses in mountainous terrain; (2) Based on the BCS estimation results, we will provide information as to which study areas should be compensated, and by how much. This investigation will provide more accurate assessment parameters for forest, agriculture and wildlife resource censuses, to improve the accuracy of resource assessment, and to provide a pathway for sustainable development of underdeveloped mountainous areas with abundant forest resources.

2. Materials and methods

2.1. Study area and data

Hubei Province, located in the central part of China (longitude of 108°21′42″–116°07′50″ E and latitude of 29°01′53″–33°6′47″N), is situated along the middle bank of the Yangtze River. The province covers an area of 2261 km^2 and accounts for 1.94% of the total area of China (Statistic 2015). A large area of central and southern Hubei make-up the Jianghan Plain; the peripheries to the west, east and north are relatively mountainous. Hubei Province is an important grain-producing area of China and the Jianghan Plain has been considered as the "land of fish and rice" since ancient times in China. Hubei Province also has rich forest resources, with 27 national forest parks. The Ninth National Survey of Forest Resources carried out by the State Forestry Administration of China shows that forests account for 39.6% of the total land surface in Hubei Province (http://www.hb.xinhuanet.com/2015–05/07/c_1115212820.htm).

Land-use data, forest BCD and a digital elevation model (DEM) for Hubei Provence (Fig. 1) were used in this investigation. The DEM was used to create a surface area raster, over which land-use data were laid with a raster to measure the surface area of each land-use type. Land-use data was sourced from the National Land use/Cover Database of China in 2015 (NLUD-C), prepared by the Chinese Academy of Sciences. NLUD-C data were produced from Landsat TM/ETM remote sensing imaging through the artificial visual interpretation of the generation. The classification accuracy of this data was more than 90%, making this the most precise land-use product available using remote sensing data in China (RESDC, 2015). NLUD-C uses a hierarchical classification method to classify 25 land categories into six categories: cropland, forestland, grassland, water, urban land and other lands. The material was obtained by giving full reference to international experience and the actual situation in China, and it is currently considered as one of the most reliable data sources.

The forest biomass carbon density map was obtained from the National Earth System Science Data Sharing Infrastructure (NESSDSI) (http://www.geodata.cn). This map was created based on China's nationwide forest resource survey conducted by the State Forestry Administration of China combined with remote sensing imaging. The estimation is based on the leaf area index of forests, the remote sensing classification map of forest vegetation, sample data, forest inventory data, and other auxiliary data. This density map is an age-based volume-to-biomass method to obtain a high spatial resolution of distribution of forest biological carbon density (Pan et al., 2004; NESSDS, 2015).

The DEM for this investigation was accessed from http://gdex.cr.usgs.gov/gdex/, a source of Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) products. These products have been developed from the new generation of the observation satellites of NASA, including Terra with a resolution of 30 m and a UTM/WGS84 geodetic coordinate system (GCS).

2.2. Methods

2.2.1. Surface area calculation

Simulation and estimation of the earth's surface was undertaken using a DEM. The DEM used a raster image to represent the undulation