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Locating spatial variation in the association between road network and forest biomass carbon accumulation

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ABSTRACT

The effects of road network on disturbance regimes of forests are less investigated in biomass carbon accumulation than in landscape pattern. To fills in this knowledge gap, we sought to explore the spatial variations in the relationships between road network and biomass carbon accumulation, taking the upstream area of the Minjiang River, Fujian Province in China, as a case. Our results showed that the biomass carbon density increased gradually as the increase of distances from road in both of the study years 2007 and 2012, with a concentration of the biomass carbon loss within the 1000–1500 m distance zone during the study period. The regression outcomes indicated that the geographically weighted regression models fit better than the ordinary least squares, with all the road network measures being statistically significant at the 1% level for the biomass carbon density in both of the study years. Basing on the sign and size of the coefficients estimated by the geographically weighted regressions for each grid, we found the tradeoff and synergistic relationships between the distribution of road network and biomass carbon density existed simultaneously in the study area. Geographical clusters (i.e., hot spots), where the marginal effects of the road network indictors on biomass carbon sequestration ability varied significantly across locations, were also identified to present spatially explicit and quantitative assessments of the geographic variations in these multiple relationships. Our analysis fills the research gap, which assumes that the road's impact holds the same everywhere within a given geographical range. Moreover, identified hot spots could facilitate the implement of more elaborate forest management policies (i.e., grid-based) to dialectically deal with the effect of road network construction.

1. Introduction

Forests contain 85%–90% of total terrestrial vegetation biomass and annually exchange around 10% of total terrestrial ecosystem carbon (C) with the atmosphere through photosynthesis and respiration (Kauppi et al., 1992; Bonan, 2008). Estimation of forest biomass C stocks and their dynamics has been one of the important issues in the study of the global C cycle. Forests especially in the mid- and high-latitude of the Northern Hemisphere are among the most significant sink for C (Kauppi et al., 1992; Turner et al., 1995; Houghton, 2007). China, one of the mid-latitude countries, has 207 million hectares of forested lands, ranked the fifth in the world (FAO, 2010), which range from tropical forests in the south to boreal forests in the north. In recent years, evaluations of biomass C stocks and fluxes for the nation's forests have been widely investigated at the multiple levels, such as the plot, regional and national levels (Fang et al., 2001; Wang et al., 2002; Guo et al., 2013). Effects of human activities, such as agricultural exploitation, forest management practice, and changing land use/cover on biomass C stocks and emissions have also been extensively investigated at different levels (Wang et al., 2001; Khoshravesh et al., 2015). It is well known that human disturbances always date from road construction (Forman and Alexander, 1998; Valipour, 2014). Several studies have also confirmed that the improvement of road network opens land for resource extraction and other human activities while increasing accessibility and mobility, thus 'scaling up' the level of human disturbances on ecosystems (Coffin, 2007; Jaeger et al., 2007; Selva et al., 2011). Recent studies suggest that road building and forest access generate at least a 30% decrease in carbon stock per hectare, but with high spatial variance (Asner et al., 2005, 2010). However, studies on the biomass C dynamics associated with road network are limited, yet it is urgent to determine the role of road network in regional C cycles. Specifically, few studies have quantified spatiotemporal effect of road network on biomass C storage and C density.

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In recent decades, biomass C stocks have been widely observed at a broad-scale using forest inventory database for the world's forests, particularly in European and North America countries (Brown and Schroeder, 1999; Fang et al., 2001; Janssens et al., 2003); e.g., on the basis of the database, Kauppi et al. (1992) estimated the C budget of European forests from 1971 to 1990; Turner et al. (1995) estimated the current pools and flux of C in forests of the conterminous United States and indicated the importance of employing an age-class-based inventory; then, Fang et al. (2001) used an improved estimation method of forest biomass to estimate 50-year changes in the C storage in China between 1949 and 1998. With the consideration of variation of forest age class, stand density and other biotic and abiotic factors (Schroeder et al., 1997), Fang et al. (1998, 2001) used a function of stand timber volume to calculate biomass expansion factor (BEF) for each forest type. This method was proved to be one of the most reasonable and accurate methods to estimate regional forest biomass C (Guo et al., 2013). Therefore, this BEF method was applied to estimate the forest biomass C stocks for each forest in our study.

Biomass C storage and C density are the most important indices in the research of global C cycles (Shao et al., 2008). The former measures the quantity of C accumulation over time and across spaces, while the latter indicates the C sequestration ability of vegetations, and also reflects the degree of human disturbances (Desai et al., 2008; Potter et al., 2008). In spite of growing attention to global C cycle research, most studies on the impacts of human disturbances on forest biomass C storage have focused on land use/cover changes and biogeochemical processes at different levels (Wang et al., 2001; Robinson et al., 2009). Relatively few studies have been conducted to investigate the effects of road construction on biomass C dynamics. Those studies on road's effect are limited to the forest landscape patterns (Reed et al., 1996; Liu et al., 2014). Therefore, there is a significant knowledge gap regarding the relationship between road network and biomass C storage. Such information is urgently needed in China due to its acceleration of the building process of road network.

Extending and upgrading of road network enhances the radiation and attraction of artificial landscape, leads the expansion of human impacts to further remote places, as well as triggers more disturbances by the following processes (Hawbaker et al., 2006). Road network has therefore been regarded as a focus of interest in landscape ecology studies (Forman, 1998). At the broader landscape level, road networks are in various forms and of different characteristics. Thus, the quantification of the spatial pattern of road network is a priority in understanding the mechanism and evaluating the ecological effects (Cai et al., 2013). Road density (RD) is among the most commonly used index, which can effectively characterize the structure of road network (Forman and Alexander, 1998). RD has been examined to be associated with many ecological effects, such as faunal movements, human access, hydrology, and fire patterns (Forman et al., 2003). However, this classic index considers geographic events in a homogeneous and isotropic space under Euclidean space representation (Yu et al., 2015), irrespective of the spatial configuration of road network on its function (Miller et al., 1996). Thus, one more effective method in measuring RD, kernel density estimation (KDE), was proposed to describe the spatial distribution of density of a particular flux across spaces (Parzen, 1962), and has recently been often introduced to study the spatial structure and impact of road network (Xie and Yan, 2008; Cai et al., 2013). Another method of road impact analysis, such as buffer analysis, has been also commonly used in landscape pattern studies (Liang et al., 2014); e.g., Liu et al. (2014) used buffer analysis to compare changes in the landscape indices associated with road network extension, indicating there was a concentration of the habitat loss within 720 m distance from road. This implies that gradient analysis within buffer zone (different distance from road, DR) is also an effective way which can discern the exact disturbance distance of ecological factor.

China's road network has been growing rapidly during the past three decades, along with the government's reform policy. As one of the most developed regions in China, Fujian Province experienced spanning development in transport infrastructure during 2007 and 2012 (Fujian Communications Department, 2013), and in the coming years, more roads will be built to enhance economic activities in conjunction with the development strategy of the West Coast Zone of the Taiwan Strait as well as the provincial strategic plan (Fujian Communications Department, 2011). Furthermore, Fujian Province is one of the four major forest regions in China, with the highest forest coverage rate (63.1%, 2008) in the country (Ren et al., 2011). It has been reported that active transformations among forest cover types (e.g., from primary and secondary forest to planted one) has been observed recently in this region (Zhang et al., 2010), which can lead to the reduction of forest biomass C storage (Carnus et al., 2006; Stephens and Wagner, 2007). Therefore, research on the association between road network and biomass C storage has a significant practical application for this region.

To fill in the knowledge gap in the e relationship between road network and biomass C sequestration, we initially introduced a local model (geographically weighted regression, GWR) to investigate the spatial variations in their relationships, taking the forests of Sanyuan District in the upstream area of the Minjiang River, Fujian Province, as a case. In the study, we firstly compared the temporal and spatial distributions of biomass C storage and C density under different DR, then examined the influences of road network on biomass C storage and C density using GWR models at a grid level, with either biomass C storage or C density as dependant variable, respectively, KDE, DR and a modified distance from road (MDR) as well as independent variables. The primary purpose of this research was to identify any clusters (i.e., grids) across the study region in terms of the significance, size and sign of road network effects. This identification is important, as it provides information on those places within the study area where marginal increases in road network measured indicators result in increasing the loss of biomass C storage or C sequestration ability.

2. Materials and methods

2.1. Study area

The study area, Sanyuan District, is located in the catchment basin between the Wuyi Mountains and Daiyun Mountains in Fujian Province, China. The district is upstream of the Minjiang River, the primary river in Fujian Province and has the seventh highest annual runoff in the country (by recent estimates). The elevations range from 100 m to over 1500 m at the highest peaks. The physiography is characterized by highly dissected terrain with steep slopes and high stream densities. The area is covered by the well-drained yellow-red soil derived from a variety of parent materials (e.g., sandstone, slate, shale, tuff and granite) (Su et al., 2012). The climate is generally moist and mild; most of the precipitation occurs between March and August (Yang et al., 2007). Forest cover is the predominant land use in the area, accounting for more than 80% of the total land area in Sanyuan District.

2.2. Data collection

Forest Management Planning Inventory (FMPI) database of the study area in 2007 and 2012 was used in this study. The structure and survey methodology of the database is prescribed by the standards of the "Technical Regulations of National Forest Resource Continuous Inventory" (State Forest Administration, 2003). FMPI,