Journal of Environmental Management 199 (2017) 158–171

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Spatially-explicit modeling of multi-scale drivers of aboveground forest biomass and water yield in watersheds of the Southeastern United States

Mukhtar Ahmed Ajaz Ahmed [a, *], Amr Abd-Elrahman [a], Francisco J. Escobedo [b], Wendell P. Cropper Jr. [c], Timothy A. Martin [d], Nilesh Timilsina [e]

[a] Geomatics Program, School of Forest Resources & Conservation, University of Florida, 1200 N Park Road, Plant City, FL, 33563, USA
[b] Biology Program, Faculty of Natural Sciences and Mathematics, Universidad del Rosario, Kr 26 No 63B-48, Bogotá, Colombia
[c] School of Forest Resources & Conservation, University of Florida, 214 Newins-Ziegler Hall, PO Box 110410, Gainesville, FL, 32611, USA
[d] School of Forest Resources & Conservation, University of Florida, 359 Newins-Ziegler Hall, PO Box 110410, Gainesville, FL, 32611, USA
[e] College of Natural Resources, University of Wisconsin-Stevens Point, 800 Reserve Street, Stevens Point, WI, 54481, USA

A R T I C L E I N F O

Article history:
Received 1 January 2017
Received in revised form
3 May 2017
Accepted 6 May 2017
Available online 19 May 2017

Keywords:
Trade-offs
Ecosystem services
Drivers
Geographically weighted regression
Watershed
Ecoregion

A B S T R A C T

Understanding ecosystem processes and the influence of regional scale drivers can provide useful information for managing forest ecosystems. Examining more local scale drivers of forest biomass and water yield can also provide insights for identifying and better understanding the effects of climate change and management on forests. We used diverse multi-scale datasets, functional models and Geographically Weighted Regression (GWR) to model ecosystem processes at the watershed scale and to interpret the influence of ecological drivers across the Southeastern United States (SE US). Aboveground forest biomass (AGB) was determined from available geospatial datasets and water yield was estimated using the Water Supply and Stress Index (WaSSI) model at the watershed level. Our geostatistical model examined the spatial variation in these relationships between ecosystem processes, climate, biophysical, and forest management variables at the watershed level across the SE US. Ecological and management drivers at the watershed level were analyzed locally to identify whether drivers contribute positively or negatively to aboveground forest biomass and water yield ecosystem processes and thus identifying potential synergies and tradeoffs across the SE US region. Although AGB and water yield drivers varied geographically across the study area, they were generally significantly influenced by climate (rainfall and temperature), land-cover factor1 (Water and barren), land-cover factor2 (wetland and forest), organic matter content high, rock depth, available water content, stand age, elevation, and LAI drivers. These drivers were positively or negatively associated with biomass or water yield which significantly contributes to ecosystem interactions or tradeoff/synergies. Our study introduced a spatially-explicit modelling framework to analyze the effect of ecosystem drivers on forest ecosystem structure, function and provision of services. This integrated model approach facilitates multi-scale analyses of drivers and interactions at the local to regional scale.

1. Introduction

The Southern United States forests are biologically diverse temperate and subtropical forests producing a set of ecosystem services or benefits to the people (Raudsepp-Hearne et al., 2010) at the local (e.g. food and timber), regional (e.g. clean water), and global (e.g. climate regulation) scales. These forest ecosystems are dynamic and may change over space and time in response to anthropogenic and other ecological drivers (Millennium Ecosystem Assessment, 2005; Raffa et al., 2008; Hautier et al., 2015). These drivers not only change land cover and land uses but also ecosystem composition, structure and function, which can then change the provision of ecosystem services (Millennium Ecosystem

* Corresponding author.
E-mail addresses: amukhtar092@gmail.com (M.A. Ajaz Ahmed), aamr@ufl.edu (A. Abd-Elrahman), franciscoj.escobedo@urosario.edu.co (F.J. Escobedo), wcropper@ufl.edu (W.P. Cropper), tamartin@ufl.edu (T.A. Martin), ntimilsi@uwsp.edu (N. Timilsina).

http://dx.doi.org/10.1016/j.jenvman.2017.05.013
0301-4797/

Assessment, 2005; Isbell et al., 2015). An important challenge of understanding ecosystem services is identifying these drivers and the interaction among different ecosystem functions across multiple scales (Millennium Ecosystem Assessment, 2005; Liu et al., 2016).

Forest biomass is a key ecological metric and indicator of ecosystem structure and functions (Houghton, 2005). Biomass is accumulated in the aboveground parts of the live tree and in coarse roots belowground (Susaeta et al., 2009). Carbon stored in terrestrial forest ecosystems may be released into the atmosphere, sequestered in long turnover time biomass or conserved in the soil (Brown et al., 1996), which makes it a major element in global climate and energy budget models. Alteration in forest biomass is directly related to changing net carbon exchange rates. These changes are important to managers and decision makers to achieve global emission targets (Brown et al., 1996).

In addition to the role of forests in regulating global climate via their function as a carbon source/sink, they play an important role in regional water cycles. Water yield is one of the most valuable services to society (Chapin et al., 2011; Brauman et al., 2007) and an integral ecosystem component that controls the living biomass, carbon cycle, and energy budget (Chahine, 1992). Water yield is a measure of the total outflow from a defined drainage basin over a time interval that can be used to assess the ecosystem function following disturbance (Brantley et al., 2015; Hallema et al., 2016). This interaction between carbon and hydrologic cycles highlights the need for modelling the outcomes from multiple forest uses and how different multi-scale drivers can result in synergies (win-win outcomes) and tradeoffs (win-lose outcomes) at the regional and local scales.

Ecological studies have documented how wildfire, wind storms, insects, and land use change are important drivers of changes in forest ecosystem carbon and biomass (Cropper and Ewel, 1987; Houghton, 2001; Wardle et al., 2003). Properly managed forest and soil quality practices also directly influence sedimentation and subsequent water quality (Brown et al., 2008). Forest soils, relative to other land uses, promote higher soil-water infiltration capacity (Bruijnzeel, 2004) and often contain high soil organic matter and hydraulic conductivity that greatly influence water regulation (Zhou et al., 2010).

Forest structural attributes such as biomass can be directly linked to carbon dynamics of forests (Houghton, 2001; Kashian et al., 2006), as well as others such as Leaf Area Index (LAI) can also affect evapotranspiration dynamics in forests and the water cycle. Forests can regulate water while providing other ecosystem service co-benefits, such as carbon sequestration, and moderating climate change (Swart et al., 2003; Ice and Stednick, 2004). As such, forest management regimes will directly affect biomass and water yield (Timilsina et al., 2013). These drivers of ecosystem functions can change through time and space, due to direct drivers changing ecosystem structure or indirect drivers such as socioeconomics and policies (Bennett et al., 2009; Liu et al., 2016). Basic understanding of forest-water relationships at the watershed-scale using basin and regional level experimental data is however complex (Sun and Liu, 2013).

Thus, there is a need to increase our understanding of how different drivers influence ecosystem functions and whether these results in trade-offs or synergies (Bennett et al., 2009). Key disturbances of SE forests include, in addition to climate change, the reversion of agricultural land, urbanization, wildfire, and pest and pathogens (Trani, 2002). These anthropogenic and natural disturbances interact with each other and influence the development of complex heterogeneous landscapes (Turner and Ruscher, 1988) that affect forest ecosystem functions. Topography has a strong influence on wetland land use and also regulates the streamflow patterns and stromflow peaks and volumes. Land managed by diverse landowners, both public and private, and economic goals of owners significantly influence the water yield ecosystem service (Douglass, 1983). Increased forest thinning (vegetation management) increases the total Water yield volume (Huff et al., 2000). Few of these studies however, have utilized a spatially explicit modelling approach to determine the ecological drivers. The use of global regression models might not explain the local drivers of services using commonly used biophysical variables as they assume stationarity across the study area. Fotheringham et al. (1998) indicated that spatial heterogeneity will also cause problems in the interpretation of parameter estimation using such global regression models. Hence, to better understand ecosystem drivers and interactions, the spatial variation of these must be accounted for as part of the modelling framework.

Geographically weighted Regression (GWR) is one approach that has been used to account for spatial non-stationarity among the relationships between modelling variables as it uses global and piecewise spatial sub-models (Crespo and Grêt-Regamey, 2013). Several studies have investigated the local geography of the relationship between socioeconomic indicators and their characteristics (Fotheringham et al., 2001; Dziauddin et al., 2015). However, few studies examined the spatially varying relationships between ecosystem services (or processes) and the drivers to account for the relationships' spatial heterogeneity. The application of the GWR method could be an effective approach for examining these relationships and to extract meaningful information about geographically influenced ecosystem services and their drivers at both regional and more local scales. These more local and plot scale drivers are often referred to as predictors, but we refer to all the multi-scale factors affecting ecosystem processes and subsequent services collectively as drivers.

Therefore, the aim of this study is to develop a modelling approach to analyze the spatial variation in drivers of two key regional forest ecosystem processes that are regularly used as indicators of ecosystem service provision; aboveground forest biomass and water yield. Specifically our objectives are to use the GWR method to: (1) demonstrate the spatial variability of the significant drivers that influence aboveground biomass and water yield at the watershed level across the SE US, (2) identify common significant drivers that influence aboveground biomass and water yield at the watershed level across the SE US forests (Bennett et al., 2009), and (3) identify watershed clusters located across the SE US forests that experience strong synergies and trade-offs among aboveground biomass and water yield. We believe that such an approach is novel in that it provides a spatially-explicit technique to find consistent patterns of synergies and tradeoffs among aboveground forest biomass and water yield using available forest inventory and geospatial data. Such a spatially explicit framework could significantly contribute a methodology for identifying and understanding the positive (win-win) and negative (win-lose) outcomes of management and biophysical drivers on ecosystem functions and services across multiple scales. Our method also facilitates further studies of local functions, processes, and interactions leading to the observed synergies and trade-offs.

2. Methodology

2.1. Study area

The SE US study region includes the states of Florida, Georgia, North Carolina, South Carolina, Mississippi, Alabama, Tennessee, and Mississippi. These states are characterized by a mild wet and humid climate with a mean annual temperature of 17° C and annual precipitation higher than 1300 mm, which provides high forest