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Carbon sequestration service flow in the Guanzhong-Tianshui economic region of China: How it flows, what drives it, and where could be optimized?

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A R T I C L E I N F O

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A B S T R A C T

The temporal and spatial delivery of ecosystem services is inevitable link between ecosystem and human. But few studies to date have visualized ecosystem services supply and demand from ecosystem process viewpoint. In this study, we simulate the supply-demand spatial matching of carbon sequestration service, visualize the magnitude- and direction-component of carbon sequestration service flows, and select suitable areas for low-carbon target-oriented optimal allocation in the Guanzhong-Tianshui Economic Region (GTER) of China. Our results indicate that carbon sequestration service supply in GTER can meet the regional demand; carbon sequestration centers (R_i > 0.04) are Tianshui, Binxian, Pucheng, Fengxiang and the urban agglomeration on Guanzhong plain which includes Xi'an, Xianyang, and Baoji; Qinling Mountains and Beishan Mountains provide carbon sequestration service for the 5 typical carbon sequestration sub-regions of GTER through carbon sequestration service flows with diverse magnitudes and directions; Ecological factors of NPP, DEM and PET are key dynamic forces for carbon sequestration service supply; Priority areas for low-carbon target-oriented optimal allocation are situated in the west of Qinling Mountains.

1. Introduction

To tackle climate change, policies on ecological protection are constantly being put forward. Ecological taxation and ecological compensation are institutional arrangements to promote the sustainable use of ecosystem services and safeguard the equal rights of people to use ecological resources. Denmark and Holland have adopted strict carbon tax policies to carbon dioxide products and services (Kerkhof et al., 2008; Sovacool, 2013). China has also approved 7 pilot cities/provinces of carbon emissions trading in 2013, which may be a signal that China is starting to levy a carbon tax in the future. These countries are or will be faced with the question of "how should the carbon tax be levied". Before answer this question, an even more basic set of geographic questions remains unanswered: "where are ecosystems producing benefits" and "who and where are people using ecosystem services" (Bagstad et al., 2013).

Ecosystem service flow is the temporal and spatial transfer of ecosystem services from the source region (supply region) to use region (benefit region) driven by natural and artificial factors (Bagstad et al., 2013; Jing et al., 2018). The source region is the area that ecosystem supplies services, while the use region is the area that human beings benefit from the ecosystem. Ecosystem service flow emphasizes the material flow and energy flow of ecosystem used or consumed by human beings. The exploration of ecosystem service flow is significant to understanding of the complex relationship between nature and human beings, and to adjusting pattern to achieve sustainable development (Bagstad et al., 2014; Turner et al., 2012). Carbon sequestration, a biochemical process of carbon dioxide fixed by terrestrial ecosystems, plays an important part in climate regulation by ecosystem services (MA, 2005). Partial productions of this process, including the atmosphere with reduced carbon dioxide content, foods, woods, and their derivatives, are transported into social economic circle through air diffusion, water flow, manual transportation or other ways, and finally utilized by human beings. The benefits that human derive from this process are known as carbon sequestration service, and the temporal and spatial delivery of carbon sequestration service from ecosystem to human is called carbon sequestration service flow. The study of carbon sequestration service flow can help to clarify the spatial location and relationship between the source region and use region of carbon sequestration service on a regional scale, and lay a foundation for ecological compensation and optimization.

Studies on the benefits of ecosystem services and ecological compensation have been of great concern to researchers (Kontogianni et al., 2010; Zander and Straton, 2010), while recently, advances between the demand and supply of ecosystem services and their spatial balance have gradually received the attention of experts around the world (Anton

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et al., 2010; Burkhard et al., 2012; Fisher et al., 2009; Kroll et al., 2012; Shuangcheng et al., 2011). The problem of spatial matching between service supply and demand is one of the main obstacles in the study of the spatial flow of ecosystem services (Brauman et al., 2007; Hein et al., 2006). Ecosystem service flow is involved in both service provision and the delivery of the ecosystem service, which makes its definition ambiguous in reference to any one aspect. Some researchers have attempted to define the ecosystem service flow. Li Shuangcheng considered ecosystem service flow as the spatial displacement of services from the providing to benefiting areas (Shuangcheng et al., 2011). Liu Huimin put forward a clearer definition that ecosystem service flow is a spatio-temporal process in basin or landscape ecosystems in which ecosystem services produced by a providing area pass to the benefiting areas in a certain direction and the path relies on a carrier driven by natural or human factors (Huimin et al., 2016). To date, works in this field can be divided into three categories: conceptual system and classification, the balance of service supply and demand, and the spatio-temporal delivery of services (Baro et al., 2016; Vigl et al., 2017). Different conceptual systems and classifications have been built according to the direction of service flow or the mobility of providers and beneficiaries (Bagstad et al., 2013; Locatelli et al., 2011; Palomo et al., 2013; Schroter et al., 2014; Serna-Chavez et al., 2014; Villamagna et al., 2013). The supply and demand of ecosystem services and their balance is also a research focus in this field. The SPANs (Service Path Attribution Networks) framework for five ecosystem services, including carbon sequestration, was designed to quantify actual ecosystem services based on multiple approaches and output maps on dependencies between provision and usage endpoints, spatial competition among users for scarce resources, and landscape effects on ecosystem service flows (Bagstad et al., 2014; Johnson et al., 2010). The theoretical and practical exploration of this framework provides valuable ideas and methods for the ecosystem service flow field (Palomo et al., 2013; Turner et al., 2012; Wendland et al., 2010), while it still has a long way to go before it can be applied to actual production activities and policy formulation because it is facing multiple implementation problems, such as the complexity of the service transport process and data accessibility (Yu et al., 2016). As to the simulation of carbon sequestration service flow, the algorithm of SPANs model only simply distributes the remaining source quantity from each location among all use locations based on the irrelative emissions, does not involve the flow of carbon sequestration service from source region to use region (Bagstad et al., 2013). A distributed simulation method more suitable for carbon sequestration service flow is absent for the field of ecosystem services.

As an important factor affecting the surface vegetation cover and people's energy consumption levels, planning land use patterns scientifically and rationally has been proven to be an effective tool for regional carbon management (ZHAO Rongqin and Xianjin, 2013). Since the field of ecosystem services flow is still at the stage of exploration and discussion, land use optimal allocation efforts based on this concept are scarce. According to differences in modelling methods and forms of expression, studies on land use structure optimization can be divided into three categories: linear programming models, system dynamics models and cellular automata (CA) model (Min et al., 2010). A CA model is a representative of land use change simulation research based on complex system theory (Huanhuan et al., 2011), which can infer the change of the whole area by taking the interaction of local spatial data to deduce rules and relying on its powerful spatial operations ability (Tobler, 1979; Xia et al., 2007). However, this approach requires historical data over a certain time period as the basis for simulating and deducing the land use change rules, which limits its application.

The spatio-temporal delivery of carbon sequestration service from ecosystem to human is a profitable fundamental research for ecological compensation and pattern optimization, but few studies to date could specifically answer the questions of how carbon sequestration service flows, what drives it, and where could be optimized. The quantification and visualization for carbon sequestration service from ecosystem process viewpoint is urgently needed.

In this paper, we simulate the supply-demand spatial matching of carbon sequestration service with flow ratio (R_i); and map the carbon sequestration service flows as arrows base on adjacency grids interrelation to further explain the ecosystem process of carbon sequestration service; discuss the driving forces of carbon sequestration supply from an ecological process viewpoint and select key factors based on Bayes probability; and provide a spatial layout optimization strategy for low-carbon development target. This study could promote an objective understanding of carbon services flow and provide an intuitive scientific theoretical basis and data support for regional carbon management such as returning farmland to forest.

For the purpose of ecological compensation and pattern optimization, the discussions about carbon sequestration service flow in this paper based on the following assumptions:

(1) Limited by the availability of data and technique, the carbon sequestration service flow in this study only refers to the relationship between the service source region and use region ideally, and does not consider the obstacles and resistance encountered in the process of service flow.
(2) The ‘flow’ in this paper is the flow of carbon sequestration service which can deliver as diverse forms such as atmosphere, woods, and foods, not only the transfer process of carbon dioxide.
(3) Carbon emissions of human in different spatial locations can be offset by carbon sequestration.
(4) Carbon sequestration locations and carbon emission locations are grid matched based on the principle of minimum distance and form carbon sequestration service flows.

2. Data and methods

2.1. Study area

The longitude range of the Guanzhong-Tianshui Economic Region (GTER) is 104°34′47″E–110°48′38″E (Fig. 1), with a latitude range of 33°21′37″N–35°51′15″N. The area is approximately 8.01×10^4 km^2, the average annual temperature is 6–13 °C, the annual precipitation is 500–800 mm, and the elevation is 200–3700 m. According to the topography and climate differences, the research area can be divided into three parts: the Qinling Mountains, the Guanzhong Plain and the Beishan Mountains. As the key ecological protection area of Shaanxi Province and the important water conservation base of the South-to-North Water Diversion Project, most of the Qinling Mountains belong to the restricted development zone, and the ecological base is excellent. This zone is the main forested area and natural carbon pool in the Guanzhong area. The soil type is mainly brown soil, yellow brown soil and cinnamon soil, among which is scattered mountain brown soil, dark brown soil, coarse soil and lou soil. The main vegetation types include evergreen broadleaf forest, evergreen coniferous forest, deciduous broadleaf forest, deciduous coniferous forest, etc. The Beishan Mountains, located between the Guanzhong Plain and the Loess Plateau, are mainly composed of Mesozoic and Palaeozoic sandstones and conglomerates. The soil type is dominated by yellow soil and cinnamon soil, among which is a sporadic distribution of small areas of red soil, coarse soil and brown soil with higher vegetation coverage. The Weihe River flows from west to east through the study area. The Guanzhong Plain is an alluvial plain from the Baoji Gap along the eastward extension of the Weihe River to Tongguan, which is flat and open, has fertile soil and adequate water, is suitable for agricultural development, and is known as the “eight hundred Qin Chuan”. In general, the ecological basis of the Qinling Mountains and the Beishan Mountains is good, human socioeconomic activities in the Guanzhong Plain are relatively dense and the ecological environment is relatively poor. In recent years, the economic development of the study area has been rapid, the construction of the Xi’an-Xianyang new area is fully