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Ecosystem service trade-offs and their influencing factors: A case study in the Loess Plateau of China

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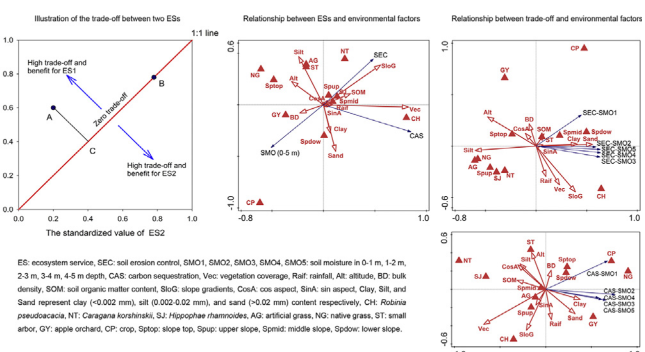
HIGHLIGHTS

- Three ESs are assessed based on field experiments.
- The ESs trade-offs are quantified and redundancy analysis is used.
- The environmental factors interact and they have complex influence on trade-offs.
- The dominant factors for trade-offs are revealed and revegetation advice is proposed.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil erosion control (SEC), carbon sequestration (CAS), and soil moisture (SMO) strongly interact in the semi-arid Loess Plateau. Since SMO has supportive effects on SEC and CAS, it can be considered as ecosystem service (ES), and there is an immediate need to coordinate the relationships among these ecosystem services (ESs) to promote the sustainability of vegetation recovery. In this study, we quantified the ESs, ES trade-offs, and the environmental factors in 151 sample plots in the Ansai watershed, and we used a redundancy analysis (RDA) to clarify the effects of environmental factors on these ESs and their trade-offs. The results were as follows: (1) the general trend in the SEC of vegetation types was *Robinia pseudoacacia* (CH) > native grass (NG) > small arbor (ST) > *Hippophae rhamnoides* (SJ) > artificial grass (AG) > *Caragana korshinskii* (NT) > apple orchard (GY) > crop (CP); the CAS trend was CH > SJ > NT > AG > CP > ST > GY > NG; and the SMO trend was CP > NG > GY > AG > SJ > ST > CH > NT. (2) For SEC-SMO trade-offs, the influence of vegetation type, altitude, silt and sand composition was dominant. The arrangement of NG, AG, and SJ could decrease the extent of the trade-offs. (3) For CAS-SMO trade-offs, vegetation coverage and types were the dominant factors, but the effects were not complex. The extent of these trade-offs was lowest for NT, and that for SJ was the second lowest. (4) Considering the relationships among the three ESs, SJ was the most appropriate afforestation plant. Combing the vegetation types, slope position, slope gradient, and soil properties could regulate these ES relationships. The dominant factors influencing ES

Abbreviations: SEC, soil erosion control; CAS, carbon sequestration; SMO, soil moisture; SMO1, SMO2, SMO3, SMO4, SMO5, soil moisture in the 0–1 m, 1–2 m, 2–3 m, 3–4 m, and 4–5 m soil depths, respectively; Tf, trade-off value; Vec, vegetation coverage; Raif, rainfall; Alt, altitude; BD, bulk density; SOM, soil organic matter content; SloG, slope gradients; CosA, cos aspect; SinA, sin aspect, Clay, Silt, and Sand represent the clay (<0.002 mm), silt (0.002–0.02 mm), and sand (>0.02 mm) contents, respectively; CH, *Robinia pseudoacacia*; NT, *Caragana korshinskii*; SJ, *Hippophae rhamnoides*; AG, artificial grass; NG, native grass; ST, small arbor; GY, apple orchard; CP, crop; Sptop, slope top; Spup, upper slope; Spmid, middle slope; Spdow, lower slope.

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trade-offs varied among the different soil layers, so we must consider the corresponding influencing factors to regulate ESs. Moreover, manual management measures were also important for coordinating the ES relationships. Our research provides a better understanding of the mechanisms influencing the relationships among ESs.

1. Introduction

Ecosystem services (ESs) are the benefits that people derive from natural ecological processes (MA, 2005), and they mainly consist of provisioning, regulating, and cultural services that directly affect human well-being, as well as supporting services that maintain the other three (Costanza et al., 1997; Daily, 1997; MA, 2005). People often hope to maximize one or several types of ESs through management, but a principal challenge is that ESs are not independent and may have highly non-linear relationships with unintentional trade-offs resulting due to ignorance of their interactions (Rodriguez et al., 2006). Trade-offs are generally defined as situations in which one ES increases at the cost of another (Bennett et al., 2009; Raudsepp-Hearne et al., 2010); the opposite is synergies, which can be defined as situations in which both services either increase or decrease (Bennett et al., 2009; Haase et al., 2012). In a broader sense, a trade-off also refers to unidirectional changes in ESs at an uneven pace or rate (Lü et al., 2014).

In recent years, trade-off analysis has emerged as a new research field, and previous studies have explored trade-offs among the four types of ESs (provisioning, regulating, cultural and supporting services) (Raudsepp-Hearne et al., 2010; White et al., 2012; Ballantine et al., 2015) and among the subtypes within a given type (e.g., the provisioning of fresh water and food) (Lautenbach et al., 2013; Frank et al., 2014). Trade-off analysis is a key issue when integrating ESs for landscape planning, management, and decision making (Mach et al., 2015; Darvill and Lindo, 2016; Gissi et al., 2016; Wang et al., 2017; Vogdrup-Schmidt et al., 2017), and it has been used to coordinate ESs in various fields, such as agriculture (Lautenbach et al., 2013), tourism (White et al., 2012), energy (Gissi et al., 2016), and ecological restoration (Wang et al., 2017), which encompasses various geographical features around the world, including wetlands (Mach et al., 2015), mountains (Wang et al., 2017), plateaus (Zheng et al., 2016), seaboards (White et al., 2012), and islands (Goldstein et al., 2012). Therefore, trade-off analysis potentially represents a new way to guide ecological restoration on the Loess Plateau of China, where the ecological system is fragile, and water resources are scarce.

The Loess Plateau, which is located in the arid and semi-arid areas of China, experiences significant soil erosion due to intense human activities and soil erodibility. The intense soil erosion threatens the ecological safety and agricultural sustainability of the region (Lü et al., 2007). Furthermore, the sediment that discharges into the Yellow River elevates the riverbed in the lower reaches of the river and increases the risk of flooding. Therefore, the soil erosion control service (SEC) is one of the most fundamental ecosystem service that ensures human welfare in the Loess Plateau. To improve SEC, the Grain-for-Green Program (GFGP) was implemented by the central government at a large scale beginning in 1999 (Chen et al., 2010), and many steep slope croplands have been converted to forested lands and grasslands. After >10 years of ecological restoration, the vegetation coverage in the Loess Plateau has obviously increased (Lü et al., 2012), and the average rate of soil erosion decreased from 3362 t/(km^2·a) in 2000 to 2405 t/(km^2·a) in 2008. Therefore, the GFGP has effectively enhanced the ecosystem service of soil erosion control (Fu et al., 2011). Furthermore, soil loss is an important source of non-point source pollution in the Loess Plateau (Wu et al., 2015), and it has simultaneously been reduced by the GFGP.

Carbon sequestration (CAS) is an ecosystem process that produces several important ecosystem services, such as provisioning of wood, fiber and fuel, regulating the concentration of greenhouse gases in the atmosphere and mitigating global warming (Upadhyay et al., 2013). The NPP (net primary productivity) and NEP (net ecosystem productivity) in the Loess Plateau have steadily increased since the initiation of the GFGP, with a total of 96.1 Tg of additional carbon sequestered during the period of 2000–2008. The Loess Plateau ecosystem shifted from a net carbon source in 2000 to a net carbon sink in 2008 (Feng et al., 2012).

Although the ecosystem services of soil erosion control and carbon sequestration have improved significantly, the GFGP has had negative effects, one of the most important of which is that local soils have become extremely dry in both the shallow and deeper layers. The two main reasons for this are (1) low precipitation and high evaporation as well as a warming and drying climactic trend (Pu et al., 2006; Fang et al., 2016) and (2) the introduction of vegetation that tends to have greater water consumption needs than the native vegetation (Yang et al., 2014a). Thus, vegetation restoration has often failed due to the lack of soil water, resulting in reductions in vegetation biomass or stunted growth, localized and/or regional vegetation die-off, and poor renewal from a lack of natural germination (Wang et al., 2004a; Wang et al., 2008). In particular, the thickness of the loess soil in this area ranges from 30 to 80 m, depths at which groundwater is not available for plants (Wang Y.Q. et al., 2013), so the soil moisture (SMO) stored in shallow (influenced by rainfall infiltration and evapotranspiration) and deep layers (below the annual rainfall infiltration depth) is critical for plant growth and serves as a key water source for sustaining the ecosystems in this region (Chen et al., 2008; Yang et al., 2012). Therefore, soil moisture is the basis for vegetation restoration, and vegetation cover is the basis for soil erosion control, carbon sequestration, and biodiversity. In this sense, we can treat soil moisture as a supportive service. Moreover, soil moisture is the most important variable regulating many ecosystem processes in water-limited landscapes (Asbjornsen et al., 2011), and soil desiccation has a negative effect on these processes. Thus, soil moisture is a scarce regulating service.

Soil erosion control, carbon sequestration and soil moisture are the three most important ESs in the Loess Plateau. After >10 years of vegetation restoration, the ESs of soil erosion control (Fu et al., 2011) and carbon sequestration (Feng et al., 2012) have been enhanced, whereas soil moisture has decreased (Wang et al., 2010). If soil desiccation continues, the achievements related to soil erosion control and carbon sequestration will be lost because of vegetation degeneration, and therefore, coordinating the relationship among the three ESs is an immediate problem both theoretically and practically. Previous research has qualitatively explored the relationships among the ESs on the Loess Plateau of China including water yield, crop production, water conservation, soil erosion control, carbon sequestration, and biodiversity (Su et al., 2012a; Hou et al., 2014; Jia et al., 2014; Lü et al., 2014; Zheng et al., 2014). However, the relationships between deep soil moisture and both soil erosion control and carbon sequestration have not been clarified, and very few researchers have paid attention to quantifying the extent of the trade-offs among the ESs (Lü et al., 2014; Zheng et al., 2016). Furthermore, the effects of environmental factors on the ES trade-offs have not been clarified. Thus, the existing theoretical knowledge is insufficient for the management of various ESs.

In this study, we estimated three ESs (soil erosion control, carbon sequestration and soil moisture (0–5 m)) based on field observations in the Ansai watershed. Feng et al. (2012) found insignificant changes in soil carbon storage after nearly ten years of vegetation restoration, so we estimated only the carbon storage by the vegetation. We also