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Original Research Article

Spatial conservation of water yield and sediment retention hydrological ecosystem services across Teshio watershed, northernmost of Japan

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ABSTRACT

There is a growing call for spatial conservation prioritization of ecosystem services (ESs) models that is both simple and scientifically credible, in order to serve ecological and environmental decision-making processes. Pressure on ecosystems to provide various and conflicting services is immense and likely to increase. Despite increasing attention to the human dimension of conservation projects, a rigorously spatial conservation planning on balancing multiple ESs has not been developed. The impacts and success of spatial conservation planning will be enhanced if the needs of competing and compromising ESs are recognized. We developed such a framework integrating watershed model into spatial conservation prioritization model and illustrated it about competing and compromising ESs in the Teshio River watershed, with the aim of developing a spatial conservation priority ranking map that balances interactive relationships between water yield and sediment retention. The sediment retention was concentrated in southeastern and some northern areas with higher precipitation, more forest lands and steeper slope, but the water yield was concentrated in southwestern and some northern places with agricultural land. The spatial priority conservation ranking map of individual ES is closely related to its spatially distributed pattern. The spatial priority conservation areas for sediment retention in southwest are traded off against those for water yield in southeast, but there are some overlaps on spatial priority conservation areas for sediment retention and water yield in north of Teshio River watershed. There are obvious differences between the spatial priority conservation ranking maps of individual ESs and those of multiple services together. The spatial priority conservation areas for multiple ESs together simultaneously include southeastern, more eastern and some northern places of study watershed, which can balance the conflict existing between sediment retention and water yield. The proposed framework in this study could be applied to similarly structural conservation prioritization problems of other more ESs, which could sustain ecosystem conservation and economic development across watershed.

1. Introduction

Ecosystem services (ESs) are the benefits that people derive from nature, which include provisioning services (food and water provisions), regulating services (flood control and sediment retention), cultural services (recreational and cultural benefits) and supporting services (nutrient cycling) (MEA, 2005). Among these ESs, water yield is an important in economic and agricultural development, through its supply to irrigation, drinking, and hydropower plant (Sahin et al., 2015). Regional water resource availability can be well described by water yield defined as the difference between received precipitation and evapotranspiration, which is a function of many driving factors including climate, land use and soil categories (Arnold et al., 1998; Sun et al., 2006). Sediment retention is an important regulating ES, which could reduce the cost of dredging sediment accumulation in the dam and keep soil fertility (Fan and Shibata, 2016a). This regulating service

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is the ability of vegetation cover to prevent soil erosion. Vegetation cover needs to be maintained in areas with high erosion to guarantee the continuous delivery of the land production and to prevent erosion and its negative consequences such as eutrophication of nearby water body. Because the hydrologic flow and cycle fluctuate greatly on spatial scale, it is often difficult to depict their characteristics on local and regional scales in heterogeneous environments. The spatial heterogeneity of water yield and sediment retention is attributed to topography, vegetation, climate, and soil properties (Liu et al., 2015; Fan and Shibata, 2016b). For example, topography can particularly affect runoff and sediment flushing in the rainy season as well as water saturation in soil. Vegetation frequently affects evapotrasnpiration, canopy water storage, infiltration and runoff that in turn influences water yield and sediment retention hydrological ESs in the watershed. Climate variables such as precipitation and temperature influence hydrological components and sediment transport and process. Soil physical properties such as soil texture, saturated water conductivity, field water holding capacity influence soil water storage, runoff and sediment loss (Somura et al., 2009; Thampi et al., 2010; Betrie et al., 2011).

The principle challenges in managing ESs are that they are not independent of each other, and that the interactive relationships between ESs may be highly non-linear. Especially, the mechanisms involved in tradeoffs between various ESs need further study to help land managers deal with the ESs conservation planning and optimize the available supplies of multiple ESs. Systematic conservation planning of ESs can consider the interactive relationships among them and provide transparent information for decision-making procedures (Egoh et al., 2011). A well-defined systematic conservation planning process with clear goals and objectives allows stakeholders to understand the conservation criteria (Bagdon et al., 2016). Once clear conservation goals of ESs are established, conserved sites can be selected in a fair, logical and transparent way using explicit and consistently applied methods supplemented by pragmatic judgment and consultation (Egoh et al., 2008). Highly transparent conservation planning processes tend to increase the accountability and credibility of decision-making. The defensibility of the systematic conservation planning is supported by the ability to report on how much of a particular ecological or biodiversity feature has been protected in a particular network design option (Naidoo et al., 2008; Nelson et al., 2008). Zonation model is one of developed tools for systematically spatial conservation model, which is intended for the analysis of biodiversity features (ESs, species, habitat types, and other biodiversity features) data with aim of identifying spatial solutions and providing good conservation outcomes. The Zonation model can account for individual or bundles of biodiversity features, their local amount levels, connectivity requirements of features, and biodiversity feature interactions, making it applicable to a range of conservation prioritization problems (Moilanen et al., 2009). Recent illustrative applications of zonation model include habitat conservation planning (Thomson et al., 2009), terrestrial species-based planning with climate change consideration (Carroll et al., 2010), ecological community level analyses for freshwater systems with hydrological connectivity (Leathwick et al., 2010), and spatial and temporal conservation planning of hydrological provision ESs across watershed (Fan and Shibata, 2014).

However, the application of models to simulate spatial conservation prioritization planning of water yield and sediment retention is less explored compared to the application of other models to estimate hydrological components and sediment load, and simulate effectiveness of soil and water conservation practices across watershed scale. This study developed an analytical framework to depict the spatial conservation prioritization planning of water yield and sediment retention, which is necessary and effective to quantify the spatial characteristics of the water yield and sediment retention and their interactive relationships. We focused on water yield and sediment retention ESs as representative of spatial biodiversity features, because water resources are fundamental and important national resources. Thus, the purpose of the present study is to undertake a preliminary study on the spatial priority conservation areas for water yield alone and sediment retention alone, and the consequences associated with these two ESs together into the systematic conservation model across catchment scale, using an example from the Teshio River watershed. The large catchment area, water yield, sediment retention, geological characteristic, interaction between the hydrologic conditions and active sediment transport and accumulation processes, together with significant catchment changes, makes the Teshio River watershed a suitable study area for the proposed problem.

2. Study site and method

The overall analytical framework includes modeling water supply (water yield) and water purification (sediment retention) ESs in the Teshio River watershed, and simulating spatial conservation prioritization areas for individual and bundles of water yield and sediment retention. We simulated the water yield and sediment retention using the hydrology and nutrient model (Soil and Water Assessment Tools, SWAT). We then simulated the spatial priority conservation areas for water yield and sediment retention using the systematic conservation model (Zonation model).

2.1. Study site

This study was conducted at the Teshio River watershed, northern Hokkaido in northern Japan which is located at 44.33° north, 142.25° east (Fig. 1). This river is the fourth longest (256 km) in Japan, originates from Mount Teshio and flows into the Sea of Japan. Catchment area of the study site is 2908 km^2. Approximately 78% of the catchment is covered by forest categorized as cool-temperate mixed forest, including deciduous broadleaf and evergreen coniferous species with dense understory of Sasa dwarf bamboo (Ileva et al., 2009) (Fig. 2a). Other land uses are mainly farmland and paddy fields, with area percentages 13% and 4%, respectively. The remaining 5% land use is urban and water body. The soil is dominated by brown forest soil (Cambisol; IUSS Working Group WRB 2006); others are gray lowland soil (Gleyic Fluvisols; IUSS Working Group WRB 2006), brown lowland soil (Haplic Fluvisols; IUSS Working Group WRB 2006), grey soil (Gleyic Fluvisols; IUSS Working Group WRB 2006), and peat soil (Histosols; IUSS Working Group WRB 2006) (Fig. 2b). The low values of field water capacity occur on the both sides of the main Teshio channel and on the southwestern watershed (Fig. 2c). The slope ranges from 0 to 83.8% with 14.5% for the average (Fig. 2d).

2.2. SWAT model

SWAT model is a watershed-scale spatially distributed hydrology model which is frequently used for quantifying the impact of land use and climate changes on water, sediment, and nutrient yields in the large complex watershed with varying soil and topography's spatial characteristics (Arnold et al., 1998; Haverkamp et al., 2005). This model is a time-continuous, spatially distributed simulator of the hydrologic cycle and pollutant transport at catchment scales, and runs on a daily time step (Williams and Berndt, 1977; Johnston et al., 2017). In this model, the watershed is divided into multiple sub-watersheds, which are then divided into units of unique soil, land-use and slope