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A process-based framework for soil ecosystem services study and management☆

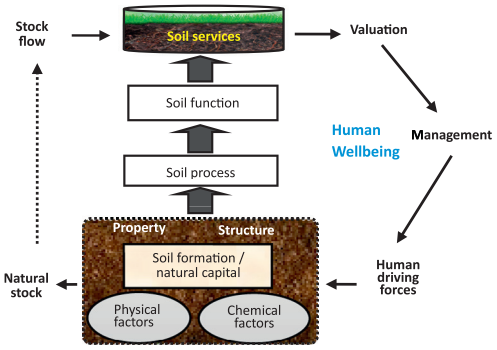
Changhong Su [a,*], Huifang Liu [a], Shuai Wang [b]

[a] Institute of Loess Plateau, Shanxi University, Taiyuan, China
[b] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, China

HIGHLIGHTS

- Soil provides multiple ecosystem services supporting human subsistence.
- A process based framework for soil services was established with due attention to soil structure and property.
- The framework is conducive to soil services mechanisms exploration and prudent soil management.

GRAPHICAL ABSTRACT



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ABSTRACT

Soil provides various indispensable ecosystem services for human society. Soil's complex structure and property makes the soil ecological processes complicated and brings about tough challenges for soil ecosystem services study. Most of the current frameworks on soil services focus exclusively on services per se, neglecting the links and underlying ecological mechanisms. This article put forward a framework on soil services by stressing the underlying soil mechanisms and processes, which includes: 1) analyzing soil natural capital stock based on soil structure and property, 2) disentangling the underlying complex links and soil processes, 3) soil services valuation based on field investigation and spatial explicit models, and 4) enacting soil management strategy based on soil services and their driving factors. By application of this framework, we assessed the soil services of sediment retention, water yield, and grain production in the Upper-reach Fenhe Watershed. Based on the ecosystem services and human driving factors, the whole watershed was clustered into five groups: 1) municipal area, 2) typical coal mining area, 3) traditional farming area, 4) unsustainable urbanizing area, and 5) ecological conservation area. Management strategies on soils were made according to the clustering based soil services and human activities.

1. Introduction

Since the 1960s, ecosystem service has been a much-discussed topic in ecological research. Ecologists have done a lot of work concerning ecosystem services' definition, classification, valuation, and service-based ecological management strategies (Costanza et al., 1997;

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* Corresponding author.
E-mail address: sxjcsch@sxu.edu.cn (C. Su).

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deGroot et al., 2002). As an integral component of the terrestrial ecosystem, soil not only provides tangible services (e.g., food and fibers), but also plays important roles in safeguarding the environment and energy safety, and preserving biodiversity (Koch et al., 2012; Novara et al., 2017; Parras-Alcántara et al., 2016). Generally, soil-related processes are complex and double-edged, e.g., sediment erosion affects soil/water quality, reduces on-site nutrient reserves, and truncates the soil profile; on the other hand, it provides valuable fertile soil and habitat for soil organisms at the lower-reach flood plain area (Lal, 2014). Throughout long history, soil's ecological functions were not given due attention, humans used to regard soil as a "free" gift. Researchers tend to focus more on aboveground ecosystems than underground soil systems. Analysis of the literature shows that within the total of 17,957 published pieces with "ecosystem services" as the key words, only 1953 relate to "soil ecosystem service."

2001 saw the inception of the integrated study of the Earth Critical Zone, a cross-disciplinary subject connecting the pedosphere, atmosphere, biosphere, hydrosphere, and lithosphere (NRC, 2001), within which the pedosphere is most active in maintaining the equilibrium of earth's surface system and control the material, energy, and information transformation. Thus understanding of soil processes constitutes the core contents of critical zone study. Researchers had tried to put forward frameworks on ecosystem services studies. Turner and Daily (2008) provided a framework including problem identification, valuation, policy making, capacity building, and re-appraisal. The OpenNESS project funded by EU FP7 tried to establish an ecosystem services cascade framework to apply the concept of ecosystem services and natural capital in 'land, water and urban management and decision-making process' by stressing the functional characteristics (Potschin-Young et al., 2017). Under the EU FP7 project, RECARE proposes an adapted framework to assess the effect of soil threats and prevention and remediation measures on ecosystem services (Schwilch et al., 2016). Robinson et al. (2013) advanced a soil framework, highlighting the final goods and services of pedosphere in a stock-fund, fund-service model, and argues merely focusing on final goods and services are not enough, due attentions should be paid to the underlying ecosystem supply chain (cascade) and ecological infrastructure.

2. A process-based soil ecosystem service study and management framework

Generally, most of the existing soil services frameworks focus exclusively on services per se, and neglect the complex links and underlying processes. It is often taken for granted that one-to-one correspondences exist between services and processes. The ignorance of the complexity of ecological processes is prone to mixing the "means of production" with actual services and cause double counting (Fu et al., 2011). Compared with other ecosystems, soil system contains more complex ecological processes and interlinks among components. Focusing on soil processes is necessary to fully comprehend the underlying formation mechanisms of ecosystem services. Thus, we propose a framework for soil ecosystem services assessment and management as follows (Fig. 1): 1) analyzing soil natural capital stock based on soil structure and property; 2) disentangling the complex links and processes underlying ecosystem services; 3) valuation of soil services based on field investigation and spatial explicit models; 4) enacting soil management strategy based on soil services and the driving mechanism.

2.1. Analyze soil property and structure in the perspective of natural stock

Soil ecosystem services used to be regarded as stock flow of soil natural capital (Costanza and Daily, 1992), constituted by soil property, structure, composition, and biota diversity. Soil properties were formed from the long pedogeniesis process including parent material decomposition, organic matter accumulation, leaching, soluble salts accumulation, and calcium carbonation (Dominati et al., 2010). Some of the soil properties might be 'inherent' and don't change considerably, e.g., soil texture and mineralogy. In contrast, some properties might be 'dynamic' and change rapidly following the soil managements or environmental condition, e.g., organic matter content, biodiversity, and moisture. Identifying the inherent or dynamic properties of soil is essential for humans to take effective measures to optimize the soil processes and improve soil ecosystem services. Soil structure was closely related to soil property, both jointly sustain soil services. The composition of soil particles, aggregate, and soil pores affects the properties of water content and soil

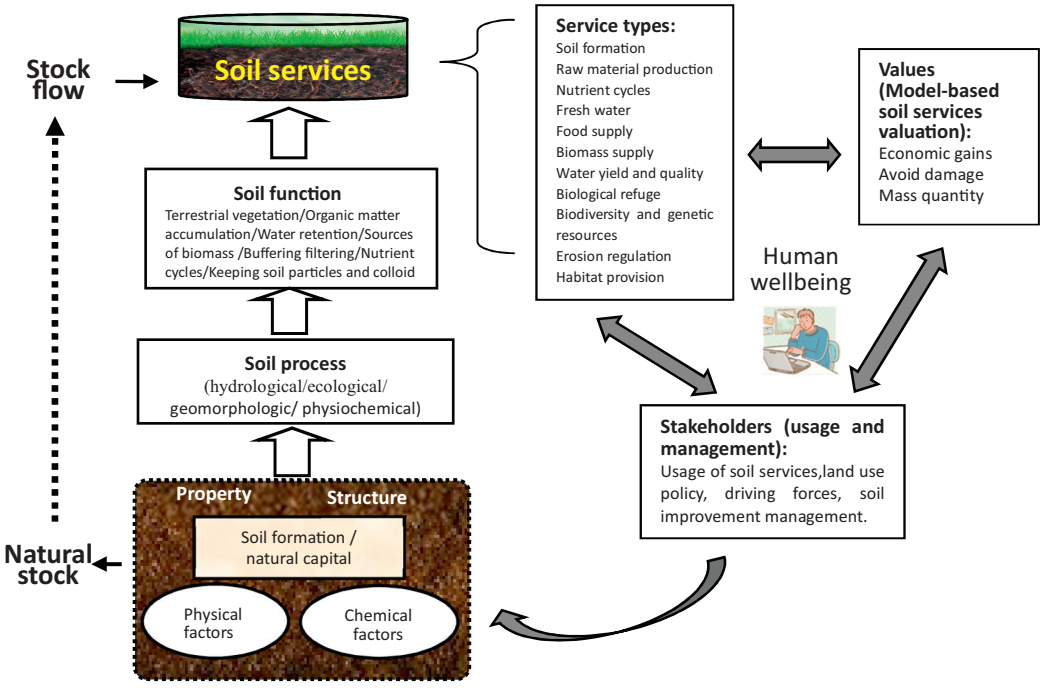

Fig. 1. A process based framework for soil ecosystem services valuation and management. Soil property and structure (natural stock) jointly form the bases for soil process, which lay the foundation for soil ecosystem function/services. Human activities reshape the soil services by altering land use pattern at macro scale or changing soil characteristics through farming practice at micro scale.