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Quantitative assessment of soil productivity and predicted impacts of water erosion in the black soil region of northeastern China

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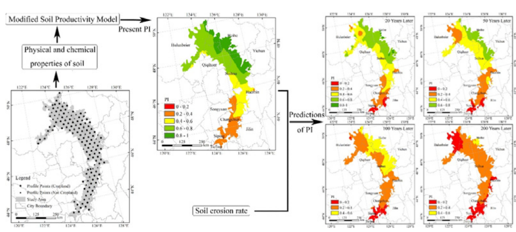
HIGHLIGHTS

- Modified Productivity Index (MPI) model was used in quantitative assessment of soil productivity in black soil region.
- Spatial and profile distribution of soil productivity were detected.
- The predicted impacts of water erosion in the black soil region were presented in this study.

GRAPHICAL ABSTRACT



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ABSTRACT

As Northeastern China is the country's most significant grain production base, soil productivity in this region has consistently attracted attention. National food security is threatened by an ongoing drain of soil nutrients and decline in soil productivity. Black soil is the key natural resource in this region of China, which is thus known as the "black soil region". It is necessary to study the impact of soil erosion on black soil and its productivity to protect this important resource and ensure its sustainable productivity. Through a field investigation and laboratory analysis, the physicochemical properties in 112 soil profiles from a typical black soil sub-region were measured to assess soil productivity using a soil productivity index (PI) model. The soil PI in the study area was relatively high and showed an increasing trend from southwest to northeast. PI values and their spatial distribution were affected by soil organic matter, soil clay content, soil thickness, slope and geomorphological position. Soil productivity and cluster analysis revealed that the southern and northwestern areas of the typical black soil sub-region under study were subject to the greatest risk. To maintain the region's soil productivity, it is vital to prevent the black soil layer, especially the topsoil, from being destroyed.

1. Introduction

Soil provides a variety of products critical to human survival, and its productivity has always been a focus of human attention. With deepening human understanding of the natural environment and its internal ecological processes, soil is increasingly recognized not only as the material basis for production, but also as an important part of environmental systems. It has a profound influence on material and energy cycles in natural systems (Wu et al., 2008). Soil is the largest pool of terrestrial organic carbon (C) in the biosphere, storing more C than plants and the atmosphere combined; it thus plays a crucial role in the global C cycle (Schlesinger, 1997). For more than a century, soil organic C (SOC) has been recognized as a key determinant of soil fertility and agricultural production (Dokuchaev, 1883; Hilgard, 1906; Jenny, 1941; Tiessen et al., 1994; Bordonal et al., 2017). Soil degradation can result from soil erosion, the transport and deposition of soil sediments and the loss of SOC stocks, all of which limit agricultural productivity in cropping systems. Soil erosion not only redistributes SOC across landscapes, but also has a broader impact on soil function and ecosystem sustainability (Olson et al., 2016).

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Soil productivity is defined as the capacity of soil to yield a particular crops or sequence of plants under a specified system of management (Soil Science Society of America, 1997; Duan et al., 2011). Soil productivity has always been concerned by researchers. These studies are mainly divided into two categories: the evaluation of the soil productivity and the influencing factors of the soil productivity. Methods of evaluating soil productivity can be categorized as qualitative or quantitative. Qualitative evaluation yields a qualitative description of the macroscopic traits of soil through field investigation and diagnosis (National Soil Survey Office of China, 1994). Quantitative evaluation can be divided into factor evaluation (Huddleston, 1982; Leng, 1992; Bauer and Black, 1994; Rhoton and Lindbo, 1997) and model evaluation (Williams et al., 1983; Onofrei, 1986; Dumanski and Onofrei, 1989; Flenet et al., 1996; Jones et al., 1998; Kiniry and Bockholt, 1998). The soil productivity is not only closely related to the physicochemical properties of the soil, but also affected by land use (Ovuka, 2000), the application of manures and fertilisers (Edmeades, 2003), conservation tillage systems (Olson et al., 2013), soil and water conservation (Liu et al., 2018). More importantly, as a major factor in the reduction in soil productivity and organic matter content of soils, the impacts of soil erosion on soil productivity has always been the research focus (Larney et al., 2000; Fenton et al., 2005).

Undoubtedly, according to previous studies, it has been shown that soil productivity is profoundly impaired by soil erosion. Topsoil, containing rich OM, is eroded and soil properties change, with important consequences for soil quality. This deterioration in soil quality in turn reduces soil productivity and grain yield (Verity and Anderson, 1990). Soil erosion can lead to variation in soil properties, soil nutrients removal, and reduced crop yields (Biggelaar et al., 2003; Tenberg et al., 2014). Soil degradation involves a long-term decline in soil productivity, which in turn adversely affects the environment (Lal et al., 1997). Therefore, it is important to accurately assess and predict the impact of soil erosion on soil productivity. However, as the process of degradation is slow, the influence of soil erosion is difficult to detect and characterize. Currently, the most effective methods of analyzing the impact of erosion on productivity involve evaluating the horizontal contrast (or similar) between plots with different degrees of erosion. These research methods can be broadly categorized as either contrast or model simulation. The contrast method determines the effect of soil erosion on productivity through long-term yield detection or field investigation in a pilot area with different degrees of erosion by human disturbance. Bakker et al. (2004) found an average reduction in crop productivity of 4.3% per 10 cm of soil loss using the comparative-plot method, 10.9% using the transect method and 26.6% using desurfacing experiments. Sui et al. (2009) held that crop productivity is substantially reduced by deep topsoil removal. The contrast method requires lengthy monitoring, and the results of different methods vary considerably. This makes it difficult to generalize from horizontal comparison. Since the 1980s, researchers have experimented with computer-based models that simulate the impact of soil erosion on productivity. Erosion Productivity Impact Calculators (EPIC) and Productivity Index (PI) model were the representative model. The structure of EPIC is relatively complex, and the simulation needs a lot of meteorological, hydrological, and crop data, which limits its promotion and verification in other countries and regions. PI model has been used to evaluate the effect of erosion on soil productivity by analyzing the physical and chemical properties of the soil profile (Kiniry et al., 1983; Pierce et al., 1983). This method is relatively simple and requires only a few easily obtained variables, and has thus been demonstrated as suitable for regional estimation in northeastern China (Duan et al., 2011). The model benefits from a simple structure, the ready availability of data, important indicators of productivity and consideration of the effects of different soil depths on crop growth. Therefore, the model has been widely used (Larson et al., 1983; Schumacher et al., 1994). Duan et al. (2010) revised the PI model through regression analysis and clustering analysis of soil physical and chemical properties and crop yield in the black soil area of northeastern China, resulting in a modified soil PI (MPI) suited to this region of northeastern China. Therefore, it provides a good method to scientifically and reasonably assess soil productivity in the black soil region of Northeast China.

Northeastern China has always been the country's "grain basket" due to its flat plain and rich black soil; it has historically been subject to neither erosion prevention nor soil conservation efforts. Northeastern China (including Heilongjiang, Jilin and Liaoning provinces), as the country's grain production base, it accounts for 17.63% of the country's total cultivated area, according to statistics released by the Ministry of Land and Resources of the People's Republic of China (PRC). In addition, according to statistics from the National Bureau of Statistics of the PRC, the region's grain yield accounted for nearly 20% of the national grain output between 2011 and 2015. However, cultivation in this region has taken place only for about 300 years due to the settlement of nomadic communities and the prohibition policy implemented in the Qing Dynasty (1644–1911). The northeast has the shortest cultivation history of all regions in China (Ye and Fang, 2011). Due to its relatively flat terrain, few soil or water conservation measures have been implemented, and erosion has led to land degradation, manifested as a thinning of the black soil layer and the appearance of erosion gullies (Yan et al., 2008). Half a century of high-intensity continuous cropping has seriously damaged the soil structure, resulting in reduced soil thickness, organic matter (OM) mineralization, soil erosion area expansion, decreased productivity and a deteriorating ecological environment. It is essential to maintain and improve soil productivity in northeastern China to ensure the sustainable development of agriculture in the region, which is under threat from soil degradation caused by erosion (Wang et al., 2009; Liu et al., 2010). However, the level of agricultural mechanization, scale, and intensification in Northeast China is relatively high. Due to its high input and output of agricultural production coupled with advanced technical conditions, such as improvements in crop varieties, the use of pesticide fertilizer can increase crop yield and cover up a decline in productivity. This threatens national food security and ecological security (State Environmental Protection Administration of China, 2004; Zhang et al., 2006; Liu et al., 2008; Yan et al., 2008). The pursuit of grain production in the Northeast China has been blindly pursued and the concern for soil productivity has been neglected for many years. Most of the existing studies aimed to maintain sustainable soil productivity, and mainly focused on small local areas and individual soil types. However, there are few studies on the regional soil productivity evaluation and early warning of soil erosion hazards in the black soil region. In this study, through a large number of field surveys, data collection, and laboratory analysis, soil samples were surveyed to determine the current status and distribution of soil productivity and the impact of soil erosion on soil productivity in the study area.

The MPI (Duan et al., 2010) was used to quantitively evaluate the effects of soil erosion on soil productivity with reference to the soil's physical and chemical properties, taking into account model applicability and data availability. The purposes of the study were to 1) quantitatively evaluate soil productivity in China's black soil region and 2) figure out the effects of soil erosion on black soil productivity. The results of the paper were intended to provide an early warning of threats to sustainable black soil productivity and fundamental scientific insights for decision makers into measures to sustain productivity and protect national food production.

2. Materials and methods

2.1. Study region

The study area was located in northeastern China (38°42′–53°36′N, 115°24′–135°12′E) and had an area of 1.25×10^6 km^2, covering Heilongjiang Province, Jilin Province, Liaoning Province and the eastern part of the Inner Mongolia Autonomous Region. This area has a geomorphological hoof structure, with Songnen Plain and Liaohe Plain in the