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Effects of soil erosion on soybean yield as estimated by simulating gradually eroded soil profiles

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ABSTRACT

The black soil region of northeastern China supplies more than half of the total grain market in China but has been suffering from accelerated soil erosion from more than 100 years under cultivation. To assess yield response to soil erosion, a new method for gradually simulating eroded soil profiles was developed for experimentation with potted soybeans in which the top 20 cm layer simulated the cultivated layer, which was mixed with soils below due to annual soil loss and a plow depth of 20 cm. The experimental results of five treatments, including “no erosion” and soil losses of the top 20 cm, 40 cm, 50 cm, and 70 cm, showed reduction rates of 5.06%, 5.97%, and 1.77% per 10 cm of soil loss on average for the biomass, yield, and harvest index, respectively. The response curve for soil erosion was concave, with a faster erosion rate at the top layer of 40 cm and a slower erosion rate for the lower layers. The declining yield rates were 9.44% and 1.51% per 10 cm of soil loss for the top and lower layers, and 7.6% and 2.48%, respectively, for declining rates of biomass. The yields were more sensitive to soil erosion than the biomass, whereas the harvest index was not as sensitive. Temperature is a factor that results in annual variations of productivity, however, the more soil loss that occurs, the less the temperature has an effect, and the more that soil erosion has an impact.

1. Introduction

Soil supports both ecosystem services and food security. However, about 15.1% of global land was suffering from human-induced degradation, 83.6% of which resulted from soil erosion and 40.4% of eroded land degradation occurred in Asia (Lal, 2001). One of the most severe adverse on-site impacts of soil erosion was productivity loss due to decreased soil depth. The most severe effect is due to loss of topsoil depth in soils with a root-restrictive layer (Lal, 2001). It is difficult to directly measure yield response to erosion over time because erosion reduces productivity so slowly that the reduction may not be recognized, and improved technology often makes a reduction in soil productivity by erosion go unidentified (Bakker et al., 2004). There have been many studies about the relationships between erosion and soil productivity using indirect methods, which could be identified as three types: (1) experiments involving the removal or addition of topsoil (Tanaka and Aase, 1989; Sibert and Scott, 1990; Flörchinger et al., 2000; Jagadamma et al., 2009; Larney et al., 2009; Munodawafa, 2011; Larney and Janzen, 2012), (2) yield comparisons along transects at various landscape positions characterized by a different soil depth to establish a relationship between erosion and crop yield (Carter et al., 1985; Calviño and Sadras, 1999; Singh et al., 1999; Kosmas et al., 2001), and (3) plot comparisons with different historical erosion rates but with similar characteristics (landscape position, slope, etc.) (Schertz et al., 1989; Rhoton, 1990; Mokma and Sietz, 1992; Weesies et al., 1994; DeHaan et al., 1999; Fenton et al., 2005; Rejman and Iglik, 2010). Methods involving the removal or addition of topsoil may have exaggerated the negative effects of erosion on productivity due to the abrupt disappearance of topsoil in the initial several years (Bakker et al., 2004; Larney et al., 2009). The experiments using yield comparisons along transects may have included the effects of other influences on plant growth because the fundamental hypothesis underpinning this approach is that the variations in soil depth and properties with landscape position are essentially due to erosion. This may not always be the case (Bakker et al., 2004). For example, landscape positions where erosion is likely to occur (steep slopes, convexities) often have reduced water availability due to lateral water movement, or initial soil development at these landscape positions may be less favorable for crop production, e.g., due to a thinner topsoil rather than erosion (Bakker et al., 2004). The plot comparisons method is believed to most closely resemble the

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effects of erosion on productivity (Bakker et al., 2004), but it is difficult to find similar characteristics and different historical erosion plots in a small area. Therefore, the removal of topsoil has been one of the most frequently used methods for studying the erosion–productivity relationship (den Biggelaar et al., 2004; Jagadamma et al., 2009; Larney et al., 2009; Munodawafa, 2011). No matter what method was used, most research has shown the negative effects of soil erosion on land productivity (Bakker et al., 2004; den Biggelaar et al., 2004). Bakker et al. (2004) reviewed studies using three methods and found an approximately 26.6% yield reduction with topsoil removal (desurfacing) methods, a 10.9% reduction with transect methods, and a 4.3% reduction with plot comparison methods, per 10 cm of soil loss. Yield decreased severely with several centimeters of topsoil removal in some soils (mainly Alfisol) with desurfacing methods, and some crops even had no yield without fertilizer and 30–95% yield reductions with fertilizer with 20 cm of topsoil removal (Flörchinger et al., 2000; Jagadamma et al., 2009; Munodawafa, 2011). The yield comparison along a transect method found approximately 10–40% yield or biomass loss from topsoil decreased by 40 cm (Carter et al., 1985; Kosmas, 2001), whereas only approximately 20% of yield was lost when topsoil decreased by 40 cm in the plot comparison plots method (Rhoton, 1990), and some comparing plots results showed that only severe erosion (not moderate or slight erosion) could reduce productivity (Weesies et al., 1994; DeHaan et al., 1999; Rejman and Iglik, 2010).

In China, widely distributed steeper cultivated slopes have resulted in serious soil erosion on the Loess Plateau and in southern China, where studies about soil erosion and productivity have been carried out (Chen et al., 2001; Jia et al., 2004; Li and Gao, 2007; He and Yin 2001; Li et al., 2012). Northeastern China has a flatter landscape for agriculture and contributed approximately 18.87% to national food production in 2011(National Bureau of Statistics of China, 2012); this area includes Heilongjiang, Jilin, and Liaoning provinces. The main crops are soybean and maize, with 45.16% and 33.07% of the national total production, respectively, in 2011 (National Bureau of Statistics of China, 2012). The undulating hilly terrain, with long slopes and long-term conventional cultivation for more than 100 years, has resulted in severe soil erosion that is threatening national food security (Liu et al., 2008, 2010; Liu and Yan, 2009). Only a few studies on the effects of soil erosion on productivity were conducted over short observation periods (Zhang et al., 2006; Sui et al., 2009; Wang et al., 2009).

It is important for sustained food security in China to evaluate the impacts of soil erosion on land productivity. A new experimental method, simulating gradually eroded soil profiles, was presented in this study to overcome the overestimation of soil productivity declines with soil loss by removing topsoil. The objective of this study was to assess soybean yield response to soil erosion by using this new method, and to estimate reduction rates of biomass, yield, and harvest index with soil loss depths.

2. Methodology

2.1. Study area

The experiments were carried out using soybean plants grown in pots with simulated gradually eroded soil profiles at the Jiusan soil conservation station of Beijing Normal University, Nenjiang county, Heilongjiang province (northeastern China), from May 2004 to October 2009 and from May to October 2011. The location is 48°59′N and 125°17′E and has a cold temperate monsoon climate. The mean monthly temperatures in January and July are approximately −24.1 °C and 20.9 °C, respectively, and the average annual rainfall is 484.7 mm. Soybean is one of the most widely planted crops, and their main growing season is from June to September.

The dominant soil in northeastern China is black soil based on the genetic soil classification of China (GSCC) (NSSO, 1998); this soil is mainly distributed in the undulating hilly areas, which are transition zones from the Xiaoxing'anling and Daxing'anling Mountains to the SongNen plain. The black soils consist of four subgroups, as follows: typical black soils, meadow black soils, albic black soils, and surface-gleyed black soils based on the GSCC. The first one, typical black soil, was chosen for this study; this soil is also known as Hapli–Udic Isohumosols in Chinese Soil Taxonomy (CST) (Gong et al., 1999; Chen et al., 2004) and is in the Mollisols order and Agriborolls group in the USDA Soil Taxonomy (ST) (Shi et al., 2006; Zhang, 2005). Its typical soil profile is A–B–C. The A horizon is the surface layer, which often refers to the topsoil or mollic epipedon, containing much more organic matter to give the soil a darker color than that of the lower horizons. The B horizon is commonly referred to as subsoil, and it has a concentration of clay or minerals that are dark gray or brownish due to clay and iron oxides that wash down from the A horizon. The C horizon is made up of parent material, which includes Quaternary lacustrine and fluvial sand beds or loess sediments (Sun and Liu, 2001). The depth of the A horizon varies between 20 and 30 cm on slopes and tends to be deeper than 50 cm in gentler areas (Wu et al., 2008).

2.2. Simulating gradually eroded soil profiles: soil used in this study

To overcome the overestimated adverse effects of erosion on productivity by abruptly removing topsoil, we used a simulated gradually eroded soil profile (SGESP) method in this study. The premise was that soil was eroded from the surface year by year and that the plow cut into the subsoil, thereby mixing the top plow layer every year. Therefore, the following assumptions were made: first, we assumed that the original soil profile was 100 cm deep, including 9 layers, with 20 cm at the surface and 10 cm thickness in the others, and that these soil characteristics were the same within each layer but varied among the layers. Second, we assumed that the topsoil was eroded annually, whereas the plow cultivated the topsoil to 20 cm and thoroughly mixed this layer every year. Therefore, the soils in the simulated top 20 cm plow layer were made up of soils from different original layers, and the soil of the original top 20 cm layer could never be totally removed. Third, the other simulated layers, beneath the simulated top plow layer, were maintained as the original layers that the plow could reach.

The original soil profile had layers of $i = 1, 2, \ldots, n$, and the depth and thickness for each layer were $D_1, D_2, \ldots, D_n$, and $h_1, h_2, \ldots, h_n$, respectively. Based on the above assumptions, the processes of the SGESP method were divided into two steps: one step was to estimate the remaining soils from the original layer in the simulated top 20 cm layer, and the other was to identify which original layers would be left below the simulated top 20 cm layer.

Soils in the simulated top 20 cm tillage layer were from different original layers due to the plow mixing and were estimated as:

$$RSL_i = TRSL_i \times \left(\frac{1-r}{20}\right)^{(t-t_{0i})} \quad \mathrm{DPL}_i > D_i \tag{1}$$

where, RSL_i was the remaining soil depth (cm) of the original layer i, r was soil erosion rate, which occurred at 0.5 cm per year in this study, and $t = 1, 2, \ldots$ erosion years. The t_{0i} was the initial year of erosion occurrence for a new original layer below the simulated top layer. It was estimated as follows: