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Assessment of the effects of shelterbelts on crop yields at the regional scale in Northeast China

Xiao Zheng [a,b,c], Jiaojun Zhu [a,b,*], Zefeng Xing [d]

[a] Key Laboratory for Management of No-commercial Forests, Liaoning Province, Shenyang 110016, China
[b] Qingyuan Forest CERN, Chinese Academy of Sciences, Shenyang 110016, China
[c] Daqinggou Ecological Station, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[d] Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130012, China

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ABSTRACT

The Three-North Shelter Forest Program (TNSFP), which is the largest ecological afforestation program worldwide, was launched in 1978 and will last until 2050 in the Three-North regions (accounting for 42.4% of China's territory). As a dominant component in the TNSFP, shelterbelts or windbreaks play an important role in preventing from wind damage and erosion and providing appropriate microclimate conditions for crop growth, thus improving crop yields. However, how shelterbelts influence crop yields at the regional scale has not yet been determined because there are certain difficulties in identifying the effects of shelterbelts on crop yields due to other factors such as climatic factors, crop seeds, fertilizer and management measures. In this study, a new approach is used to estimate the effects of shelterbelts on crop yields while overcoming these difficulties. The specific processes used in this study are detailed as follows. First, the climatic potential productivity, which is a combination of solar radiation, temperature and precipitation, was estimated using the multi-sensor remote data. All farmland in the region was divided into high, middle and low climatic potential productivity zones. Second, the crop (i.e., maize) yield across the Northeast China was estimated using the harvest index method and MODIS data. Third, according to the effectively protected distance, the levels of protection provided by the shelterbelts to the farmland at the regional scale were calculated by combining the stand age and the growth status of the shelterbelts using a time series of Landsat images. Finally, the levels of protection and the corresponding maize yields in pixels were extracted and averaged to identify the effects of shelterbelts on crop yields. The results of this study indicated that shelterbelts could enhance crop yields at the regional scale. The contribution rates of shelterbelts to increasing maize yields were found to be 4.68%, 4.28% and 9.45% in the high, middle and low climatic potential productivity zones, respectively. In Northeast China, the average level of protection of farmland was 18.28%, which was obviously lower than the optimal level of protection (i.e., approximately 80%); thus, many shelterbelts must be planted in the future. The findings of this study provide a sound theoretical foundation for increasing crop yields by planning shelterbelts in farmland regions similar to those in Northeast China.

1. Introduction

The Three-North Shelter Forest Program (TNSFP) is known as China's Green Great Wall and the world's largest afforestation project. The TNSFP started in 1978 and is expected to last 73 years (i.e., until 2050) to complete. The objectives of the TNSFP are to improve environmental conditions (e.g., to prevent mobile sand from wind erosion, to harness soil and water losses) and to produce multiple forest products in the Three-North regions (i.e., the western regions of Northeast China, and the northern regions of North China and Northwest China) (Zheng and Zhu, 2015a, 2015b). As a dominant type of protective forests used by the TNSFP, shelterbelts or windbreaks may offer a range of potential advantages, which include increased crop productivity and stability under climate change, optimization of inputs, resilience to disruption and ecological sustainability (Kort, 1988). Shelterbelts are the most important and widespread agroforestry systems used in America (Brandle et al., 2004; Garrett, 2009), Australia (Cleugh et al., 2002; Nuberg and Mylius, 2002), Canada (Kort, 1988), England (Grace, 1977), Russia (Chendev et al., 2015) and others countries (Caborn, 1957; van Eimern et al., 1964; Nair, 1993).

The primary direct effect of shelterbelts is to reduce wind speed, which in turn alters other microclimate parameters (Easterling et al., 1997; Cleugh, 1998; Campi et al., 2009; Rivest and Vezina, 2015), including reductions in turbulent air mixing, which increases the

* Corresponding author at: Institute of Applied Ecology, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, PRChina.
E-mail address: jiaojunzhu@iae.ac.cn (J. Zhu).

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efficiency of the use of soil moisture by reducing evaporation from the soil surface, leaving more water for crop growth (Grace, 1988; McNaughton, 1988; Cleugh, 2002). Shelterbelts have been shown to have minimal influence on the direct distribution of incoming radiation (Brandle et al., 2004). Shelterbelts can also offer important benefits to farmers, particularly through the improvement of agricultural production (Kort, 1988; Puri et al., 1992; Grala and Colletti, 2003). In general, on high-stress sites or during years of high stress, shelterbelts tend to produce the most positive influences on crop yields (Kort, 1988; Peri and Bloomberg, 2002); however, shelterbelts may also have certain detrimental effects on crop productivity (Rivest and Vezina, 2015). In the zone adjacent to the shelterbelt (0.25 H–1.15 H, where H = the height of the shelterbelt, which is conventionally used as the distance from the shelterbelt), productivity is typically decreased due to shading and competition with the shelterbelt for moisture, light and nutrients (Kort, 1988; Ding and Su, 2010; Rivest and Vezina, 2015).

Although different analyses in the literature have highlighted a global positive net effect from temperate-zone shelterbelts on crop yield (Kort, 1988; Nuberg, 1998; Brandle et al., 2009), a more in-depth reading of several individual studies reporting these beneficial effects has revealed a wide variability in the reported yield results, and the shelterbelt effect on crop yield is somewhat equivocal (Rivest and Vezina, 2015). For example, Kort (1988) summarized the effect of shelterbelts on corn yields over 209 sites and reported an overall weighted mean yield increase of 12% in Canada. Similarly, Sun et al. (2010) reported that the wheat yield with the protection of shelterbelts was 4.7% higher than without shelterbelts in Northern China. Bao et al. (2012) reported that the weighted average yield in a sheltered zone was 30% larger than the yield from an unsheltered zone based on local observations in Northern China. A key problem with these previous studies is that they primarily considered field observations that were generally near the shelterbelt or at the network scale (Puri et al., 1992; Foereid et al., 2002; Peri and Bloomberg, 2002; Dierickx, 2003); thus, the effects of the shelterbelts on the crop yields at the regional scale have not been well described to date (Shi et al., 2011). Moreover, the crop yield response to shelterbelts seems to be strongly dependent on the edaphic context and particularly the climatic context of a given study. For example, using a modeling approach, Easterling et al. (1997) showed that the positive effects of shelterbelts on maize yield decreases as precipitation levels increase. Therefore, realistic estimates of the effects of shelterbelts on crop yields at the regional scale with climatic gradients are still required.

Four challenges must be addressed if the effects of shelterbelts on crop yields at the regional scale are to be determined with climatic gradients. First, it is difficult to identify the effects of shelterbelts on crop yields due to other factors such as climate, crop seeds, fertilizer and management measures. Second, it is difficult to achieve a high accuracy and reliability in the calculation of crop yields at the regional scale. Third, there is no established quantitative method to determine the level of protection of farmland provided by shelterbelts at the regional scale. Fourth, it is essential to develop a comprehensive climate index to quantify climate differences in a given study area.

Remote-sensing techniques may be a sound alternative to meet the abovementioned challenges because they have the ability to provide spatial and temporal information across a wide area (Ferencz et al., 2004; Chernetskiy et al., 2011), which is required in this study. First, the climatic potential productivity refers to the maximum crop output determined by solar radiation, temperature and precipitation conditions, respectively, when soil, seed, and other agricultural techniques are suitable (Yuan et al., 2012; He et al., 2014). To describe the impacts of climatic factors on crop yields, the climatic potential productivity can be estimated using the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Tropical Rainfall Monitoring Mission (TRMM) (Immerzeel et al., 2009; Vancutsem et al., 2010; Zheng et al., 2013a). To estimate accurate crop yields at large spatial scales, the integration of a crop growth model and satellite data is an appropriate quantitative-analysis methodology (Moriondo et al., 2007). Additionally, to determine the level of protection provided to the farmland by the shelterbelts in the study region, the temporal-spatial variation of the shelterbelts can be observed using the Landsat series images, which span more than 30 years and provide high spatial resolutions (Zheng et al., 2013b).

The purposes of this study include the following: (1) to describe crop potential productivity using multi-sensor remote sensing data; (2) to estimate crop yield with a sufficient level of accuracy and reliability in Northeast China; (3) to propose a new methodology to quantify the level of protection provided to farmland by shelterbelts at the regional scale; and (4) to assess the effects of shelterbelts on crop yields at the regional scale across a climatic potential crop productivity gradient.

2. Study area

The TNSFP is operating in the Three-North regions and covers a total area of 4.069×10^6 km^2, which accounts for more than 42.4% of China's total territory (Fig. 1a). The study area is located in the western regions of Northeast China in the Three-North regions (38°43′ to 53°47′N, 118°50′to 134°46′E) and covers an area of approximately 58.42×10^4 km^2, encompassing the four provinces of Heilongjiang, Jilin, Liaoning and Inner Mongolia (Fig. 1b). This area is characterized as a continental, semi-humid to semi-arid, monsoon climate in the warm temperate zone and has a mean annual temperature of approximately 1 to 7 °C, annual precipitation varies widely from 300 mm in the west to 550 mm along the east coast, and the average annual wind speed is 2.6 m s^{-1}. The study area is one of the most important agricultural production bases and the most representative area of the Three-North regions in terms of farmland shelterbelts. Maize (*Zea mays* L.) is the dominant crop in this region, comprising approximately 50% of the total farmland area in Northeast China, and is one of the most widely planted crops in the world. Maize in this region is sowed in late April and harvested in late September, leaving the soil bare for approximately 5 months from October to May of the following year.

3. Methods

3.1. Climatic potential crop productivity

Many studies have shown that shelterbelts can improve crop yields; however, the degree of this effect varies with the climate conditions (Peri and Bloomberg, 2002; Bao et al., 2012). Therefore, the farmland in Northeast China was segmented into several climatic zones based on their climatic potential crop productivity to lessen the influence of climatic factors on crop yields at the regional scale. The climatic potential crop productivity, which considers many climatic factors (i.e., solar radiation, temperature and precipitation) concurrently, in a given location refers to the yield of a crop when grown under the conditions of full nutrient supply, thorough control of pests and weeds, and optimum farming techniques and management (He et al., 2014). In addition, the climatic potential crop productivity is a foundation for the study of the comprehensive grain-production capacity and provides important theoretical guidance for agricultural productive distribution, agricultural structure adjustment, and determining the reasonable use of climate resource (Yuan et al., 2012; Jiang et al., 2013).

The climatic potential productivity of maize was calculated using the following equation:

$$Y = Y1 \times f(T) \times f(R) \tag{1}$$

where Y_1 is the photosynthesis potential productivity, $f(T)$ is the temperature modification function, and $f(R)$ is the water correction function.