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Research paper

Estimating maize yield potential and yield gap with agro-climatic zones in China—Distinguish irrigated and rainfed conditions

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ABSTRACT

Understanding yield potential (Yp) and yield gap (Yg) in current intensive maize (*Zea mays* L.) production is essential to meet future food demand with the limited resources. In this study, we used the agro-climatic zones (CZs) and the reference weather stations (RWS) buffer zones, together with the Hybird-Maize model to estimate maize Yp in the four maize-growing-regions of China under both irrigated and rainfed conditions. In irrigated maize areas, we got 70 RWS buffer zones, and total maize area in the RWS buffer zones covered 67% of the whole irrigated maize area. In rainfed maize areas, we got 106 RWS buffer zones, which covered 51% of the whole rainfed maize area. As a result, the average Yp was 14.2 t ha^{-1} and farmers have achieved 58% of Yp. The average water-limited yield potential (Yw) was 10.7 t ha^{-1} and farmers have achieved 65% of Yw. Further analysis for four maize-growing-regions showed that precipitation was a limiting factor for Yw to fully achieve Yp except in Southwest China (SW), whereas the average precipitation was more than 653 mm during maize growing season. The ratio between Yw and Yp (Yw/Yp) was 51% in Northwest China (NW), and around 80% in both Northeast China (NE) and North China Plain (NCP). The comparison of Yp in different regions showed the low Yp in NE was due to low temperature while Yp in both NCP and SW were limited by low solar radiation. In conclusion, our findings highlight the efficiency and importance to estimate Yp, Yw and Yg by the upscaling method with CZs and RWS buffer zones. Meanwhile, the comparison of Yp, Yw and Yg in different regions was important to improve maize production in future in China.

1. Introduction

Maize has become the largest cereal food crop in China since 2013, and the maize production was 215 Mt in 2014, which accounted for more than one-third of China's cereal production and was responsible for 21% of the global maize output (FAO, 2016). With the economic growth and changing diet, demand for maize in China by 2030 is estimated to be 47% higher than now (Chen et al., 2014). Until the middle 1990s, China's maize yield increased in a near-linear fashion, but has stagnated at around 5.0 t ha^{-1} since 1995 (Meng et al., 2013). However, high-yielding experiments have showed that the maize yield was higher than 15 t ha^{-1} at 159 sites in China from 2006 to 2010 (Chen et al., 2012). Hence, understanding the yield potential (Yp) and yield gap (Yg) in the current intensive maize production is essential to meet the future food demand.

Yield potential is defined as the yield of an adapted crop variety when grown with optimal water and nutrients management and without yield losses due to biotic and abiotic stresses (Evans, 1993; van Ittersum and Rabbinge, 1997; Fischer, 2015). Yg is the difference between Yp and actual farmers' yield (Ya) (Lobell et al., 2009). Estimating Yp and Yg can help assess the status of current farmers' yield relative to Yp and the possible space for yield gain in the future (Lobell et al., 2009; Hochman et al., 2013). In addition, the analysis of spatial distribution of maize yield gap can help reveal major yield limiting factors and thus effective efforts will be made to increase yield efficiently (Aggarwal and Kalra, 1994; Naab et al., 2004; Bhatia et al., 2008; Mueller et al., 2012).

Recently water scarcity has already been a critical issue in the world (Rijsberman, 2006; McLaughlin and Kinzelbach, 2015).

Abbreviations: Yp, yield potential; Yw, water-limited yield potential; Yg, yield gap; Ya, actual farmers' yield; Yg_I, the difference between Yp and Ya; Yg_R, the difference between Yw and Ya; CZs, agro-climatic zones; RWS, reference weather station; NE, Northeast China; NW, Northwest China; NCP, North China Plain; SW, Southwest China; GYGA-ED, Global Yield Gap Atlas Extrapolation Domain; GDD, growing degree days.

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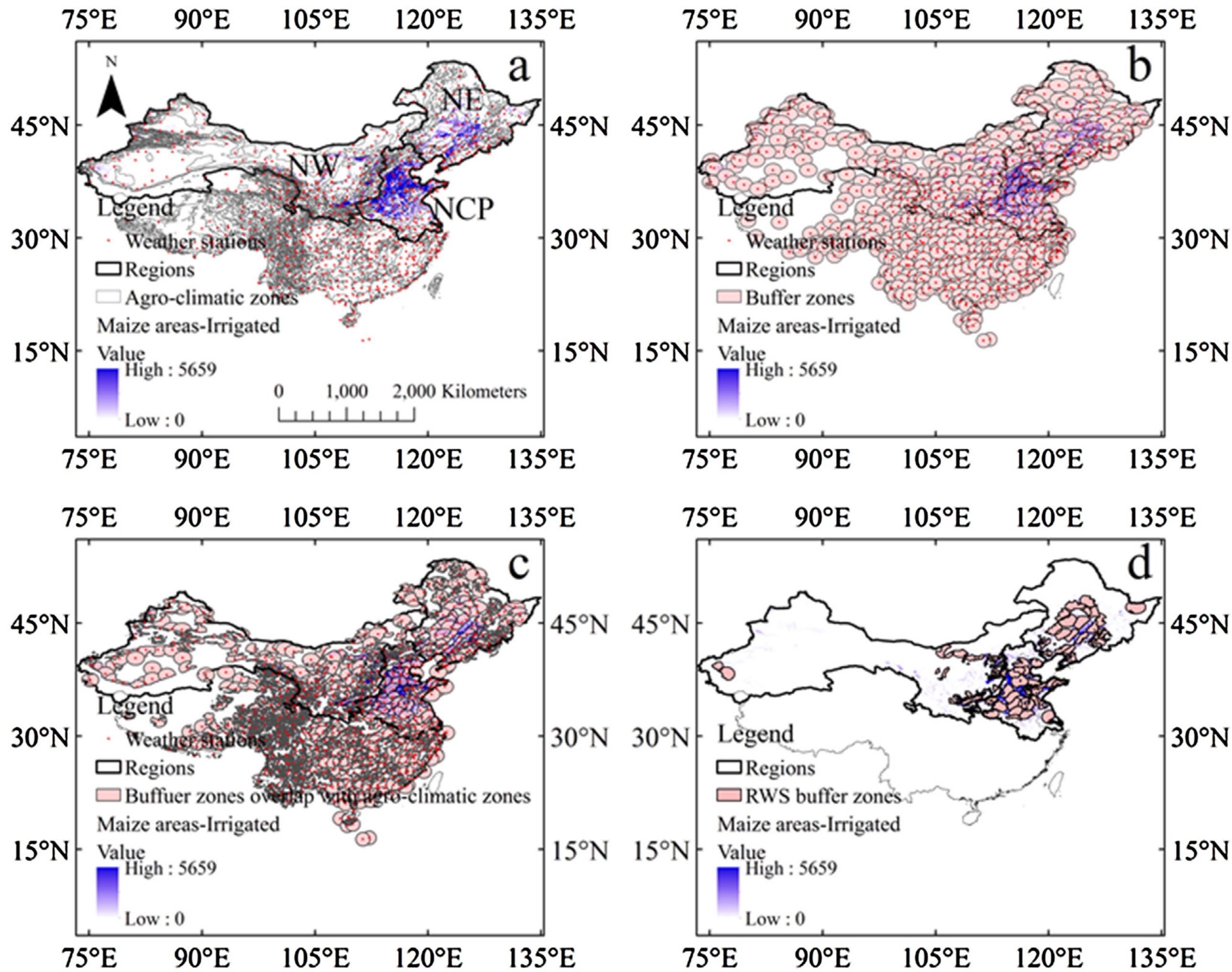

Fig. 1. Selected buffer zones on the harvest areas in the three irrigated maize-growing-regions in China: Northeast China (NE), Northwest China (NW), North China Plain (NCP). (a) Distribution of weather stations with 30 years of weather data since 1985 and harvested areas (hectare) of irrigated maize, agro-climatic zones (CZs) delineated based on the GYGA protocol. (b) Buffer zones with a 100 km radius surrounding a weather station. (c) Overlap the buffer zones with the agro-climatic zones in order to ensure the homogeneity of the agricultural climate in each buffer zones (d) Reference weather station (RWS) buffer zones which selected from the buffer zones according to their covered maize harvest areas from big to small.

Estimating yield potential separately for irrigated and rainfed conditions is important for evaluating the impact of water on food production. Crop yield obtained with no other manageable limitation apart from water supply is the water-limited yield potential (Yw) (Lobell et al., 2009; Fischer, 2015). Irrigation is the essential measure to increase Yw to fully achieve Yp. However, it is often difficult to distinguish irrigated crop areas with the rainfed ones in a large spatial scale. The crop distribution map of the global major crops harvested area is often used in global studies (Mueller et al., 2012), but often at the cost of precision. At the region scale, typical locations are often used to represent both irrigated and rainfed areas (Grassini et al., 2009; Liu et al., 2016). Therefore, estimating crop Yp and Yw separately at a high precision raster map is necessary.

Yield potential for several crops has been estimated in previous studies in various scales including global, regional and farm. A grid-based approach is generally used in the global studies with datasets on climate, soil, agricultural land use and general crop calendars (van Ittersum et al., 2013). The advantage for this global method is that it provides a framework for upscaling. However, many details are ignored because of the large scale. For example, it doesn't distinguish irrigated and rainfed crops (Licker et al., 2010; Foley et al., 2011), or explicitly describe the management information (cropping systems, planting date, cultivar maturity, planting density, etc.) (Neumann et al., 2010; Mueller et al., 2012), or ensure representation of the weather data with model or the yield ceiling with empirical approaches (Foley et al., 2011). In comparison, regional scale studies have the advantage of location-specific environmental conditions and management information, which results in more locally relevant results. However, the region studies usually ignore the upscaling process. For example, Grassini et al. (2009) applied 18 sites to estimate the Yp in Western Corn-Belt of US. Meng et al. (2013) used 50 sites to estimate maize Yp of the whole China with all sites being high-yielding fields from the published literatures. The method to select the sites and their representativeness for a region is worth of further discussion. In order to improve the representation for a region, appropriate upscaling methods should be further considered on the region scale studies.

Two questions should be considered when upscaling locations to a large spatial scale: (1) the homogeneity of the climate, and (2) acquire observed location-specific data. However, the challenge of using a bottom-up approach is the time, expense and access to acquire observed data, e.g., weather data, soil data and crop management data. The Global Yield Gap Atlas Extrapolation Domain (GYGA-ED) aims to estimate the yield gap for major food crops based on locally observed data. The GYGA-ED approach is used in