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# Assessing the harvested area gap in China

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ABSTRACT

Total crop production is a function of the harvested area and the yield. Many studies have investigated opportunities to increase production by closing the yield gap and by expanding cropland area. However, the potential to increase the harvested area by increasing the cropping frequency on existing cropland has remained largely unexplored. Our study suggests that the attainable harvested area gap (HAG) in China ranges from 13.5 to 36.3 million ha, depending on the selected water allocation scenario, relative to the current harvested area of 160.0 million ha. Spatially, South China and the Lower Yangtze region have the largest potential to increase harvested area, as these regions allow triple-cropping, have sufficient water available, and have a good irrigation infrastructure. The results imply that management factors are equally important for exploring the potential against the resource endowment: water allocation has a large impact on both the size and the spatial pattern of the attainable HAG. This indicates the necessity of further examining the spatial-temporal dynamics of HAG at national and regional scales, and its potential contribution to food security and sustainable agricultural development.


## 1. Introduction

In China, providing enough food for its 1.3 billion inhabitants has always been a challenge. Although food import has increased recently, grain self-sufficiency is still the most important agricultural policy goal for the country (Ye et al. 2012; Ghose 2014; Lu et al. 2015). Previous studies have mostly focused on two ways to increase production: increasing yields on existing cropland, and/or bringing new land under cultivation (Fan et al. 2012; Yu et al. 2012). However, neither approach has much potential in China. On the one hand, there has been very little or no growth in yields of Chinese staple crops such as rice, wheat, and maize for the past decade (Ray et al. 2012; Grassini et al. 2013). The "yield gap" – the difference between yield potential and the average farmers' yield – has decreased in the main breadbaskets across China, and the actual yield reaches nearly 80% of the potential yield at the North China Plain, which is much higher than the global average (Li et al. 2014). Considering that climate change may further reduce the potential yield, the possibility for future yield improvement is extremely low (Wang et al. 2014; Tao et al. 2015). On the other hand, although expanding cropland is a straightforward way to increase crop production (Wu et al. 2014), China has lost nearly 10 million hectares of productive cropland from 1990s to 2010s due to rapid urbanization, industrialization, and ecological restoration (Liu et al. 2014). Cropland expansion to increase crop production is undesirable in China, because it may lead to severe environmental consequences, e.g. land degradation, desertification, deforestation, and loss of biodiversity. (Wu et al. 2014; Eitelberg et al. 2015).

Since China is experiencing both extensive yield stagnation and increasing competition for land resources, new approaches are needed to increase China's domestic crop production along with these traditional solutions (Wu et al. 2014). Although the definition and measurement of land use intensity are still under debate, it basically means the increase of productivity on a given cropland, and can be measured from either input or output perspective (Erb et al. 2013). Cropping frequency is one of the core indicators of intensification as increasing the number of crop cycles per year will increase the production. Much cropland in regions where climate conditions are able to sustain multiple cropping, is left fallow or is harvested less frequently than it could be (Ray and Foley 2013; Iizumi and Ramankutty 2015). Consequently, using a concept similar to the yield gap, a harvested area gap exists if the actual harvested area is lower than the potential harvested area within a specific cropping system.

A recent study from Mauser et al. (2015) reported that the earth's current cropland has the potential to double biomass production by increasing cropping intensity. However, this study did not explicitly map

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the gap of cropping frequency and harvested area. Instead, they measured the maximum production potential and then assumed that the lower production was caused by cultivating crops with lower cropping frequency. In addition to this global analysis, independent efforts have been made for mapping potential and actual multiple cropping in China (Liu et al. 2013; Yan et al. 2014; Zuo et al. 2014), which found that more than half the cropland in China is multi-cropped (e.g. triple-cropping in the south and double cropping in the north). However, none of these studies provides an assessment of how much potentially harvested area is left unused in China, and how much this area could potentially contribute to the country's crop production. In this study, we conceptualized the harvested area gap analogous to the yield gap, and present a first assessment of the harvested area gap in China considering both biophysical and management constraints. In addition, we discuss the possibilities for closing the harvested area gap and its relevance for food security and sustainable development.

## 2. Methods

### 2.1. The concept and assessment of harvested area gap

The term yield gap has been widely used in the literature over the past few decades to express the difference between the average actual yield ($Y_a$) and the potential yield ($Y_p$) (Lobell et al. 2009; van Ittersum and Cassman 2013). The yield gap is typically expressed in Mg ha$^{-1}$ (Lobell et al. 2009) and sometimes as a ratio (%) (Zhang et al. 2016). To better understand how $Y_p$ is related to $Y_a$, an attainable yield ($Y_t$), or sometime referred as exploitable yield, has been introduced to quantify how various factors reduce $Y_p$ (van Ittersum et al. 2013). Consequently, the yield gap consists of an unattainable yield gap (the difference between $Y_t$ and $Y_p$) and an attainable yield gap (the difference between $Y_t$ and $Y_a$). $Y_t$ may vary in different assessments depending on which constraining factors are considered. Some studies have considered water as the only factor to determine the attainable yield, while others have included more factors such as nutrient availability (Fig. 1).

By analogy to the yield gap, the harvested area gap (HAG) can be conceptualized as the difference between the actual harvested area

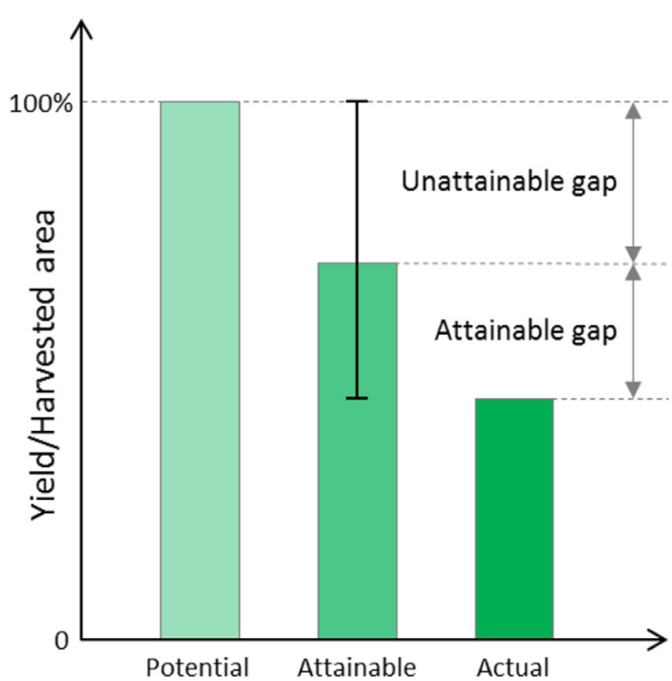


**Fig. 1.** Illustration of yield gap and harvested area gap, and the role of attainable yield/harvested area, modified from van Ittersum and Cassman (2013).

($HA_a$) and the maximum harvested area potential ($HA_p$) in a given spatial unit, expressed in hectares. Accordingly, the attainable harvested area ($HA_t$) can be used to quantify the influence of various constraining factors on the exploitation of $HA_p$. The HAG can be decomposed to unattainable HAG (differences between $HA_t$ and $HA_p$) and attainable HAG (differences between $HA_t$ and $HA_a$). Similar to the attainable yield ($Y_t$), the estimation of $HA_t$ varies depending on which constraining factors are considered (Fig. 1). Sown area is different from harvested area when not all sown area is harvested. We use harvest area in this study, because using the sown area does not allow to differentiate between attainable and unattainable parts, while harvested area does.

The HAG is determined by three factors: the maximum potential cropping frequency, the current cropland area and the currently harvested area (Fig. 2). While the cropping frequency only measures the number of annual harvested cycles, HAG focuses the value of harvested area that combines this frequency with the cropland extent. Although the estimation of HAG is relatively straightforward, the estimation of attainable HAG is more complicated because the influence of various constraining factors on the exploitation of $HA_p$ needs to be quantified. Similar to the measurement of attainable yield gap the $HA_t$ can be assessed in a step by step manner starting from the estimation of $HA_p$, and subsequently reducing this number based on constraining factors.

In this paper, the HAG is calculated for China for grain crops. Moreover, the attainable HAG is estimated based on water availability and water allocation schemes, as key determinants constraining the HAG. This assessment is based on the water requirements of a generic crop to estimate how much additional harvested area is attainable. We acknowledge that other factors may further constrain the full exploitation of $HA_p$. However, these have not been assessed in this study due to the unavailability of spatial datasets at the scale of China to make such an assessment possible. The flowchart of the study is shown in Fig. 2.

### 2.2. Data preparation

We estimate the HAG for the year 2005, because this is the only year for which all the required datasets are available. The analysis was performed in a spatially-explicit way, based on the SPAM dataset (Spatial Production Allocation Model, see www.mapspam.info), with grid cells at a 5 arc-minute resolution (roughly 9 × 9 km at the equator). SPAM is a global level spatial model of crop allocation, which estimates harvested area, irrigation area, and unit yield for 42 crops at a grid level and reveals spatial patterns of crop performance, creating a global gridscape at the confluence between geography and agricultural production systems (You et al. 2014). The quality of SPAM is evaluated as good and is particularly high in China (Tan et al. 2014). Details for this dataset are provided in the SI. Several SPAM results have been used for this study: the harvested area for individual crops is summed up to obtain the total harvested area in each grid cell; the irrigated area is used for measuring the conditions of irrigation infrastructure.

The cropland mask is derived from the global IIASA-IFPRI cropland map, which indicates the percentage of cropland per pixel for the baseline year 2005, based on an integration of existing cropland maps at global, regional and national scales (Fritz et al. 2015). The cropland mask has been used by SPAM as an input, which means a conversion from cropland percentage to area has been made to enable the intercomparison of the cropland and the crop allocation layers. The multi-cropping system map is adopted from Yang et al. (2015), and is overlaid with the cropland mask to represent the theoretical ceiling of harvested area. The monthly temperature, cloud cover, and relative humidity from the global gridded climate time series data CRU TS 3.22 (Harris et al. 2014) are used to calculate crop irrigation depth, based on the reference evapotranspiration (ET) with the Priestley-Taylor method. Data on the availability of additional water is available at the river basin level from the National Water Resource Planning Report by the Chinese Ministry of Water Resources. Water allocation schemes are designed to relocate water from river basin to grid cells, so that the grid level irrigation