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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 (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.

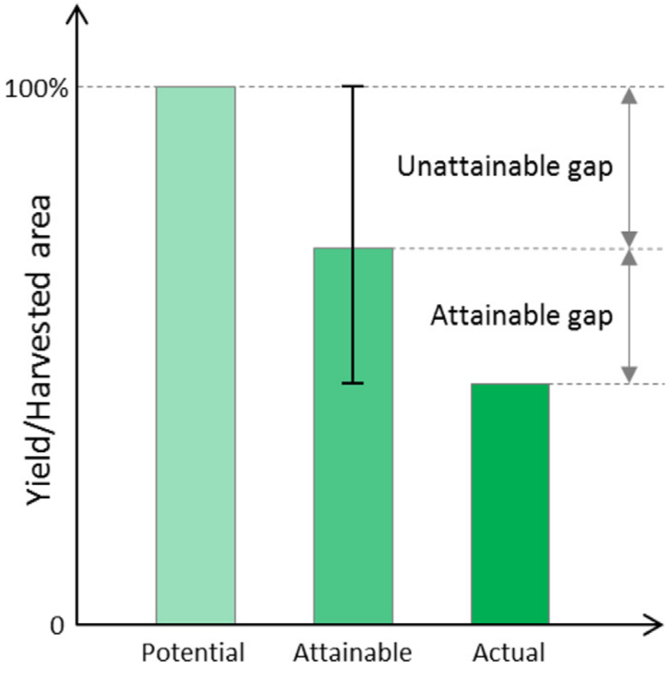


Fig. 1. Illustration of yield gap and harvested area gap, and the role of attainable yield/harvested area, modified from van Ittersum and Cassman (2013).

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

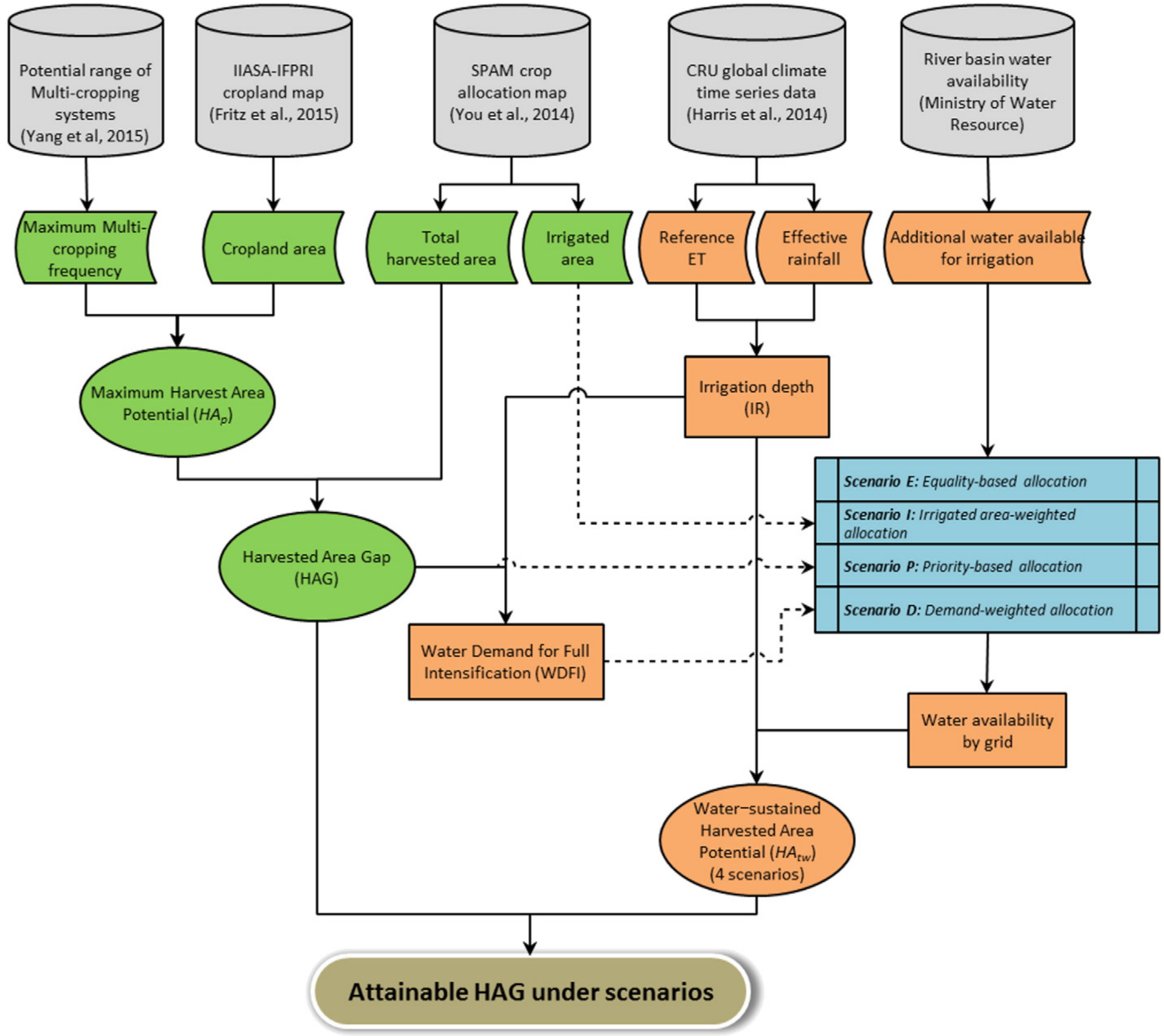


Fig. 2. Flowchart indicating the procedure for the harvested area gap analysis and the datasets applied in this study for China. Gray indicates the data input; green indicates the intermediate estimations of HA_p and HAG; orange indicates the estimation of HA_t under water constraint; blue indicates the scenario design for water relocation.

depth can be compared with the additional water availability to present the water constraint on increasing cropping frequency. Finally, the ability for increasing cropping frequency was assessed based on the Cropping System Regionalization by the Chinese Ministry of Agriculture, to inform the regional priority and agricultural policy design in increasing multi-cropping. The use of these datasets is briefly illustrated in Fig. 2 and details about the data are elaborated in the SI.

2.3. Procedure of the harvested area gap analysis

The procedure followed for analyzing the HAG based on the spatially-explicit data is presented in Fig. 2. Within this procedure, the following factors are calculated:

Maximum Harvested Area Potential (***HA_p***) indicates the maximum cropping area that can be achieved in a given spatial unit, by considering the double- and triple-cropping opportunities for the given cropland area. Specifically:

$$HA_{pi} = L_i \times MCI_i \tag{1}$$

Where L_i is the cropland area within a particular grid cell i; MCI_i is the maximum multi-cropping index within a particular grid cell, and i represents the grid ID.

Harvested Area Gap (***HAG***) represents the difference between HA_a and the HA_p. HAG in each grid cell can be calculated as:

$$HAG_i = HA_{pi} - HA_{ai} \tag{2}$$

Where HA_{ai} is the actual harvested area within a particular grid cell, obtained from SPAM dataset.

Table 1
Scenario setting for analyzing attainable harvested area gap determined by water allocation schemes.

Scenario	Scheme	Rational
Priority-based (P)	Grid cells with higher intensity area gap are given the priority to receive water	To improve the efficiency of building new irrigation infrastructure
Demand-weighted (D)	Using grid level water demand under full intensification as weight	To equalize crop water stress across grid cells when water shortage presents
Equality-based (E)	Irrigation water is equally distributed across grid cells	Not considering water competition among administrative units
Irrigated area-weighted (I)	Using current irrigated area as weight	Assuming that grid cells with more irrigated area are more likely to have a better irrigation infrastructure and therefore need less additional investment and have higher possibility to receive water

The HAG is calculated based on grid cells which are then summed up for presenting a national/regional level overview. In some cases – if the HA_a is higher than HA_p, which is possible owing to greenhouse agriculture or data errors – the negative HAG value will be set to zero to indicate that such grid cell has already approached its maximum cropping frequency.

Irrigation depth (***IR***) refers to the depth of additional water needed for the potentially harvested area to meet crop evapotranspiration requirements (expressed in mm), considering the actual effective rainfall. In most cases, the additional water is obtained through irrigation, which is estimated using the following equation for a generic grain crop:

$$IR(t)_i = \begin{cases} ET_0(t)_i - P_{eff}(t)_i, & ET_0(t) \geq P_{eff}(t) \\ 0 & ET_0(t) < P_{eff}(t) \end{cases} \tag{3}$$

Where IR stands for irrigation depth for a particular grid cell, ET_0 for reference evapotranspiration, and P_{eff} for effective rainfall. The time interval of calculation is monthly, represented by t. The final value adopted in the assessment is the yearly average. Detailed description can be found from the SI.

Water-sustained Harvested Area Potential (***HA_{tw}***) represents the extra harvested area that can be sustained based on water availability. HA_{tw} is determined by water availability and water allocations schemes in this study. It is calculated at the grid level using irrigation depth and water availability allocated to grid cells:

$$HA_{twi} = WA_i / IR_i \tag{4}$$

Where WA is the water availability within a particular grid cell. The water allocation scheme follows the scenarios below.

Attainable HAG represents the exploitable area gap after water constraints are considered. The minimum value of either HAG_i and HA_{tw} will be retained as the final attainable harvested area gap:

$$AttainableHAG_i = \min(HAG_i, HA_{twi}) \tag{5}$$

2.3.1. Water availability and allocation scheme design

Water allocation is a major limiting factor for crop intensification (Matson et al. 1997). A complete assessment of HAG therefore needs further information of crop water requirements and deficits as well as water availability for irrigation. With an adequate storage and conveyance infrastructure, water can be redistributed within a river basin. Therefore, we designed four scenarios of water allocation, to examine the consequences of these allocation schemes for limiting HAG. These scenarios are named as *Priority-based allocation* (*P*), *Demand-weighted allocation* (*D*), *Equality-based allocation* (*E*), and *Irrigated area-weighted allocation* (*I*) respectively (see Table 1).

Except *Scenario P*, in which grid cells with higher HAG are given the priority to receive water to meet the full requirement of irrigation until the additional water in the river basin is completely distributed, the other three scenarios use a weighting factor to allocate the available water within a given river basin:

$$WA_i = \frac{A_i \times WA_{riverbasin}}{\sum\limits_{riverbasin} A_i} \tag{6}$$

Where A is the weighting factor, alternatively being the water demand for full intensification (*Scenario D*), grid size (*Scenario E*), or current irrigation area (*Scenario I*), depending on different scenarios.

In *Scenario I*, water is allocated based on the current irrigation pattern. With that assumption, grid cells with higher irrigation area are more likely to have better irrigation infrastructure and therefore need less additional investment. *Scenario I* is regarded as the most realistic water allocation scenario. To calculate the capacity to increase cropping frequency, we have divided the HAG_I (attainable HAG under *Scenario I*) by the HAG, and referred this as attainable HAG fraction hereafter (Table 2 and Fig. 4).

3. Results

3.1. Maximum harvested area potential

When the full multi-cropping potential in China is used, the HA_P is 236 million ha. This is about 1.80 times the current cropland area and

Table 2
Summary of the harvested area gap analysis at the national/regional level.

Cropping regions	Cropland (Million hectares)	HA_a	HA_p	HAG[a]	HAG_P	HAG_D	HAG_E	HAG_I	Current cropping frequency	Attainable HAG fraction[b]
NE	24.2	18.9	24.5	6.9	4.4	3.7	1.6	1.0	0.78	0.14
N Plateau	19.5	14.9	20.8	8.1	0.7	0.8	0.5	0.1	0.76	0.02
NW	5.8	4.2	5.8	2.3	0.0	0.0	0.0	0.0	–	–
N Plain	29.4	39.5	58.6	19.8	0.4	0.2	0.1	0.1	1.35	0.01
Tibet Plateau	0.6	1.7	0.6	0.2	0.0	0.1	0.1	0.0	–	–
Lower Yangtze	16.5	24.6	38.2	14.6	6.3	5.3	2.2	4.3	1.50	0.30
SW Basin	9.9	14.6	19.5	5.8	4.1	4.1	2.1	1.0	1.47	0.18
S Hills	9.0	16.3	26.6	11.0	7.2	7.0	4.0	3.7	1.81	0.34
SW Plateau	9.0	11.8	19.7	8.5	6.4	6.2	3.5	0.9	1.31	0.11
S Tropics	7.1	13.4	21.2	8.8	6.6	6.3	4.1	2.2	1.88	0.26
China	**131.0**	**160.0**	**235.6**	**86.1**	**36.3**	**33.7**	**18.2**	**13.5**	**1.22**	**0.16**

[a] The HAG is calculated based on grid cells that are then summed up for presenting the national/regional level overview. At the national/regional level, the HAG can be higher than the gap between HA_p and HA_a, because negative HAG values at the grid level have been set to zero (see Section 2.3).

[b] Attainable HAG fraction represents HAG_I divided by HAG (see Section 2.3).

1.50 times the current harvested area (Table 2). The higher HA_P areas are mainly distributed in part of the North China Plain and the Lower Yangtze Plain (Fig. 3a). Both regions are considered as important breadbaskets in China, as these areas not only have good climatic condition to allow multi-cropping, but they are also heavily cultivated currently (see SI, Fig. S2).

3.2. Harvested area gap

While the theoretical cropping frequency (i.e. HA_p divided by cropland area) for the country as a whole is as high as 1.80, the current cropping frequency (i.e. HA_a divided by cropland area) in China is roughly 1.22. This suggests that there is room to increase the cropping frequency in China. The total HAG in China is approximately 86 million ha, which is over 50% of the *current harvested area*. Although high HA_p area were mainly located in North China Plain and Yangtze Plain, higher HAG are mainly found in the Lower Yangtze Plain and parts of the North China Plan while other areas are already cultivated close to the maximum cropping frequency. Moreover, HAG > 0 can be found in many single-cropping areas in Northeast and Northwest China, suggesting that a certain amount of cropland there might have been left uncultivated, abandoned, or under fallow (Fig. 3b and Fig. 4a).

3.3. Attainable harvested area gap under different water allocation scenarios

In the *priority-based allocation scenario* (HAG_P), HAG values of grid cells in a basin are ranked in descending order and additional available water is allocated to fully meet irrigation water requirement of the grid cell with the highest HAG, and then to the one with the second highest HAG, and so forth. Results show that the HAG_P is concentrated in Northeast and South China as both regions have a relatively high HAG and are able to provide additional water for crop intensification. Many other large areas cannot increase cropping frequency due to water shortage (Fig. 3c and Fig. 4b). Estimated total HAG_P is about 36.3 million ha, the highest among all the scenarios considered in this study (Fig. 4b and Table 2).

The *demand-weighted allocation scenario* (HAG_D) allocates additional water in a basin to grid cells proportional to full intensification irrigation water requirement (i.e. HAG multiplied by irrigation depth). The spatial pattern of the results of *Scenario D* is very similar to that of *Scenario P*, but water is allocated to more grid cells (Fig. 3d), because each grid cell within a water abundant river basin can get a certain amount of water, regardless of the magnitude of their HAG values. Consequently, the total HAG_D is about 33.7 million ha, slightly less than HAG_P (Fig. 4b and Table 2).

In the *equality-based allocation scenario* (HAG_E), water is allocated evenly across grid cells within a river basin, thereby the water competition among administrative units is ignored. No clear pattern could be found from *Scenario E*. In addition, almost all the grids keep a relatively low attainable HAG, and the total HAG_E is much less than HAG_P, about 18.2 million ha (Fig. 3e, Fig. 4b and Table 2).

The *irrigated area-weighted allocation scenario* (HAG_I) assumes that grid cells with higher existing irrigated area are equipped with better irrigating infrastructure, thereby water is allocated across grid cells in a river basin in proportion to their current irrigated area. The spatial pattern of *Scenario I* allocation is very clear: high HAG_I grids are mainly distributed in the Central-South regions, while HAG_I in other regions are very low (Fig. 3f). This is because the Central-South regions have not only relative higher HAG, but also sufficient water supply and irrigation infrastructure. The total HAG_I is about 13.5 million ha, the lowest among all the scenarios (Fig. 4b and Table 2).

3.4. Harvested area gap in the major cropping regions

For an overview of the above results, we summarized the gridded results for the 8 cropping regions in China (see SI, Fig. S5). The South Tropics have the highest actual cropping frequency (1.88), followed by the South Hills (1.81) and Lower Yangtze (1.50). The cropping frequency in Northeast (0.78) and North Plateau (0.76) are below the national average (1.22) (Fig. 4a). The Northwest and Tibet Plateau are excluded from the assessment as they are not major grain-producing zones and they have little potential for intensification (Table 2).

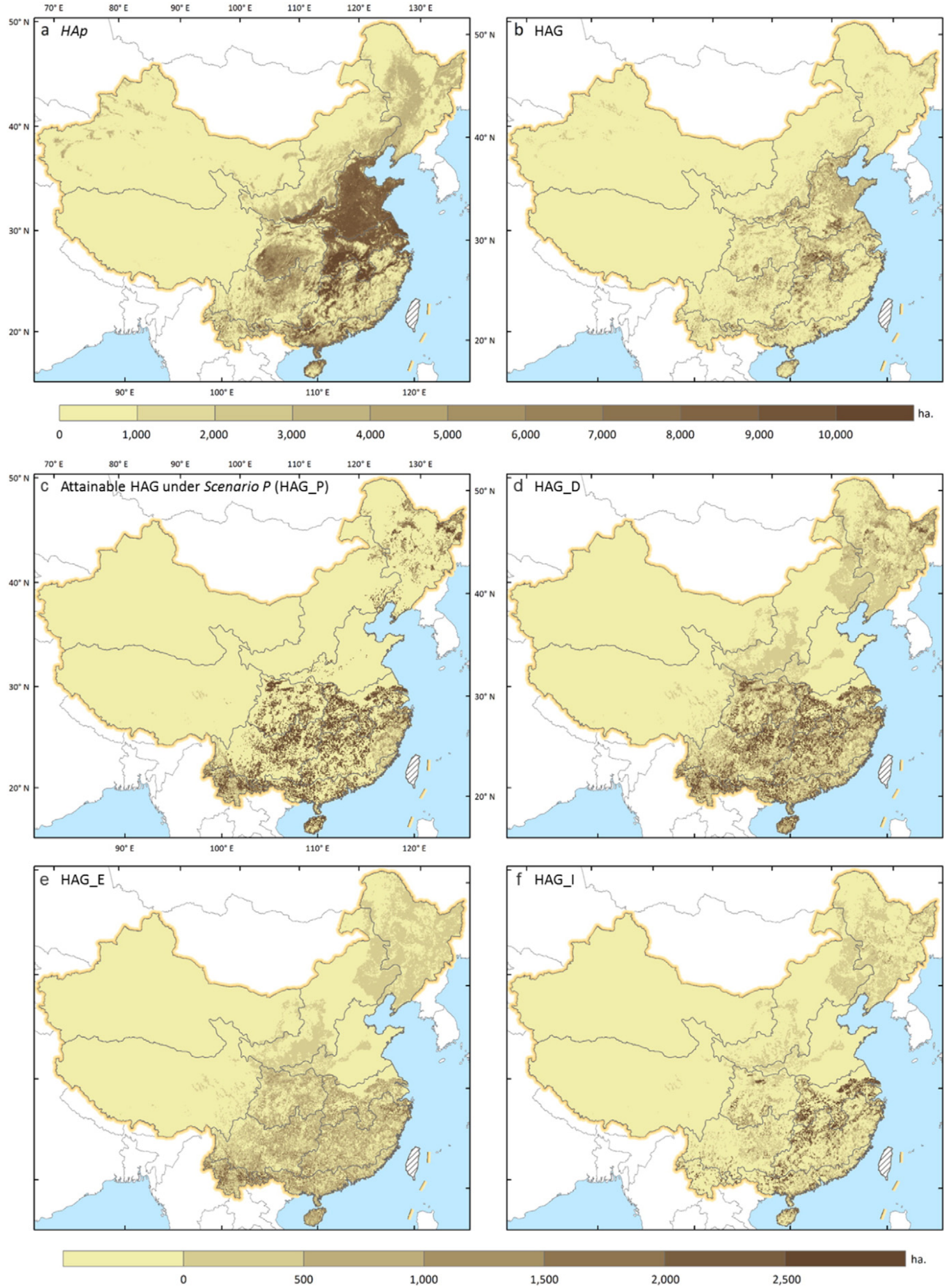
The HAG was divided by the results of *Scenario I* to assess the Attainable HAG faction. We found that the South Hills and Lower Yangtze regions have the highest potential for intensification. The Northeast, Southwest Plateau, and Southwest basin could improve their investment in infrastructure, because the low irrigation support capacity – represented by the relatively low irrigation area – strongly limits the increase of cropping frequency in these regions (Fig. 4b and Table 2).

4. Discussion

4.1. Assumptions and uncertainties in the HAG assessment

The presented assessment is based on a number of assumptions, from which we first estimate a potential ceiling. This analysis is followed by a gradual revision on this ceiling, by considering water availability and water allocation schemes as constraining factors (similar to yield gap analysis). The assumptions are: first, we did not consider the crop mix and the role of greenhouse agriculture. Instead, a generic field crop was applied for estimating the potential range of multi-cropping systems and for estimating the irrigation depth. Although this generic crop simplifies the assessment, it might overlook some details such as specific crop allocation and rotation. For example, the irrigation depth was estimated on a monthly basis for a whole year. However, due to the lack of seasonal crop allocation and crop rotation information at the grid level, using the whole year irrigation depth instead of the specific crop growing season could overestimate the constraint of water resource, and thus underestimate the attainable HAG. Second, the irrigation efficiency varies from place to place (Nair et al. 2013). We did not take this into account for estimating the attainable HAG because grid level irrigation efficiency is not available, which may underestimate the water constraint and thus overestimate the attainable HAG. These two factors, respectively over and under-estimating the impacts of water availability, might offset each other and the final results might not be affected significantly. We quantify the influence of irrigation efficiency by adopting the average river basin level values (Robinson et al. 2015) (see SI for details) in *Scenario I*: the attainable HAG for China was reduced to 9.3 Mha, comparing to 13.5 Mha, the assessed HAG_I without considering irrigation efficiency as a constraining factor (Table 2). This implies further studies are required for a comprehensive consideration on the current irrigation status, practices, challenges, as well as the differences between irrigation requirements for different cropping practices (e.g. paddy rice in the south vs maize in the north). Third, we assume that all additional water could be used to increase the cropping frequency. However, water usage for agriculture in China increased only marginally since the late 1980s, suggesting difficulties in using more water for irrigation. This is at least partly caused by a competition for water from other sectors, despite the surplus in water

Fig. 3. Upper part: spatial distribution of HA_p (a) and HAG (b) across China. Lower part: spatial distribution of attainable HAG under different water allocation scenarios: (c) *Priority-based allocation*, (d) *Demand-weighted allocation*, (e) *Equality-based allocation*, and (f) *Irrigated area-weighted allocation*. The values indicate hectares of per 5 arc-minute grid cell. Details about the water allocation scenarios can be found in Section 2.3 high resolution, large versions of the maps can be found in SI.


a HAp
b HAG
c Attainable HAG under Scenario P (HAG_P)
d HAG_D
e HAG_E
f HAG_I
70° E
80° E
90° E
100° E
110° E
120° E
130° E
50° N
40° N
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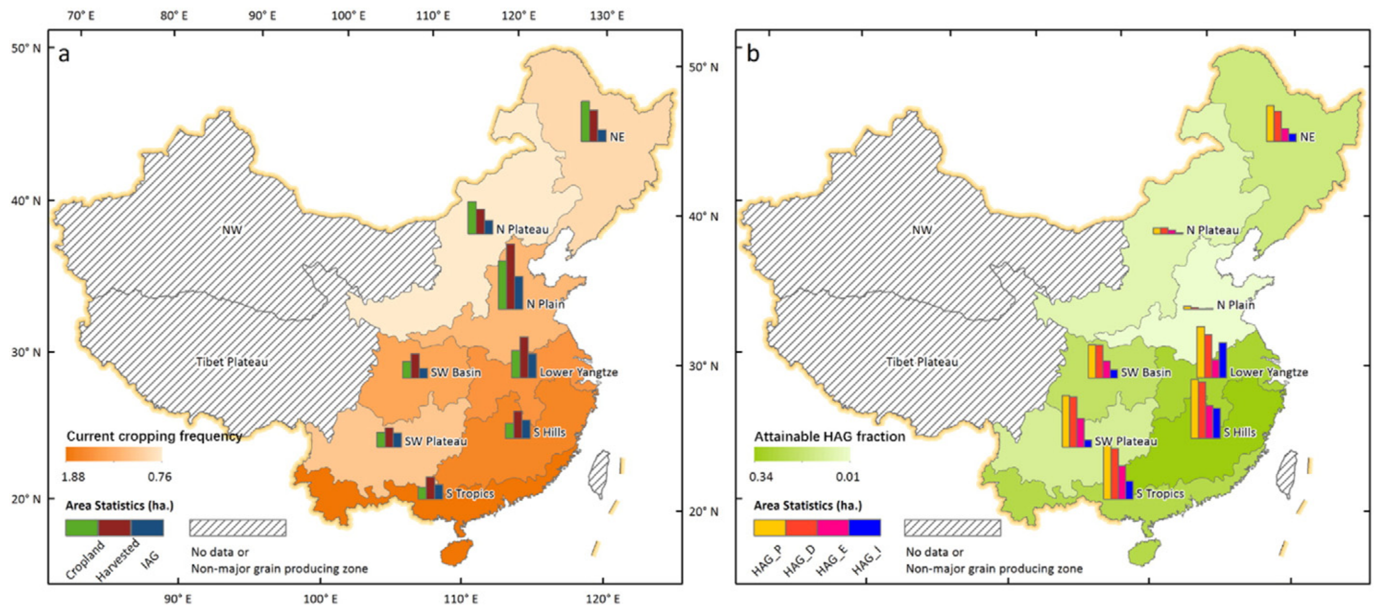

Fig. 4. Harvested area gap assessment for the major cropping regions in China: (a) actual frequency, cropland area, harvested area, and harvested area gap; and (b) attainable harvested area gap under the four water allocation scenarios and attainable HAG fraction. The values of the bars are presented in Table 2. The concept of attainable HAG fraction is elaborated in Section 2.3 and footnote of Table 2.

availability in some river basins. Thereby, our estimation on the attainable HAG represents an ideal situation, and the real-world water constraint could be more limiting. The size of the river basin has not been considered directly in this analysis: in large basins it may not be practical to transfer the basin's available water to remote grid-cells. However, the irrigation pattern in *Scenario I* indirectly reflects that the remote area may unable to receive water. Moreover, China has already launched the South-to-North Water Diversion Project, which diverts water across river basins and thus challenges our assumption that water can only be reallocated within a river basin. This might affect the spatial pattern of attainable HAG. However, we believe it is too early to take this factor into account for the current assessment, because the consequences of this project are still debatable (Barnett et al. 2015).

Uncertainty in some of the assumptions made in the assessment may have impact on our estimates of attainable HAG. In absence of more information (with sufficient spatial detail) to refine the assumptions, we have tested the sensitivity of a number of potential uncertainties on the estimated ranges of results. Specifically, we considered the sensitivity towards three factors, independently, relative to HAG as determined in the *Scenario I*, by using the values of national level average, but without considering their spatial heterogeneities: irrigation efficiency (the regional-level values are presented in Table 3), crop-specific evapotranspiration, and land fallow (Fig. 5). The results suggest that crop-specific evapotranspiration causes the greatest uncertainty, increased land fallow within crop rotations will potentially lead to a notable decrease of HAG, while irrigation efficiency has relatively little influence. This implies that an inappropriate crop choice would not only lead to a lower yield, but may also pose greater challenges to the environment as it requires more water. At the same time, the practice of land fallow, which is believed necessary to prevent soil depletion in many cropping systems (Kassam et al. 2009), would influence the attainable HAG considerably, even if the land has only one fallow year in every five years. This implies that land use pressure would increase considerably when China rests their soils for conservation agriculture, while improving irrigation efficiency only has a marginal effect. Therefore, adopting rotation with difference crop types, which is a very common practice in China (Frolking et al. 2002), may have better outcomes than land fallow (Swinkels et al. 1997). To summarize, most of the uncertainty exists because information on the crop configuration in both time and space are insufficient. Further research on the spatial and temporal configuration of cropping patterns and its related biogeochemical processes, such as soil depletion and crop specific irrigation efficiency, would help improving future HAG analyses.

4.2. The implication of the HAG

Sustainable intensification of agricultural production is a means to increase food security without the negative consequences of cropland expansion (Smith 2013; Wu et al. 2014). However, most existing studies only explain the potential and pathways for increasing crop yield (i.e. closing the yield-gap) from an agronomic perspective (Fan et al. 2012; Mueller et al. 2012). From the geographical perspective though, attention has been paid to land use intensity based on the measurements of biomass or NPP (Mauser et al. 2015; Maria et al. 2016), or to the annual cropping frequency (e.g. multi-cropping index) based on counting the peaks of vegetation indexes from time-series of remote sensing images (Ray and Foley 2013). While these studies identify areas with lower land use intensity, they do leave the "gap" undiscussed, e.g. the gap of cropping frequency and its corresponding amount of harvested area as well as the corresponding production increase that can be attained. Moreover, cropping frequency alone cannot be used directly in food security assessment, because a higher cropping frequency does not necessarily directly translate into a higher harvested area, as it also depends on how much cropland the unit currently has. As a new approach for the study of agricultural intensification, the analysis of HAG is able to explicitly indicate the locations where additional harvested area is possible. Closing the HAG could yield the same benefits as cropland expansion, but with less environmental impacts, such as a loss of aboveground biomass or habitat (Eitelberg et al. 2016).

In this study, the HAG and attainable HAG are calculated to identify the locations that have the potential to increase the harvested area, given their biophysical (e.g. climate) and socioeconomic constraints (e.g. policy and infrastructure). It shows that China's cropping frequency is able to reach 1.50, relative to its current frequency of 1.22, which would add 36.3 million ha harvested area. A comparable study from Zuo et al. (2014) suggested that the actual multi-cropping frequency in China is 1.53, based on a remote sensing approach, and the potential multi-cropping frequency is 1.75 based on a stochastic frontier analysis.

Table 3
Influence of irrigation efficiency (IE) on the attainable HAG under *Scenario I*.

	NE	N Plateau	N Plain	Lower Yangtze	SW Basin	S Hills	SW Plateau	S Tropics	Total
Perfect IE	1.0	0.1	0.1	4.3	1.0	3.7	0.9	2.2	13.5
Actual IE	0.6	0.1	0.1	3.2	0.6	2.5	0.6	1.6	9.3

These values – both at the country level value and in the spatial patterns – are higher than our estimation. The peak-counting approach based on remote sensing images applied in Zuo et al. (2014) may indicate the gross cropping frequency because each pixel reflects a mixed ground features including crop and non-crop vegetation, while the SPAM dataset applied in our study presents the net harvested area per grid cell. This implies that different approaches result in different estimates of the actual and the potential and thus identifies a knowledge gap that requires further assessment. Based on the current study, we are able to identify the locations with lower cropping frequency, but also the potential increase in harvested area that is attainable under different water allocation, crop choice and irrigation strategies. These results provide directions for improving the existing (in)efficiency assessments on regional agricultural land use to guide more effective agricultural policies for intensification (Neumann et al. 2010).

The potential increasing production as a consequence of filling the HAG depends on selected crop types and management options. To get a more realistic estimation of potential production increase, the actual crop distributions at the grid level were obtained based on the harvested area of each crop. Using this distribution of crop types and their corresponding yields to fill the HAG would increase the crop production between 96 (*Scenario I*) and 290 (*Scenario P*) million ton. This corresponds to an increase between 16% and 48% relative to the current production of 597 million ton. However, increasing the cropping frequency often requires a different selection of crop types and crop cultivars, which most likely have lower yields than the crops and cultivars that are used currently. Therefore, these values can be considered as an upper ceiling and the increased crop production upon filling the HAG is expected to be lower in reality.

This study has shown, with earlier studies, that the current cropland extent has a large potential to increase biomass production by increasing cropping intensity and implementing more efficient spatial allocation of crops. Yet, multiple environmental and socioeconomic constraints hinder the full exploration of these potentials, and the trade-offs between intensification and environmental impacts at a broader-scale remain largely unassessed. Intensified agriculture has put an enormous pressure on available resources such as land, water, and even social capitals (Smith 2013). Further increasing the harvested area might be unfeasible or undesirable in some locations, because fallow or uncultivated land is sometimes required in crop rotations for soil restoration and nutrient balancing. Sustainable intensification should consider the interactions between crop production, carbon storage, habitat provision, social welfare, and other ecosystem services (Garnett et al. 2013).

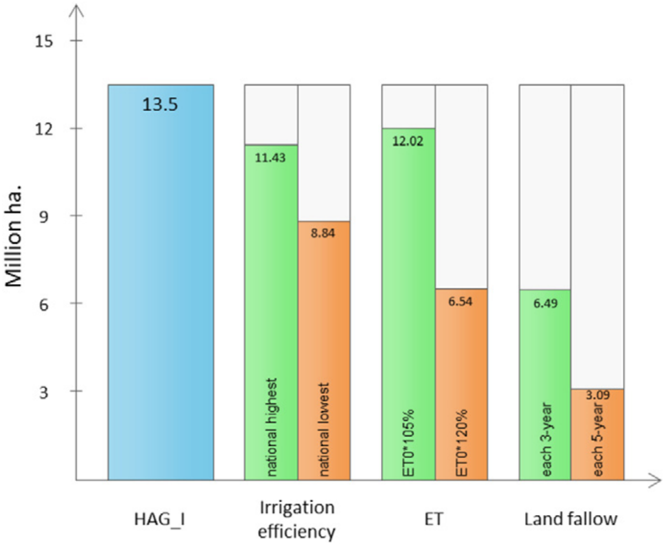

Fig. 5. The influence of irrigation efficiency, crop-specific evapotranspiration (ET), and land fallow relative to the attainable HAG under *Scenario I*. The parameters for irrigation efficiency are the highest (70.9%) and lowest (47.4%) in China respectively (Robinson et al. 2015), see SI; for crop-specific ET are 105% and 120% times of ET0 respectively (Allen et al. 1998); and for land fallow are one year complete fallow in each third and each fifth year, respectively.

5. Conclusions

We conceptualized HAG as an indicator that combines the state of climate potential, existing cropland and currently harvested area. We considered water as the most critical biophysical constraint for the attainable HAG, which has been assessed through four different water allocation schemes in this study. Results suggested that the attainable cropping frequency can as high as 1.50 on average across China, standing between the theoretical ceiling of 1.80 (without water constraint) and the current frequency of 1.22. This corresponds to a 13.5–36.3 million ha attainable HAG, equal to between 8% and 23% of currently harvested area in China. Our results suggest that infrastructure and management are as important as resource endowment: different water allocation strategies result in considerable variations of the attainable HAG. Our assessment also indicates that there are many constraints on closing the HAG and raises the necessity of relevant data to facilitate the follow-up studies to better assess the potential of constraints and their spatial distribution.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.agsy.2017.02.003.

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