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Global cropping intensity gaps: Increasing food production without cropland expansion

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ABSTRACT

To feed the world's growing population, more food needs to be produced using currently available cropland. In addition to yield increase, increasing cropping intensity may provide another promising opportunity to boost global crop production. However, spatially explicit information on the cropping intensity gap (CIG) of current global croplands is lacking. Here, we developed the first spatially explicit approach to measure the global CIG, which represents the difference between the potential and actual cropping intensity. Results indicate that the global average CIG around the year 2010 was 0.48 and 0.17 for the temperature- and temperature/precipitation-limited scenarios, respectively. Surprisingly, global harvest areas can be expanded by another 7.36 million km^2 and 2.71 million km^2 (37.55% and 13.83% of current global cropland) under the two scenarios, respectively. This will largely compensate the future global cropland loss due to increasing urbanization and industrialization. Latin America has the largest potential to expand its harvest area by closing the CIGs, followed by Asia. Some countries in Africa have a large CIG, meaning that some additional harvests can potentially be achieved. Our analysis suggests that reducing the CIG would provide a potential strategy to increase global food production without cropland expansion, thus also helping achieve other Sustainable Development Goals such as biodiversity conservation and climate change mitigation.

1. Introduction

The Sustainable Development Goals of the United Nations adopted in 2015 articulate a road map to "the future we want" in terms of human welfare and environmental sustainability (Obersteiner et al., 2016; Gao and Bryan, 2017). One of these 17 ambitious goals is to end global starvation and achieve zero hunger by 2030. However, this goal faces great challenges as global demand for food production continues to increase due to global population growth, changes in diets, and biofuel consumption (Godfray et al., 2010; Kastner et al., 2012). Several estimations show that global agricultural production may need to grow by 70–110% to meet the increasing demands associated with human uses and livestock feed by 2050 (Alexandratos, 2009; Tilman et al., 2011). This requires searching for effective strategies to raise future food production (Erb et al., 2016).

Agricultural land expansion or extensification has made a great contribution to past increases in global food production (Macedo et al., 2012; Levers et al., 2016). However, further extensification of cropland in future, often through altering natural ecosystems through land clearing, seems to be unlikely because cultivation of this potentially available land is at odds with efforts toward biodiversity conservation, greenhouse gas emission mitigations, and the management of regional climate and hydrological changes, and would incur high costs associated with the provision of necessary infrastructure. Thus, the most likely scenario is that more food needs to be produced from the same amount of (or even less) land through the intensive use of cropland (Wu et al., 2014a,b). Agricultural intensification is normally achieved either by increasing the yield per unit area of individual crops or by increasing the number of crops sown on a particular area of land, or both (Gregory et al., 2002).

Numerous studies have revealed a large yield gap and proposed solutions for closing this gap by growing adoption/application of fertilizers, irrigation, mechanization, and improved seed varieties (Licker et al., 2010; Neumann et al., 2010; Mueller et al., 2012; Kravchenko et al., 2017). However, while acknowledging the great implications of crop yield growth for global food security, some scientists doubt its ability to meet increasing future food demand (Pugh et al., 2016). Although yields continue to increase in many areas, yields also either

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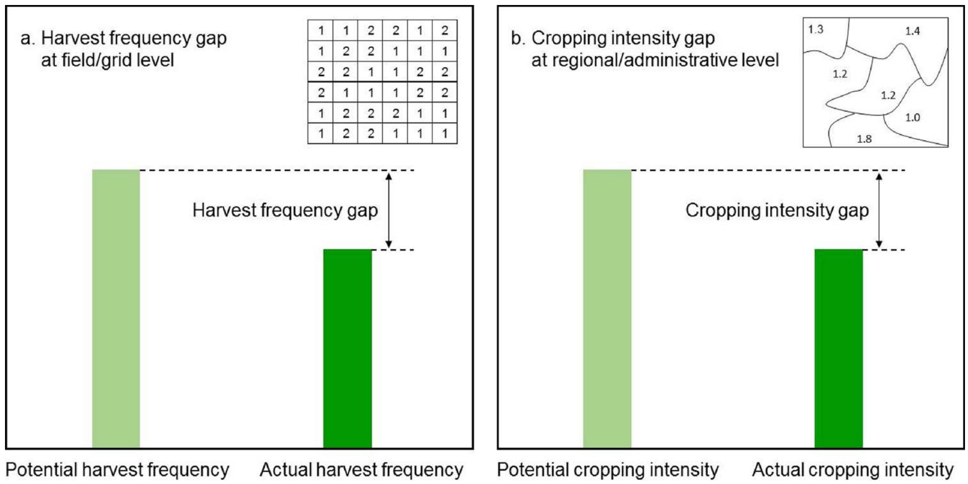

Fig. 1. Illustration of the concept of harvest frequency and cropping intensity gap.

never improve, stagnate, or collapse in other areas (accounting for about 25% of global croplands) (Ray et al., 2012; Grassini et al., 2013). Projections on future yields found that yield increase is obviously less than the expected annual growth rate required to double global production by 2050 (Ray et al., 2013). This could be the real future situation because it becomes more difficult to sustain further yield increases as farmers' yields approach the potential threshold. Furthermore, how best to close the yield gap largely depends on the capacity of local farmers to access and use seeds, water, nutrients, pest management, soils, and knowledge, all of which face considerable technical and/or market constraints, such as high input costs or low returns from increased production. Closing yield gaps is also associated with uncertain impacts on the environment and the potential for negative feedback effects that could undermine future food production (Foley et al., 2011).

More intensive use of existing croplands by increasing cropping intensity may provide a possible alternative for increasing global food production (Dias et al., 2016; Meng et al., 2017). An increase in cropping intensity by increasing the number of crops per cropping cycle or intercropping with other crops can increase the frequency of harvests each year, resulting in increased food supplies without additional cropland expansion (Mauser et al., 2015). Numerous studies have assessed cropping intensity potential using climatic indicators (IIASA/FAO, 2012; Liu et al., 2013a,b; Zhang et al., 2013; Yang et al., 2015) or to map the actual cropping intensity across space using multiscale remote sensing data or by integrating remote sensing and consensus data (Galford et al., 2008; Siebert et al., 2010; Biradar and Xiao, 2011; Jain et al., 2013; Langeveld et al., 2014; Zuo et al., 2014). These studies generally focusing on either actual or potential cropping intensity have helped to shed light on the status of cropping intensity and its contribution to global production growth, while the global-scale gap between actual and potential cropping intensity remains little explored. Ray and Foley (2013) analyzed the "harvest gap", that is, the gap between the maximum harvest frequency that is theoretically possible and the harvest frequency seen today. However, they computed the maximum harvest frequency using only a temperature variable and excluded the significant impacts of precipitation. Moreover, their study used FAO agricultural statistics to calculate actual harvest frequency, which was restricted to a country-level analysis, thereby ignoring the spatial heterogeneity, in particular in large countries such as China, India, and the United States. Furthermore, the FAO agricultural statistics were taken from different and inconsistent data sources. This may create some inconsistencies in the results and may introduce errors such as underestimation in some places and overestimation in others. Spatially explicit and accurate information on the cropping intensity gap (CIG) is thus critically needed as it can help to identify regions that can harvest their croplands more frequently and those that have the potential to increase harvest areas by a more intensive use of their standing croplands to achieve the Sustainable Development Goals (Yu et al., 2017).

The objective of this study is thus to propose a spatially explicit approach to exploring the global CIG in 2010. We used an adapted IIASA/FAO GAEZ approach to calculate potential harvest frequency (HF_p) and satellite observation data consistently to map actual harvest frequency (HF_a) at a grid level. The results of HF_p and HF_a were then aggregated to calculate the potential cropping intensity (CI_p) and the actual cropping intensity (CI_a), as well as the CIG for individual countries. Using this CIG, we finally identified regions where a large potential CIG exists, and evaluated the case for increasing cropping intensity to expand the harvest areas without cropland expansion.

2. Methods and materials

2.1. The CIG concept

CIG was introduced here to measure the amount of incremental cropping intensity that is possibly available if all croplands in a given region are fully intensively used. Intensive use of cropland is widespread across the world. Several concepts, e.g., harvest/cropping frequency, cropping intensity, multiple cropping index, exist as a proxy for cropland use intensity (Iizumi and Ramankutty, 2015; Stephan et al., 2016; Yu et al., 2018). Harvest/cropping frequency, normally expressed in integer numbers, measures the number of harvests of a particular plot or field in one specific year (Fig. 1a). Cropping intensity is essentially related to what other scientists have called "multiple cropping" and is defined as the ratio of the sum of the annual harvested area to total cropland for a given region or administrative unit. It is expressed as an average value in floating numbers, which is slightly different from harvest frequency (Fig. 1b). In the current study, the terminology of cropping intensity is preferable as the main objective is to understand the CIGs at regional to global scales, rather than field or plot level. The CIG can then be conceptualized as the difference between the potential cropping intensity (CI_p) and the actual cropping intensity (CI_a) in a given spatial unit. However, the potential harvest frequency (HF_p) and the actual harvest frequency (HF_a) for each grid cell of cropland need to be first determined.

2.2. Measuring potential harvest frequency

To estimate the regional CI_p, the HF_p for each grid of cropland was first determined. Theoretically, the success of a crop harvest for a plot or field of land is critically dependent on the crops in question and the