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Review

Yield gaps in rice-based farming systems: Insights from local studies and prospects for future analysis

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ABSTRACT

The important contribution of rice to global food security requires an understanding of yield gaps in rice-based farming systems. However, estimates of yield gaps are often compromised by a failure to recognize the components that determine them at a local scale. It is essential to define yield gaps by the biological limitations of the genotype and the environment. There exist a number of methods for estimating rice yield gaps, including the use of crop growth simulation models, field experiments and farmer yields. We reviewed the existing literature to (i) assess the methods used to estimate rice yield gaps at a local scale and to summarize the yield gaps estimated in those studies, (ii) identify practical methods of analysis that provides realistic estimates of exploitable rice yield gaps, and (iii) provide recommendations for future studies on rice yield gaps that will allow accurate interpretation of available data at a local level.

Rice yield gap analysis can be simplified without sacrificing precision and context specificity. This review identifies the comparison of the attainable farm yield (the mean of the top decile) with the population mean, as a practical and robust approach to estimate an exploitable yield gap that is highly relevant at the local level, taking into account what is achievable given the local socio-economic conditions. With this method we identified exploitable yield gaps ranging from 23 to 42% for one particular season in four different rice growing areas in Southeast Asia. To enable accurate estimation and interpretation of yield gaps in rice production systems, we propose a minimum dataset needed for rice yield gap assessment. Future studies on rice yield gaps should consider the region, season and crop ecosystem (e.g. upland rainfed, lowland irrigated) as a minimum to facilitate decisions at a local level. In addition, we recommend taking into account the cultivar, soil type, planting date, crop establishment method and nitrogen application rates, as well as field topography and toposequence for rainfed systems. A good understanding of rice yield gaps and the factors leading to yield gaps will allow better targeting of agricultural research and development priorities for livelihood improvement and sustainable rice production.

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1. Introduction

Rice (*Oryza sativa* L.) is the main staple food for more than half of the world's population (Pandey et al., 2010), most of whom live in less developed countries in Asia, Africa and Latin America. In 2050, the world's human population is projected to reach over 9 billion—an addition of two billion people to current estimates (Godfray et al., 2010). To help ensure global food security and keep pace with the growing demand for rice, there is a need to increase rice production by 26% by 2035 (FAO, 2009; GRiSP, 2013; Sayer and Cassman, 2013; Fischer et al., 2014). However, agriculture has been facing enormous challenges with less land, water and labor availability (Rosegrant and Cai, 2002; Bouman et al., 2007; Lampayan et al., 2015). In addition, agriculture is associated with a number of environmental threats, including climate change, land and water degradation and biodiversity loss (Lobell et al., 2009; Mueller et al., 2012; Phalan et al., 2014). With increasing human population and decreasing availability and quality of resources, it is clear that increases in food productivity must be achieved sustainably in the remaining agricultural land.

One key strategy identified to meet future rice demand is closing existing "yield gaps" (Foley et al., 2011). Yield gaps can be a useful measure to determine the difference between mean farm yield (FY) and either potential yield with water and nutrients non-limiting (PY) or economically attainable yield (EY) using optimum crop management practices (van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999). This can provide a versatile framing device in policy discourse (Sumberg, 2012). In 1999 and 2000, two expert consultations on yield gaps in rice production convened by FAO identified that a clear understanding of yield gaps in rice, and their causes, should lead to better strategies to overcome the yield gap in a sustainable way (Papademetriou et al., 2000; FAO, 2001). By estimating and explaining yield gaps, we can determine the potential to increase food supply within a given area and highlight the importance of yield limiting and reducing factors (van Ittersum and Rabbinge, 1997). Using this knowledge we can (i) prioritize locations and needs for agricultural research and development, such as improving practices, infrastructure, research or training (knowledge transfer); (ii) assess the effectiveness and impact of introduced technologies, improved practices and other approaches that aim to improve rice productivity; or (iii) evaluate the impact of future scenarios, such as climate change, that will influence land and natural resource use (Alston et al., 2009; van Ittersum et al., 2013).

Global yield gap analysis has identified significant yield gaps in rice-based farming systems across the world, highlighting the possibilities to increase rice yields in many areas (Licker et al., 2010; Neumann et al., 2010; Foley et al., 2011; Mueller et al., 2012). Such global studies are useful to understand the spatial variations of yield gaps on a large scale, along with trends across regions (Neumann et al., 2010; Mueller et al., 2012). However, there are a number of caveats associated with top-down yield gap estimates that make it difficult to interpret them in absolute terms (Lobell et al., 2009; Mueller et al., 2012; Sumberg, 2012; van Ittersum et al., 2013). For example, yield data are often extrapolated across agro-ecological regions, seasons and rice ecosystems (Lobell et al., 2009; Sumberg, 2012; van Ittersum et al., 2013). In such cases, yield estimates can be highly variable, misleading, and have little value in identifying realistic yield gaps at a local scale. Misinterpretation of yield gaps can thus make it difficult for policy makers, donors and government agricultural agencies to make informed decisions on where to prioritize research and development. Thus, it is only through context-specificity that yield gaps become meaningful (van Ittersum and Rabbinge, 1997). There also are a multitude of methods to estimate and explain yield gaps, each with its advantages and disadvantages (Lobell et al., 2009; Sumberg, 2012). With different methods being used, it is a challenge to make yield gaps consistent and clear for the end user. To enable timely estimates of rice yield gaps that have local and current relevance, there is a need to simplify analysis of rice yield gaps without sacrificing precision and context specificity.

We reviewed the existing literature on local studies of rice yield gaps to (i) assess the methods used for its estimation and explanation, (ii) identify practical methods of analysis that provide realistic estimates of exploitable rice yield gaps at a local scale, and (iii) provide recommendations for future studies that will allow accurate interpretation of the data at a local level so as to set clear targets for policy makers, donors, government agricultural agencies, researchers, or even smallholder farmers. We then present a case study of yield gaps in four lowland irrigated rice growing locations in Southeast Asia estimated using recently collected data.

2. Review of local studies reporting rice yield gaps

2.1. Scope of literature review

Using the search words "yield gaps" and "rice" on the Web of Science and Scopus citation databases, we conducted a comprehensive search for peer-reviewed journal publications reporting yield gaps in rice production systems. In 1999 and 2000, the proceedings of two expert consultations on yield gaps in rice production comprehensively summarized yield gaps in rice producing countries (Papademetriou et al., 2000; FAO, 2001). To bring this review up to date with current relevance, we restricted our review to papers published between January 2000 and December 2015. Additional journal publications within the same date range were included when cited by the studies found using the methods above. We reviewed the published literature to investigate the rice yield gaps reported, the methods used for its estimation and explanation. Other types of publications, such as books and reports, or journal publications published before January 2000 were not part of the comprehensive review, but were used to inform the discussion if relevant to the topic. We acknowledge that production frontier analysis is similarly used to identify yield gaps based on estimates of technical inefficiency (Hoang, 2013; Villano et al., 2015), but such