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

Alexander M. Stuart^a, Anny Ruth P. Pame^a, João Vasco Silva^b, Rowell C. Dikitanan^a, Pieter Rutsaert^a, Arelene Julia B. Malabayabas^a, Rubenito M. Lampayan^a, Ando M. Radanielson^a & Grant R. Singleton^a

^aInternational Rice Research Institute, DAPO Box 7777 Metro Manila, Philippines.

^bPlant Production Systems, Wageningen University, P.O. Box 430, 6700 AK, Wageningen, The Netherlands

Author for Correspondence:

Alexander M. Stuart, International Rice Research Institute, DAPO Box 7777 Metro Manila, Philippines. Email: a.stuart@irri.org. Telephone: +63 580 5600 ext. 2523.

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 23-42% 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 N application rates, as well as field topography and topographic sequence 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.

Keywords: Southeast Asia, food security, yield constraints, smallholder farmers, sustainable rice production

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.

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

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111 **2. Review of local studies reporting rice yield gaps**

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113 **2.1. Scope of literature review**

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

studies in which field experiments were conducted to investigate yield constraints that could similarly be considered yield gap analysis (Bouman et al., 2005; Zhao et al., 2013). However, in this review we only analyzed literature in which ‘yield gaps’ were explicitly mentioned so as to identify issues specific to the reporting of this topic. Publications for which we could not access the full text (5% of papers) were not included in this review. van Ittersum et al. (2013) provide a comprehensive review of yield gap studies covering various crops at a global level. Thus, in this review, we focus on local studies of yield gaps in rice production systems (n = 39 papers).

2.2. Measures of crop yield gaps

In simplest terms, crop yield gaps have been defined as the difference (i.e. gap) between two yield estimates (Sumberg, 2012). This allows for a range of interpretations and as a consequence there exist a number of different approaches to calculate the “yield gap” (Lobell et al., 2009; Sumberg, 2012). The general consensus is that a crop yield gap is the difference between a “potential yield” or a “water-limited potential yield” and the “farm yield” over a specified temporal and spatial scale of interest (Lobell et al., 2009). “Farm yield” (FY), also known as ‘actual yield’, is the mean yield achieved by farmers in a given location (van Ittersum et al., 2013). “Potential yield” (PY) is the “yield of a crop cultivar grown in environments to which it is adapted with non-limiting water and nutrient conditions, and effective control of biotic stresses” (van Ittersum and Rabbinge, 1997; Evans and Fischer, 1999). Following this definition, PY in rice-based systems can be estimated using field experiments and crop growth simulation models. These two methods give an estimate of the “experiment potential yield” (PY_e) and the “climatic potential yield” (PY_c), respectively (see Table 1 for summary of yield benchmarks). Water-limited potential yield (PY_w), is most commonly estimated using crop growth simulation models considering water supply for crop growth is only provided by rainfall and depends on soil type and field topography (Lobell et al., 2009; van Ittersum et al., 2013). This is most relevant for rainfed systems (Van Asten et al., 2003b; Boling et al., 2010; Boling et

al., 2011) but can also apply to irrigated systems experiencing water shortages (FAO and DWFI, 2015).

When analyzing yield gaps, we need to take into consideration the environmental, economic and social consequences of reaching target yields. In most cases it is not desirable or practical to completely close yield gaps due to economic constraints and environmentally damaging consequences (Mueller et al., 2012; Cunningham et al., 2013). It also is considered impossible to achieve perfection in crop management needed to reach PY on a large-scale (Koning and van Ittersum, 2009; Lobell et al., 2009; van Ittersum et al., 2013). As farm yields approach PY, it becomes increasingly difficult, time consuming and costly to eliminate the imperfections needed to make small gains in yield (Cassman et al., 2003). For example, Witt et al. (1999) demonstrated that the most efficient use of nutrients would only produce rice yields at 70–80% of PY, after which the yield response to additional nutrient inputs diminishes. To gain the additional 20% in yield to close the gap, a disproportionate 70–90% increase in nutrient inputs are required, considering a perfect growing environment with no biotic constraints. Such inefficient use of inputs to reach PY would in most cases reduce profit as well as increase greenhouse gas emissions and pollution of waterways (Sayer and Cassman, 2013; Wu and Ma, 2015). This would be further exacerbated in cases where nutrient inputs are applied in excess of the plants uptake (West et al., 2014).

An alternative definition that has more functional relevance for real farming conditions is the “economically attainable yield” (abbreviated as EY as in Fischer, 2015), which is defined as the optimum (i.e. profit maximizing) yield given local economic conditions, as well as taking into account risks and existing institutions (Fischer et al., 2009; Hengsdijk and Langeveld, 2009; Fischer et al., 2014). At a local scale, EY may be determined by identifying the best yields achieved in farmers’ fields through skillful use of the best available technology (Tittonell and Giller, 2013; FAO and DWFI, 2015). In rice production systems, this has been measured as the mean of the top decile of farmers’ yields (e.g. Laborte et al., 2012; Tanaka et al., 2015), which

we define as the “attainable farm yield” (abbreviated as EY_f , see Table 1). Alternatively, several authors define the economically attainable yield as 80% of PY (Lobell et al., 2009; Laborte et al., 2012; van Ittersum et al., 2013; Fischer, 2015). We define 80% of PY as the “exploitable yield” (as in van Ittersum et al., 2013; abbreviated as EY_e). However, the 80% benchmark value should be used with caution as it depends on a number of factors such as input-output price ratios, including input subsidies (Lobell et al., 2009; Laborte et al., 2012). Using the definitions above, PY is only constrained by genotype and environment, whereas, EY is limited by both these factors as well as by optimal agronomic practice (e.g. efficient use of resources) and socio-economic and institutional issues that influence decision making and access to inputs and technology. The difference between EY and FY is then considered to represent the “exploitable yield gap” whereas the difference between PY and EY can be defined as the “unexploitable yield gap” (Tran and Nguyen, 2001). In theory, unexploitable yield gaps cannot be completely closed on a large-scale due to reduced economic gains, non-transferable factors and increased risk of pests, disease and lodging associated with high input use, whereas, exploitable yield gaps can be closed using optimal management practices with the best technologies available (Tran and Nguyen, 2001).

Defining economically attainable yields are certainly a step in the right direction towards identifying practical yield targets in underperforming areas. But there is still a need to identify whether the management practices applied to meet these targets are socially, environmentally and economically sustainable, e.g. are they technically and resource-use efficient? In some countries where there has been a high demand for increasing rice production, “economically attainable yields” have been achieved on a large scale but resources are being used inefficiently (Witt et al., 1999). For example, in China and Vietnam, overuse of fertilizers (e.g. Ma et al., 2014) and other inputs (e.g. Heong et al., 2013) in rice cultivation recently resulted in the introduction of national best management approaches (Three Controls Technology and One Must Do Five Reductions, respectively) that aim to reduce input use (Heong et al., 2010; Zhong et al., 2010). Thus, identifying such issues are of key importance when targeting yield gaps.

2.3 Yield gaps in rice production systems

2.3.1. Geographic spread of rice yield gap studies

Since the year 2000, estimates of yield gaps in rice production systems have been published for at least 20 countries, across three continents, with magnitudes of yield gaps ranging from 0-79% (Tables 2 & 3). The majority of publications report rice yield gaps in Asia, the largest rice producing and consuming continent, where almost 90% of the world's rice harvested area is present (Fig. 1). South and East Asia are relatively well represented relative to their proportion of global rice harvested area in 2013, but Southeast Asia appears to be under-represented. The proportion of literature on rice yield gaps is higher for Africa than for Southeast Asia or East Asia, even though Africa has considerably less rice production area than either of these regions (Fig. 1). This perhaps signifies the current importance and focus on increasing rice productivity in a part of the world where rice is the fastest growing staple but experiences severe rice production constraints (Vitousek et al., 2009; GRiSP, 2013; Tittonell and Giller, 2013; Fischer et al., 2014). Aside from Southeast Asia, another region that appears to be under-represented by the published literature is South America. This continent had almost five million ha of harvested rice area in 2013, 3% of the global total and almost half as much as that in Africa, but aside from global yield gap studies (Licker et al., 2010; Neumann et al., 2010; Foley et al., 2011; Mueller et al., 2012), we were not able to find peer-reviewed journal publications from the last 15 years investigating rice yield gaps in South America using the selected search engines. In the FAO Proceedings from the Expert Consultation on Yield Gap and Productivity Decline in Rice Production, Pulver et al. (2001) provide estimates of potential yields and rice yield gaps for the most important rice producing countries in Latin America. However, the calculations of potential yields are not always clearly defined, coming from a range of sources comprising on-site appraisals, expert opinions and the yields of progressive farmers. In a recent ACIAR report,

Fischer, 2014 provide a detailed analysis of rice yield gaps in Brazil (Fischer et al., 2014). However, scientific research of rice yield gaps in South and Central America in recent years appears to be lacking.

2.3.2. Methods used to estimate rice yield gaps

As mentioned in Section 2.1, there are a number of methods being used to calculate yield gaps. Tables 2 and 3 illustrate the variety of methods used across yield gap studies in rice production systems. With such variety, it is thus important to be aware of which data collection method was used and how the yield gap was calculated. The sources used to calculate FY include household surveys, national statistics, on-farm field trials and experiment-station trials. The common methods used to estimate yield benchmarks (PY, EY, MY) included crop-growth simulation models, field experiments, measuring yields at the mean of top decile and maximum farmer's yields (see Table 1). Each of these methods has its own advantages and disadvantages, which have been well reviewed elsewhere (Lobell et al., 2009; van Ittersum et al., 2013; Beddow et al., 2015; FAO and DWFI, 2015; Fischer, 2015). The magnitude of the yield gap also depends on the method employed, with larger yield gaps expected and typically observed when comparing FY with PY, than when comparing FY with EY (see Tables 2 and 3). However, within each of these methods, a number of variations exist. For example, for rice yield gap analysis using crop growth models and field experiments, FY was calculated from a range of sources, including: national statistics at a national or sub-national level; farmer-managed on-farm plots; researcher-managed field plots that received a treatment emulating farmer practice; or simulated yields based on common irrigation and fertilizer management practices. For yield gap analyses using field or farmer survey data, one study defined "best farmers' yield" as the yield at the 90th percentile, one defined it as the mean yield from the top decile (i.e. EY_f), whereas others defined the "best farmer's yield" as the maximum yield produced from a sample of farmers, more commonly referred to as maximum farmer's yield (i.e. MY). Unfortunately, such variation in methods adds to the confusion surrounding yield gaps and makes it difficult to

compare yield gaps across studies (Lobell et al., 2009) that could be useful for understanding differences in yield gaps between locations and over time.

Aside from the common methods described above, a number of additional methods have been employed to estimate yield. For example, Bastiannssen and Ali (2003) and Samarasinghe (2003) used remote sensing from satellite imagery to estimate crop yields. They estimated the yield gaps as the difference between the upper fifth percent, or 95th percentile, and the average yield. The use of remote sensing to estimate crop yields is a promising area of research that is undergoing refinement, but requires local calibration and validation with empirical farm level data (Lobell, 2013). An additional method that is gaining interest for yield gap analysis is production frontier analysis (Job, 2006; Hoang, 2013; Villano et al., 2015). By taking into account growth defining, limiting and reducing factors (van Ittersum and Rabbinge, 1997), methods of frontier analysis can be applied to individual household data to decompose yield gaps into technology, resource and efficiency yield gaps in a consistent and transparent manner (Silva et al., in press).

Few studies have compared different methods for calculating yield gaps in rice production. Laborte et al. (2012) compared methods for yield gap analysis in four intensive irrigated rice systems across Southeast Asia and reported that values of EY_f (the mean of the upper decile), came close to EY_e (i.e. 80% of climatic potential yield). Similar results also have been obtained in wheat and maize systems (Liang et al., 2011). On the other hand, Becker et al. (2003) and Haefele et al. (2001) identified that the maximum farmer's yields (i.e. MY) from field surveys were close to PY_c . However, use of MY should be used with caution due to the high likelihood that this value is an outlier either as a result of reporting error or from favorable circumstances that enable it to exceed PY for the geographic location of interest (Lobell et al., 2009; Fischer, 2015). Thus, these results suggest that, in intensive irrigated systems, EY_f provides a reasonable estimate of "economically attainable yields" (Laborte et al., 2012).

When calculating exploitable yield gaps in less intensive rainfed systems, additional factors need to be taken into consideration. Affholder et al. (2012) compared farmers' yields measured at the 90th percentile (a somewhat lower value than EY_f) with PY_w in upland rainfed rice ecosystems in Northern Vietnam and found that yields at the 90th percentile only reached 60% of PY_w . The authors hypothesized that in such environments, high yielding farmers are likely to have more favorable water retaining soils. Even so, they concluded that these yield gaps were still locally relevant and attributable to nutrient and agronomic management practices that could be addressed using available technologies. In addition, Hengsdijk and Langeveld (2009) suggest that in rainfed production systems, the economically attainable level may be lower than 70-80% of PY_w due to increased risks and uncertainty in farmer decision-making as a result of rainfall unpredictability (Fischer et al., 2014). For example, Poulton et al. (2014) demonstrated that in Cambodian rainfed lowland rice ecosystems, where farmers can only afford to apply low levels of fertilizer, the APSIM-ORYZA simulated rice yield for commonly practiced nitrogen fertilizer rates was in fact close to the farmers' yield at the 90th percentile. When locally recommended (optimum) rates of nitrogen fertilizer were applied by the farmers, the farmers' yield at the 90th percentile was again close to the simulated rice yield at the same fertilizer rate. Such calculations allow us to identify what is attainable with conditions enabling optimum nutrient resource use. These results also suggest that in less intensive systems, EY_f is likely to give a more accurate estimate of EY than arbitrarily calculating 80% of the YP. But then in such situations, there is then a need to identify how to increase EY_f , for example, through improving socio-economic conditions or disseminating affordable technologies, such as stress tolerant varieties, that reduce risk (Emerick et al., in press), as well as how to reduce the yield constraints contributing to the yield gap.

2.3.3. Common issues across all yield gap methods

While there are advantages and disadvantages for each method of yield gap analysis, there are clear issues that should be addressed across all methods. One of the main issues is the

aggregation or extrapolation of potential or actual yield data across regions, seasons or rice ecosystems (e.g. Singh et al., 2001; Samarasinghe, 2003). Such use of data prevents us from disentangling the yield gaps at the farm level from yield variation across different growing environments. Thus, aggregation or extrapolation of data that disregards the variability in biophysical conditions should be avoided.

Comparing on-station yields to on-farm yields also can be misleading (Tittonell and Giller, 2013). For example, several authors compared FY from regional statistics to PY_e acquired from experimental stations (Singh et al., 2001; Fischer and Edmeades, 2010; Akintayo et al., 2011), in some cases without even providing information on the location of the experiments, or the rice ecosystem in which they were conducted. This can accentuate the yield gap, as experimental stations are often located in fertile, low-lying areas (Tittonell and Giller, 2013; van Ittersum et al., 2013) and are managed in such a way that yield constraints can be quite different to those in farmers' fields (Sanders and Lynam, 1982). This makes them irrelevant to typical conditions found on-farm (Waddington et al., 2010). In addition, if yield benchmark data are indeed estimated for a different region and extrapolated, this can render the analysis meaningless due to spatial variation in agro-climatic conditions (Mishra et al., 2014; Beddow et al., 2015).

Another common issue is temporal inconsistency, the comparison of FY from one year with PY or EY that were calculated using historical data from previous years (Haefele et al., 2000; Haefele et al., 2001; Van Asten et al., 2003a). Haefele et al. (2001) do acknowledge this was done due to unavailability of data during the year the FY data were collected. However, climatic variation between years and seasons can have a significant effect on PY (Casanova et al., 1999; Lobell et al., 2009; Mishra et al., 2014). Some studies even fail to report the years in which the yield benchmark was calculated (e.g. Singh et al., 2001; Weerakoon et al., 2011; Hoang, 2013), which makes the results difficult to interpret. On the other hand, when identifying the mean yield gap over longer time periods, van Ittersum et al. (2013) recommend that data should be collected across a minimum of three years to capture climatic variation between

years. Longer time scales may be needed for rainfed systems, but the time scale should be short enough to avoid trends associated with technological and environmental change (Tran and Nguyen, 2001; van Ittersum et al., 2013). Depending on the objectives of the study, different time scales may be used, but the assumptions should be transparent for critical interpretation of the results (van Ittersum et al., 2013). Most importantly, the range of years used for calculating PY or EY and FY should be the same (Grassini et al., 2015).

When generalizing about rice yield gaps in a particular location, one has to question the validity of the yield gap for the present-day situation. Data on yield gaps published more than ten years after they were collected are certainly relevant when analyzing temporal trends in response to events such as climate or technological change (Angulo et al., 2012; Laborte et al., 2012). They also remain applicable for well-designed field experiments investigating specific yield constraints. However, when reporting yield gaps to inform policy makers or to prioritize areas for research and development, the limitations of yield gaps collected more than ten years ago need to be acknowledged as they may no longer be applicable due to changes in socio-economic conditions, management practices and technologies used, among other issues.

Issues of data quality and bias also need to be considered when interpreting rice yield gaps. These include the use of crop cuts for extrapolating yields to field level that can over or underestimate yields depending on the location, size and timing of the crop cut. The accuracy of the plot size measurement and the reliability of farmer estimates of yield also depend upon factors such as the accuracy of plot size estimates and the standardization of grain moisture content, especially if this is not measured using a moisture meter. Other issues to consider are the use of large spatial resolutions for climate and remote sensing data, the use of interpolated weather data, and the potential for errors and uncertainties associated with simulation modeling. These issues on uncertainties have been comprehensively reviewed (Lobell et al., 2009; van Ittersum et al., 2013; Beddow et al., 2015). Thus we will not discuss these in any further detail in this review.

377 *2.3.4. Interpreting rice yield gaps with accuracy*

378 To identify and address rice yield gaps as well as allow comparisons across studies, genotypic
379 and environmental factors need to be accounted or controlled for in order to keep yield gaps
380 context-specific and isolate the effects of different technologies or environments. It is important
381 to recognize that for yield gaps to be meaningful, estimates of PY or EY and FY should be made
382 within broadly similar agro-ecological conditions (Sumberg, 2012), over a specified spatial and
383 temporal scale of interest (Lobell et al., 2009). Grassini et al. (2015) provide a useful framework
384 on how to disaggregate data for yield gap analysis using crop growth simulation models, and
385 specifies that water regimes or rice ecosystem (e.g. rainfed, irrigated) and the cropping season,
386 along with their relative harvested area, as essential to interpret yield gaps accurately from local
387 to national scales. These pre-requisites to quantify the cropping-system context are also
388 relevant for other methods of calculating yield gaps (Lobell et al., 2009; van Ittersum et al.,
389 2013). To have local meaning, the yield gap should be analyzed at a local scale (e.g. village,
390 municipality, county or sub-district), whilst maintaining a suitable sample size. To understand
391 yield gaps on a broader context, FY and benchmark yield data should both be measured at a
392 local scale (at least at a sub-national level) to account for spatial heterogeneity in physiographic
393 and climatic conditions and then aggregated for up-scaling (FAO and DWFI, 2015). Another
394 approach to achieve the same objective is to disaggregate data by agro-climatic zones (van
395 Ittersum et al., 2013; van Wart et al., 2013b).

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397 To take into account the biophysical and socio-economic constraints under which farmers
398 operate, van Wart et al. (2013a) highlight the importance of specifying current crop
399 management practices to obtain relevant estimates of PY. Yield potential is determined by 1)
400 cultivar features (e.g. growing period till maturity), 2) soil type (in particular soil texture that
401 determines root zone water holding capacity and runoff), 3) sowing date and 4) plant density (or
402 crop establishment method) (van Ittersum and Rabbinge, 1997; Lobell et al., 2009; van Ittersum
403 et al., 2013). For example, for irrigated rice in China, a change in planting date by seven days

changed the simulated yield by one mt ha^{-1} due to variation in climatic conditions (van Wart et al., 2013a). It could be argued that soil data are not needed in irrigated systems due to continuous irrigation (van Wart et al., 2013a). However, in irrigated rice growing areas in developing countries, water availability may not always be continuous, especially in dry seasons or during periods of unusually low rainfall. Thus, it is important to disaggregate data by these four key factors where possible (Grassini et al., 2013; van Ittersum et al., 2013). If it is not possible, then it is important to adequately report them so as to avoid misinterpretations of yield gaps. Such information is often lacking in rice yield gaps studies (see below). Failure to report assumptions and limitations leads to difficulty in setting targets at a local scale.

To identify the level of detail or disaggregation when calculating rice yield gaps, we scanned the literature identified using the methods described in Section 2.1. to see how often the following key factors were explicitly taken into account (i.e. reported or controlled for in the analysis) when calculating yield gaps: rice ecosystem, cropping season, region measured at a sub-national scale (or agro-climatic zone), cultivar type, soil type, sowing date and crop establishment method. In this review, 36% of the publications accounted for all seven of the above factors for both benchmark yields and FY, but just as many papers did not take into account more than three of these factors (Table 4). Of all the publications, 10-18% failed to account for the rice ecosystem, cropping season or region, factors that we consider to be the most important for rice yield gap data to be meaningful, with 28% failing to account for all three factors (Table 4). For the other key factors, 41% of the reviewed literature did not account for cultivar type, a major yield determining factor and 44-49% did not account for either the crop establishment method, soil type or sowing date. We suggest that future rice yield gap studies take into account all seven of these key factors in their analysis for both benchmark yields and FY, but as a minimum to facilitate decisions at a local level, account for the rice ecosystem, cropping season and region. By taking environmental and genotypic factors into account, more accurate investigations into yield limiting and reducing factors are also able to be conducted.

433 3. Case study: Rice yield gaps in Southeast Asia assessed using farm-level data

434 To illustrate the points made above and to supplement the existing literature on yield gaps in
 435 rice-based farming systems, we analyzed the difference between attainable farm yields (EY_f)
 436 and mean farm yields (FY) to demonstrate how this can be used to provide useful estimates of
 437 exploitable yield gaps. Using the same dataset, the effects of management practices,
 438 environmental conditions and socio-economic conditions on farm yields can be analyzed to
 439 identify socio-economic issues and biophysical constraints contributing to the yield gap.

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441 3.1. Methods to estimate exploitable rice yield gaps

442 3.1.1. Household survey

443 We calculated “exploitable rice yield gaps” ($EY_f - FY$) using data collected from household
 444 surveys that were recently conducted in four intensive lowland irrigated rice areas in Southeast
 445 Asia: Yogyakarta (Indonesia), Bago (Myanmar), Nakhon Sawan (Thailand) and Can Tho
 446 (Vietnam). At each location, survey respondents were randomly selected from a list of rice
 447 farmers in each of four geographical units (i.e. village or commune), except for Thailand where a
 448 complete enumeration of farmers from each of four village community rice centers was
 449 conducted (see Supplementary information for details). In each study site, all geographical units
 450 were located within a 25km radius. We surveyed farmers using a structured questionnaire to
 451 collect data on current farming practices, rice production output (mt ha^{-1} for largest parcel of
 452 land), various input quantities and costs for rice cultivation for their largest parcel of land, farm
 453 and socio-demographic characteristics. Mineral and organic fertilizer inputs were used to
 454 calculate the quantity of nitrogen (N) applied.

455

456 EY_f was defined as the mean yield from the top decile of farmer’s yields (calculated from yields
 457 equal to and above the 90th percentile). We argue that this is a more suitable measure than
 458 taking the yield at the 90th percentile, as this allows us to attribute factors relating to these top

decile farmers when making comparisons with the mean. The exploitable yield gap was defined as the difference between EY_f and FY (i.e. the mean yield from the full sample of farmers). This value was divided by EY_f to calculate the yield gap as a percentage of EY_f .

3.1.2. Crop modeling

The ORYZA rice crop model (Bouman et al., 2001) was used to simulate climatic potential yield (PY_c) for locally available high-yielding varieties for each site in non-limiting water and nutrient conditions and with full control of pests and disease assumed. PY_c was estimated for the mean sowing date observed from the household survey. The varieties and sowing dates included Inpari 6 sown on November 16, 2013 for Indonesia; Jasmine 85 sown on April 10, 2014 for Vietnam; NSIC Rc222 sown on July 2012 for Myanmar and RD31 sown on June 17, 2013 for Thailand.

Data from researcher-led field trials in each study site were used to parametrize the model for each considered variety in terms of crop phenology, crop responses to water deficit and biomass partitioning (Harvest Index) by considering the crop management practices applied. The model was run using the dominant crop establishment method at each site. For Indonesia and Myanmar, soil information was obtained from analysis of soil samples collected from the study sites. For Vietnam and Thailand, soil information was estimated from the known classification of the soil type. Climatic data for the considered year was obtained from the NASA Tropical Rainfall Measuring Mission (downscaled to a 25x25km grid) based on the geo-coordinates of the sites.

3.1.3. Statistical analysis

Using SPSS version 18 (SPSS Inc., Chicago, IL, USA), general linear models (ANCOVA) were used to investigate the importance of crop production factors as determined by agronomic practices and environmental conditions against rice yield ($mt\ ha^{-1}$) for each country location. Key yield determining factors that were identified in Section 3.4 were included in the model as

independent variables. These included: geographical unit, date of planting, crop establishment method, variety and soil type. Other potential explanatory variables for rice yield variation included in the model were the quantity of N (as an indicator of fertilizer use) and the third season crop in Yogyakarta. This model allows us to control for each of these factors when analyzing the different variables. Each country location was analyzed in a separate model.

3.2. Exploitable rice yield gaps in Southeast Asia

Across the four survey sites, there was a substantial gap between FY and EY_i during a single wet season rice crop, ranging from 1.4 to 3.8 $mt\ ha^{-1}$ (23.3 - 42.4% of AY) (Table 5). The highest yield gaps were in Yogyakarta and in Bago indicating that these sites have the greatest potential to increase yields given current crop management practices, available technologies and socio-economic conditions. The differences in farm and socio-demographic characteristics and agronomic management practices between mean and best-yielding farmers varied between study sites. There also are substantial differences in the farming practices and socio-economic conditions between countries that need to be considered, highlighting the need to acknowledge site-specific information when interpreting yield gaps.

In Nakhon Sawan and Bago, the rice variety had a significant effect on yield (Table 6). In these sites, a greater proportion of the top decile farmers planted higher yielding inbred varieties than the mean (Table 4). These results indicate that the rice variety partly explains the yield gap observed in these sites. In Can Tho, the crop establishment method had a significant effect on yield, with lower yields attained by farmers that transplanted their crop. All of the top decile farmers practiced direct-seeding. In Yogyakarta and Bago, there was a significant positive relationship between N use and yield (Table 6). On average, the top decile farmers in both locations applied a higher rate of N than the mean, with higher N use efficiency, as indicated by higher partial productivity of applied N ($N\ PFP$; Table 5). This however does not mean that the top decile farmers applied N at optimum rates. In Yogyakarta for example, the local

recommended rates for the wet season, based on site-specific nutrient management, is roughly 250 kg N ha⁻¹. This value lies in-between the rate applied by the mean and top decile farmers. Thus, due to the law of diminishing returns, EY_f in this case may in fact be a slight over-estimate of the yield that is attainable with optimum N use. This is further demonstrated in Figure 2A, where the nitrogen application rates by many farmers far exceed the recommended rate of 250 kg N ha⁻¹ with no overall increase in rice yields. However, EY_f may still be a good measure of the “economically attainable yield” due to the provision of high subsidies for inorganic fertilizer in Indonesia. In addition, EY_f in Yogyakarta was almost identical to EY_e calculated as 80% of the simulated PY_c . The results also indicate that there is scope for the high input farmers to reduce the amount of nitrogen applied without compromising yield. For those farmers applying less than 250 kg N ha⁻¹, optimizing fertilizer application would be expected to increase rice productivity, although this depends on the variety grown, as the yield response to nitrogen is variety specific (Witt et al., 1999).

In Bago on the other hand, very low levels of N were applied, even by the best-yielding farmers. The positive linear trend between yield and N application rate (Table 6; Fig. 2D) and the substantial gap between EY_f and EY_e indicates that EY_f is likely to be below the yield that is attainable with optimum nutrient use. But EY_f may still be an accurate reflection of EY based on high input prices, poor access to inputs (such as high yielding varieties and fertilizer) and risk aversion, e.g. due to flooding events (N. Htwe, pers. comm.). In contrast, in Nakhon Sawan and Can Tho, where similar nitrogen application rates were applied among farmers (Fig. 2B and 2C), the top decile farmers were on average applying slightly lower rates of nitrogen fertilizer than the mean, with higher N PFP (see Table 5). This suggests that the top decile farmers are likely to be achieving yields that are attainable with optimum nutrient use efficiency. In both of these sites, EY_f is very close to EY_e (80% of PY_c).

In two of the study sites; Nakhon Sawan and Bago, rice yield was significantly affected by geographic location (i.e. village). This might indicate some biophysical difference between the village sites. However, one should also consider socio-economic differences between villages such as group decision-making on varietal selection, irrigation scheduling or community ownership of machinery, such as four wheel tractors. These collective factors are still largely unexplored. Also, individual farmer characteristics might directly or indirectly affect yield gaps. Due to large standard error values, there are no clear differences in non-rice income, education and total farm size between top decile farmers and the mean (Table 5). However, less obvious variables such as access to information through formal and informal networks or distance between home and the field could be further investigated.

Our results indicate that exploitable yield gaps can be reduced by optimizing fertilizer use in Yogyakarta and Bago, and by planting improved rice varieties in Bago and Nakan Sawan. Based on fertilizer use during the wet season crop, these four lowland rice growing environments can be classified across an intensification gradient with high intensively managed systems in Yogyakarta, moderately intensive managed systems in Nakhon Sawan and Can Tho and low intensively managed systems in Bago. This provides an interesting case study to investigate and explain rice yield gaps in a comparative way using farm-level data. In the intensive sites, EY_f and EY_e were similar, indicating that both estimates of EY can be applied in intensively managed rice systems that have limited socio-economic constraints, as suggested by Laborte et al. (2012). However, in Myanmar, there was a substantial gap between EY_f and EY_e . These results support the suggestion made in Section 2.3.2. that in low intensively managed systems, EY_f is a more suitable measure of EY when taking into account local socio-economic and institutional conditions, but EY_e (derived from PY_o) can still be useful for informing policy makers, donors and government agricultural agencies on what is theoretically attainable without such limitations so that steps can be taken to increase EY_f and FY.

To further understand EY with optimum resource use, such as nitrogen and water, crop growth simulation models can be used as well as production function analysis, which can disentangle efficiency, resource and technology yield gaps among farmers (Beddow et al., 2015; FAO and DWFI, 2015; Silva et al., in press). For example, frontier analysis can be used to explain causes of yield gaps and yield variability across different farmer's fields. These approaches were not applied in this paper. We acknowledge that we were only able to explain part of the yield gap in each of our study sites due to the limited number of factors investigated. For example, we were not able to include biotic yield reducing factors in our analysis, such as from pests and disease. These are likely to explain a portion of the yield gap (Oerke, 2006), as well as other possible factors, such as socio-economic and institutional factors that influence agronomic management decisions and access to technology. Understanding these factors would require further information through diagnostic surveys, e.g. using more detailed questionnaires or focus group discussions to understand socio-economic and institutional issues, and though detailed studies in farmers fields to identify yield-limiting and yield-reducing factors (e.g. Becker et al., 2003; Saito et al., 2013; Tanaka et al., 2015).

Our results demonstrate that yield gaps estimated using EY_f provide a valuable starting point from which to further investigate and address yield constraints. By looking at EY_f , we can quickly identify the attainable yield that farmers are currently able to achieve in a region for a given season using household survey data. Exploitable yield gaps can then be estimated within comparable biophysical and socio-economic conditions, e.g. between neighbors with similar topography and soils (FAO and DWFI, 2015). If such yield gaps can be readily addressed using existing technologies, minimal investments by farmers may therefore be needed (Pulver et al., 2001). Identifying exploitable yield gaps and the yield constraints at a local scale also has a practical meaning to farmers, which can help to facilitate adoption of improved practices, such as site-specific nutrient management (Buresh et al., 2007), through on-farm demonstrations and field days.

Exploitable yield gaps calculated using EY_f can also be used to monitor study impacts with minimal input and simplicity (FAO and DWFI, 2015), for example, to assess the effectiveness and impact of introduced technologies, best management practices and other approaches that aim to improve rice yield and also rice system productivity. These impacts can be measured with the use of farmer diaries or repeated household surveys. For example, analysis of a continuous loop survey in the Central Luzon, Philippines by Laborte et al. (2012) demonstrated that following the introduction of modern rice varieties in the 1970s, the best farmers' yields (mean over three years) increased by 69% for the wet season crop (almost two $mt\ ha^{-1}$) from 1966-1974 to 1979-1986 (Fig. 3). The actual yields also increased by 62% across the same time scale, but the exploitable yield gap was only reduced from 38% to 31%. From 1979 to 2008, there was very little change in EY_f , which is likely a consequence of the minimal genetic gains in PY made during this period (Dingkuhn et al., 2015). However, FY also stagnated, indicating a lack of progress in closing exploitable yield gaps for the wet season crop. Reasons for this may be due to high input prices and a high risk of losses due to typhoons that frequent the area during the wet season (Silva et al., in press). Whereas, yield progress has been made in the dry season, when climatic risk is lower and the crop response to solar radiation is greater.

The causes of yield gaps can vary widely between seasons and years (Duwayri et al., 2000). For our case study, we only analyzed one particular season. Thus our results are only relevant to that particular point in time. This case study was also restricted to irrigated lowland systems. In rainfed systems, other yield determining factors need to be considered when analyzing yield gaps, such as field topography and topographic sequence, which can have important implications for water availability, flooding risk and soil fertility (Van Asten et al., 2003b; Boling et al., 2010; Boling et al., 2011; GRiSP, 2013; van Oort et al., 2015b). Rice PY has been demonstrated to differ between upper, medium and lower slopes (Boling et al., 2011), thus in rainfed systems, exploitable yield gaps should be disaggregated by toposequence position or the variability in soil and climatic conditions associated with this.

625 **4. Conclusions**

626 In this review, we identified a range of issues that compromise analysis of rice yield gaps, thus
627 making them difficult to interpret. To allow accurate interpretation of the data, it is important that
628 future studies on yield gaps in rice production systems take into account three key factors,
629 consisting of the region, season and crop ecosystem as a minimum to facilitate decisions at a
630 local level and four main factors to understand the biological limitations of the genotype and the
631 environment: the cultivar, soil type, planting date and crop establishment method. All of these
632 factors should be accounted for when investigating yield limiting and reducing factors. In
633 addition, the results of our household surveys suggest N application rates should also be taken
634 into account to understand yield limitations due to fertilizer use. In rainfed systems, field
635 topography and topographic sequence should also be considered.

636

637 Crop growth simulation models, if validated and applied correctly, can provide estimates of
638 potential yields without constraints, aside from climate and water, for a specific location.
639 However, data required to calibrate or validate them are not widely available at the local scale
640 (van Ittersum et al., 2013; George, 2014). In addition, in many developing countries, the ability
641 to close yield gaps is often constrained by socio-economic and institutional factors at the farm
642 level (Duwayri et al., 2000). To help identify yield benchmarks that are achievable using
643 sustainable management practices, “economically attainable yields” (EY) have been defined.
644 However, these may be difficult to accurately estimate at a local level using crop growth
645 simulation models due to a range of factors, such as price ratios, risk aversion and indigenous
646 nutrient supply that differ according to local conditions (Cassman et al., 1996; Lobell et al.,
647 2009; Laborte et al., 2012). It is thus a challenge to relate such estimates to actual farming
648 conditions, especially when attempting to demonstrate this to farmers. We suggest that future
649 studies that aim to calculate climatic or water-limited potential yield with nutrients non-limiting
650 should also run simulations using locally-recommended nutrient application rates. This would

help to identify a more sustainable yield target that would increase farmer profits and reduce environmental pollution.

The true meaning of yield gaps in rice-based farming systems can be lost in the complexity of detailed models, but we argue that in the developing country context, where the majority of rice is grown, a simple approach can yield the most relevant answer at a local level. This review identifies the comparison of the attainable farm yield (the mean of the top decile) with the mean farm yield as a practical and robust approach to estimate the exploitable yield gap, taking into account what is achievable given the local socio-economic conditions. The same set of data used to calculate these yield gaps can also be used to investigate the effects of management practices, environmental conditions and socio-economic conditions on farm yields to identify factors contributing to the yield gap. This can help to identify priority areas for research and development in order to address food security concerns and ensure the future sustainability of rice production.

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974 Table 1. Common methods used to estimate yield benchmarks in rice production systems and a
975 summary of their main limitations.

Yield benchmark	Estimation method	Main limitations
Potential Yield (PY):		
Climatic potential yield (PY_c)	Crop growth simulation models for irrigated systems	Requires site-specific data, that are not widely available at a local scale, and rigorous validation under field conditions
Water-limited potential yield (PY_w)	Crop growth simulation models for rainfed ecosystems	As above
Experiment potential yield (PY_e)	Field experiments with no yield constraints	Difficult to eliminate yield-limiting and yield-reducing factors; may not represent agro-ecological conditions of farm yields
Economically attainable Yield (EY):		
Exploitable yield (EY_e)	80% of potential yield	Depends on price ratios and environmental conditions
Attainable farm yield (EY_f)	The mean of the upper decile of farmers' yields	Related to the best technologies that are available and affordable at a given time
Maximum farmer yield (MY)	The maximum observed yield from a sample of farmer's fields	Must rely on farmer reported values; likely to be an outlier; can exceed PY

976 Sources: Cassman et al. (2003); Lobell et al. (2009); Affholder et al. (2012); Laborte et al. (2012); van
977 Ittersum et al. (2013); Fischer (2015)
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980 Table 2. Comparison of methods used across peer-reviewed journal publications (from 2000-
981 2015) to calculate yield benchmarks (Y), farm yields (FY) and the respective yield gap (YG;
982 calculated as % of Y) in rice production systems of Asian countries (Further details in
983 Supplementary Table S1).

Source	Country	Method ^a	Y calculation	FY source	% YG
Poulton et al. (2014)	Cambodia	PY _c	APSIM-ORYZA with low N	Farmer's practice	21
Zhang et al. (2014)	China	PY _c	ORYZA2000	Regional statistics	9 - 33
van Wart et al. (2013a)	China	PY _c	NOAA	5 year national average	18
Mishra et al. (2014)	India	PY _c	DSSAT	Simulated actual practice	0 - 53 ^b
Boling et al. (2010)	Indonesia	PY _c	ORYZA2000	Farmer's practice	41
Angulo et al. (2012)	Philippines	PY _c	ORYZA2000	Regional statistics	37 - 71
Boling et al. (2011)	Thailand	PY _c	ORYZA2000 at 60 kg N ha ⁻¹	Farmer's practice	41
Affholder et al. (2012)	Vietnam	PY _w	PYE model	Farmer's practice	67
Alam et al. (2013)	Bangladesh	PY _e	National experiments	Farmer's practice	24
	Bangladesh	PY _e	National experiments	On-farm BMP ^c	13
Huang et al. (2013)	China	PY _e	Experiments	Experiments	18 - 41
Zhao et al. (2015)	China	PY _e	High N experiment	Farmer's practice (researcher led)	26 - 29
Nirmala et al. (2010)	India	PY _e	On-farm demonstration	Farmer survey	12
Patel et al. (2010)	India	PY _e	Flooded experiment	Anaerobic experiment	18 - 38
Hoang (2013)	Sri Lanka	PY _e	National experiments	Regional statistics	40 - 41
Singh et al. (2001)	Thailand	PY _e	National experiments	Regional statistics	40 - 42
Fischer and Edmeades (2010)	Japan	PY _e	Experiments	National statistics	41
	Philippines	PY _e	Experiments	Regional statistics	33 - 51
Regmi and Ladha (2005)	Nepal	EY _e	CERES-RICE (80% of PY _c)	Farmer's practice	41 - 51
Laborte et al. (2012)	Indonesia	EY _e	ORYZA2000 (80% of PY _c)	Farmer survey	16 - 32
	Philippines	EY _e	ORYZA2000 (80% of PY _c)	Farmer survey	40 - 47
	Thailand	EY _e	ORYZA2000 (80% of PY _c)	Farmer survey	22 - 23
	Vietnam	EY _e	ORYZA2000 (80% of PY _c)	Farmer survey	6 - 37
	Indonesia	EY _f	Top decile	Farmer survey	31 - 32
	Philippines	EY _f	Top decile	Farmer survey	36 - 39
	Thailand	EY _f	Top decile	Farmer survey	19 - 20
	Vietnam	EY _f	Top decile	Farmer survey	27 - 29
Weerakoon et al. (2011)	Sri Lanka	MY	Highest yield	Farmer survey	31 - 48
Liu et al. (2014)	China	MY	Highest yield	Expert survey	31 - 34
	Indian sub-continent	MY	Highest yield	Expert survey	40 - 45
Waddington et al. (2010)	East Asia Pacific	MY	Highest yield	Expert survey	31 - 34
	South Asia	MY	Highest yield	Expert survey	39 - 46
Job (2006)	India	O	Production frontier	Farmer survey	23 - 37
Bastiaanssen and Ali (2003)	Pakistan	O	5% highest yield	Remote sensing	40
Villano et al. (2015)	Philippines	O	Production frontier	Farmer survey	29 - 44
Samarasinghe (2003)	Sri Lanka	O	95 th percentile	Remote sensing	27
Affholder et al. (2012)	Vietnam	O	90 th percentile	Farmer's practice	47
Ashraf et al. (2010)	Pakistan	nd ^d	nd ^d	Farmer survey	50

984 ^aMethods used to determine yield benchmarks: PY_c = climatic potential yield; PY_w = water-limited potential yield; PY_e =
985 experiment potential yield; EY_e = exploitable yield; EY_f = attainable farm yield; MY = maximum farmer yield; O = other method
986 ^b Estimated from published figures
987 ^c BMP = Best management practice
988 ^d nd = not defined

Table 3. Comparison of methods used across peer-reviewed journal publications (from 2000-2015) to calculate yield benchmarks (Y), farm yields (FY) and the respective yield gap (YG; calculated as % of Y) in rice production systems of non-Asian countries (Further details in Supplementary Table S1).

Source	Country	Method ^a	Y calculation	FY source	% YG
Audebert and Fofana (2009)	Cote d' Ivoire	PY _c	ORYZAS	Experiments	17 - 58
Haefele et al. (2001)	Mauritania	PY _c	ORYZAS	Farmer's practice	49
Van Asten et al. (2003b)	Mauritania	PY _c	ORYZAS	Farmer survey	50 - 69
Casanova et al. (2000)	Spain	PY _c	ORYZA1	Field survey	5 - 23 ^b
van Oort et al. (2015a)	Sub-Saharan Africa	PY _c	ORYZA2000	Regional statistics (irrigated rice)	17 - 79
Becker et al. (2003)	Cote d' Ivoire	PY _c	ORYZAS	Farmer's practice	48 - 63
	Mali	PY _c	ORYZAS	Farmer's practice	39
	Senegal/Mauritania	PY _c	ORYZAS	Farmer's practice	60
van Oort et al. (2015a)	Sub-Saharan Africa	PY _w	ORYZA2000	Regional statistics (rainfed rice)	59 - 71
Akintayo et al. (2011)	Nigeria	PY _e	National experiments	Farmer survey	39 - 67
Haefele et al. (2000)	Mauritania	EY _e	ORYZAS (80% of PY _c)	Farmer's practice (researcher led)	32
	Senegal	EY _e	ORYZAS (80% of PY _c)	Farmer's practice (researcher led)	31
Tanaka et al. (2015)	Senegal	EY _f	Top decile	Farmer survey	31 - 35
Segda et al. (2004)	Burkina Faso	MY	Highest yield	Farmer's practice	38 - 54
Delmotte et al. (2011)	France	MY	Highest yield	Field survey	37 - 57
Poussin et al. (2003)	Senegal	MY	Highest yield	Farmer's practice	30 - 38
Waddington et al. (2010)	Sub-Saharan Africa	MY	Highest yield	Expert survey	38 - 43
Becker and Johnson (2001)	Cote d' Ivoire	O	On-farm trials for BMP ^c	Farmer's practice	7 - 34

^aMethods used to determine yield benchmarks: PY_c = climatic potential yield; PY_w = water-limited potential yield; PY_e = experiment potential yield; EY_e = exploitable yield; EY_f = attainable farm yield; MY = maximum farmer yield; O = other method

^b Estimated from published figures

^c BMP = Best management practice

- 1000 Table 4. Number of publications that took into account different numbers of key factors (n = 39).
- 1001 Key factors include region, season, crop ecosystem, cultivar, soil type, planting date and crop
- 1002 establishment method (Further details in Supplementary Table S1).

No. of factors accounted for	No. of publications
0	2
1	1
2	3
3	9
4	0
5	2
6	8
7	14

Table 5. The rice yield gaps between the mean yield reported by farmers within a district (FY) and the mean yield from the top decile of farmer's yields (EY_f), and a comparison of the respective farm socio-demographic characteristics and agronomic management practices across four countries during a single wet season rice crop. The year in which the survey was conducted for each site is given in parentheses. Yield is reported at 14% moisture content.

	Yogyakarta, Java (2014)				Nakhon Sawan, Thailand (2013)				Can Tho, Vietnam (2015)				Bago, Myanmar (2012)			
	FY	(s.e.)	EY_f	(s.e.)	FY	(s.e.)	EY_f	(s.e.)	FY	(s.e.)	EY_f	(s.e.)	FY	(s.e.)	EY_f	(s.e.)
	(n = 178)		(n = 24) ^a		(n = 84)		(n = 9)		(n = 180)		(n = 18)		(n = 100)		(n = 10)	
Yield (mt ha ⁻¹)	5.2	(0.2)	9.0	(0.3)	4.8	(0.1)	6.2	(0.2)	4.9	(0.1)	6.7	(0.2)	2.6	(0.1)	4.1	(0.1)
Yield Gap (%)	42.4				23.3				26.9				36.6			
Total farm size (ha)	0.17	(0.01)	0.22	(0.1)	4.9	(1.2)	4.9	(1.3)	2.1	(0.1)	2.1	(0.3)	5.0	(0.5)	4.2	(1.0)
N application (Kg)	234.9	(9.9)	287.4	(32.3)	96.5	(26.0)	92.9	(13.9)	101.4	(2.7)	100.6	(4.0)	18.4	(1.9)	36.0	(4.6)
N PFP (Kg rice/Kg N)	28.5	(1.5)	40.4	(4.8)	58.6	(2.4)	69.7	(7.6)	81.7	(1.9)	98.3	(4.3)	127.2 ^b	(16.0)	155.8	(42.7)
Date of sowing (week no.)	40.4	(1.2)	43.2	(3.0)	25.1	(0.2)	23.9	(0.9)	15.6	(0.3)	14.5	(0.9)	27.2	(0.5)	31.1	(1.8)
Non-rice income (USD/yr)	804	(76)	711	(192)	4077	(584)	7344	(2394)	2041	(220)	2294	(902)	145	(38)	99	(76)
Education (years)	9.0	(0.3)	9.6	(0.7)	6.6	(0.4)	6.6	(1.2)	9.2	(0.2)	8.3	(0.7)	6.9	(0.3)	7.1	(2.3)
Crop establishment (%):																
Transplanting	100		100						6				92		100	
Wet direct seeding					86		88		94		100		6			
Dry direct seeding					14		12						2			
Variety (%):																
Main variety	68		71		83		100		69		66		39		90	
2nd variety	12		13		17				29		28		26		10	
Others	20		16						2		6		35			
Soil type (%):																
Clay	23		29		68		38						28		20	
Loam	10		8		2								5		30	
Sandy	10		13										14			
Sandy loam	57		50		12		13						49		40	
Clay loam					7		13									
Sandy clay					11		37									
Acid Sulphate									100		100					

^a This sample size is high due to many farmers achieving yields on the 90th percentile.

^b Excluding 37 farmers who applied < 5 kg N ha⁻¹

N PFP = nitrogen partial factor productivity

Table 6. General linear model of the effects of farm characteristics and agronomic management practices on farm yield (mt ha⁻¹) in each of four sites during a single wet season rice crop, and their parameter estimates presented as Beta coefficients (β).

	Yogyakarta				Nakhon Sawan				Can Tho				Bago			
	β	d.f.	F	P	β	d.f.	F	P	β	d.f.	F	P	β	d.f.	F	P
N application	0.003	1	6.080	0.015	0.002	1	1.026	0.315	-0.003	1	1.680	0.197	0.011	1	4.752	0.032
Date of sowing	-0.001	1	0.014	0.904	-0.034	1	0.276	0.601	-0.018	1	0.763	0.384	-0.029	1	2.370	0.127
Crop establishment	-	-	-	-		2	0.184	0.833		1	4.101	0.044		2	2.546	0.084
Transplanted					0*				-0.606				0.714			
Wet direct seeded					0.155								0.052			
Variety		3	0.397	0.755		1	5.748	0.019		2	0.552	0.577		2	3.323	0.041
Main variety	0.431			0.401	0.746				-0.443				0.580			
2nd variety	0.720			0.293	0*				-0.109				0.368			
3rd variety	0.517			0.5049												
Soil type		3	2.105	0.102		4	0.415	0.797	-	-	-	-		4	1.885	0.120
Clay	-0.078				-0.214								0.238			
Loam	-1.423				0.207								0.660			
Sandy	0.003												-0.258			
Sandy loam	0*				0.197								0.091			
Clay loam					0.004											
Sandy clay					0*											
Geographical unit		3	1.916	0.130		3	4.222	0.008		3	2.098	0.102		3	4.633	0.005
Village A	0.742				1.021				-1.015				0.435			
Village B	-0.583				0.538				-0.084				-0.053			
Village C	0.364				0.898				-0.014				-0.463			
Third season crop		3	0.865	0.461	-	-	-	-	-	-	-	-	-	-	-	-
Corn	0.552															
Legumes	-0.234															
Other	-0.366															
Rice	0*															
Error		143				69				169				85		
Total		157				82				178				99		
R ²				0.212				0.245				0.115				0.504
Adjusted R ²				0.135				0.113				0.073				0.428

*This parameter is set to zero as it is the reference group.

Figure 1. Regional spread of publications on yield gaps in rice production and the harvested rice area in 2013 (source: <http://faostat3.fao.org>).

Figure 2. Relationship between N application (kg N ha⁻¹) and rice farm yields (mt ha⁻¹) in A) Yogyakarta, Indonesia; B) Nakhon Sawan, Thailand; C) Can Tho, Vietnam and; D) Bago, Myanmar. Yield is reported at 14% moisture content. PY_c = climatic potential yield (estimated using ORYZA – see methods section for details); EY_e = exploitable yield (calculated as 80% of PY_c; EY_f = attainable farm yield; 90th % = 90th percentile.

Figure 3. Comparison of mean farm yields (FY) and attainable farm yields (EY_f) during the wet season in Central Luzon, Philippines from 1966 to 2008 [Adapted from Laborte et al. (2012)]. The data came from a loop survey that is conducted every four years with an average sample size of 100 farmers per wet season.