How does inter-annual variability of attainable yield affect the magnitude of yield gaps for wheat and maize? An analysis at ten sites


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ABSTRACT

Provision of food security in the face of increasing global food demand requires narrowing of the gap between actual farmer's yield and maximum attainable yield. So far, assessments of yield gaps have focused on average yield over 5–10 years, but yield gaps can vary substantially between crop seasons. In this study we hypothesized that climate-induced inter-annual yield variability and associated risk is a major barrier for farmers to invest, i.e. increase inputs to narrow the yield gap.

We evaluated the importance of inter-annual attainable yield variability for the magnitude of the yield gap by utilizing data for wheat and maize at ten sites representing some major food production systems and a large range of climate and soil conditions across the world. Yield gaps were derived from the difference of simulated attainable yields and regional recorded farmer yields for 1981 to 2010. The size of the yield gap did not correlate with the amplitude of attainable yield variability at a site, but was rather associated with the level of available resources such as labor, fertilizer and plant protection inputs. For the sites in Africa, recorded yield reached only 20% of the attainable yield, while for European, Asian and North American sites it was 56–84%. Most sites showed that the higher the attainable yield of a specific season the larger was the yield gap. This significant relationship indicated that farmers were not able to take advantage of favorable seasonal weather conditions. To reduce yield gaps in the different environments, reliable seasonal weather forecasts would be required to allow farmers to manage each seasonal potential, i.e. overcoming season-specific yield limitations.

1. Introduction

Projected increases in demand for food, feed, fuel and fiber (Alexandratos and Bruinsma, 2012; Tilman et al., 2011) have sparked a growing interest in studies on the sustainable intensification of plant production systems (Foley et al., 2011; Godfray et al., 2010). A common aspect of these studies is the quantification of the gap between actual farmer yield and maximum attainable crop yield to assess the possible scope of intensification (Tao et al., 2015; van Ittersum et al., 2013). Such yield gap studies typically distinguish between potential yield (YP), which is the yield defined by temperature, solar radiation, CO2 and crop properties, water-limited yield (YW), which is additionally limited by water supply, water-and/or -nutrient limited yield (YN), and actual farmer yield (Ya) (van Ittersum et al., 2013). Possible factors reducing Yn to Ya are weeds, pests, diseases, and air pollutants such as ozone. The maximum attainable yield for farmers, assuming that all

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Table 1
Summary of location and climate conditions for the study sites.

<table>
<thead>
<tr>
<th>Site</th>
<th>Country</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Altitude m a.s.l.</th>
<th>Annual mean temperature °C</th>
<th>Precipitation mm/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>Jokioinen</td>
<td>23°3 E</td>
<td>60°4 N</td>
<td>104</td>
<td>4.6</td>
<td>627</td>
</tr>
<tr>
<td></td>
<td>Kulumsa</td>
<td>39°1 E</td>
<td>8°2 N</td>
<td>2200</td>
<td>17.0</td>
<td>832</td>
</tr>
<tr>
<td></td>
<td>Hays, Kansas</td>
<td>99°2 W</td>
<td>38°5 N</td>
<td>613</td>
<td>12.3</td>
<td>592</td>
</tr>
<tr>
<td></td>
<td>Lleida</td>
<td>1°1 E</td>
<td>41°5 N</td>
<td>330</td>
<td>15.0</td>
<td>342</td>
</tr>
<tr>
<td></td>
<td>Rothamsted</td>
<td>0°2 W</td>
<td>51°5 N</td>
<td>128</td>
<td>9.9</td>
<td>712</td>
</tr>
<tr>
<td></td>
<td>Nossen</td>
<td>13°2 E</td>
<td>51°4 N</td>
<td>255</td>
<td>9.1</td>
<td>653</td>
</tr>
<tr>
<td>Maize</td>
<td>Luancheng</td>
<td>114°4 E</td>
<td>37°5 N</td>
<td>50</td>
<td>12.2</td>
<td>530</td>
</tr>
<tr>
<td></td>
<td>Awassa</td>
<td>38°5 E</td>
<td>7°6 N</td>
<td>1710</td>
<td>19.2</td>
<td>1007</td>
</tr>
<tr>
<td></td>
<td>Nyankpala</td>
<td>0°6 W</td>
<td>93° N</td>
<td>183</td>
<td>27.7</td>
<td>995</td>
</tr>
<tr>
<td></td>
<td>Boone, Iowa</td>
<td>93°5 W</td>
<td>42°2 N</td>
<td>317</td>
<td>8.8</td>
<td>962</td>
</tr>
</tbody>
</table>

* For Luancheng both maize and wheat cropping.
* For Nyankpala the period 2000–2012 was used to calculate temperature and precipitation.

Table 2
Dominant soil textural classes on the study sites and their maximum rooting depth.

<table>
<thead>
<tr>
<th>Site</th>
<th>Texture</th>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Rooting depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jokioinen</td>
<td>Silty sand</td>
<td>15</td>
<td>35</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Boone, Iowa</td>
<td>Deep silty clay</td>
<td>50</td>
<td>45</td>
<td>5</td>
<td>210</td>
</tr>
<tr>
<td>Hays, Kansas</td>
<td>Deep silty loam</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>205</td>
</tr>
<tr>
<td>Luancheng</td>
<td>Clay</td>
<td>53</td>
<td>29</td>
<td>18</td>
<td>190</td>
</tr>
<tr>
<td>Awassa</td>
<td>Sandy loam</td>
<td>2</td>
<td>31</td>
<td>67</td>
<td>130</td>
</tr>
<tr>
<td>Kulumsa</td>
<td>Clay loam</td>
<td>52</td>
<td>30</td>
<td>18</td>
<td>150</td>
</tr>
<tr>
<td>Rothamsted</td>
<td>Medium silty</td>
<td>23</td>
<td>63</td>
<td>14</td>
<td>150</td>
</tr>
<tr>
<td>Nossen</td>
<td>Loam</td>
<td>42</td>
<td>38</td>
<td>20</td>
<td>150</td>
</tr>
<tr>
<td>Lleida</td>
<td>Silty loam</td>
<td>21</td>
<td>58</td>
<td>21</td>
<td>90</td>
</tr>
<tr>
<td>Nyankpala</td>
<td>Sandy clay loam</td>
<td>28</td>
<td>23</td>
<td>49</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3
Crop and cultivars used in the study.

<table>
<thead>
<tr>
<th>Site</th>
<th>Simulated crop</th>
<th>Cultivar name</th>
<th>Avg. growth duration (days)</th>
<th>Main growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jokioinen</td>
<td>Spring wheat</td>
<td>Kruunu</td>
<td>104</td>
<td>May–Aug.</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>2137</td>
<td>290</td>
<td>Sept.–June</td>
</tr>
<tr>
<td>Kulumsa</td>
<td>Wheat</td>
<td>Soissons</td>
<td>186</td>
<td>Oct–July</td>
</tr>
<tr>
<td></td>
<td>Winter wheat</td>
<td>240</td>
<td>Oct–June</td>
<td></td>
</tr>
<tr>
<td>Rothamsted</td>
<td>Winter wheat</td>
<td>Jimai26</td>
<td>242</td>
<td>Oct–June</td>
</tr>
<tr>
<td>Nossen</td>
<td>Winter wheat</td>
<td>Maize</td>
<td>197</td>
<td>June–Sept.</td>
</tr>
<tr>
<td>Lleida</td>
<td>Winter wheat</td>
<td>Obatanpa</td>
<td>110</td>
<td>March–Aug.</td>
</tr>
<tr>
<td></td>
<td>Maize</td>
<td>Okeh</td>
<td>164</td>
<td>April–October</td>
</tr>
<tr>
<td>Nyankpala</td>
<td>Maize</td>
<td>BHS40</td>
<td>145</td>
<td>May–Sept.</td>
</tr>
</tbody>
</table>

Reducing and limiting factors would be eliminated, is Yp for irrigated and Yw for rainfed systems (van Ittersum et al., 2013). Economically, however, such yield levels are not realistic and a benchmark value of 80% of the maximum attainable yield, which might vary according to the socio-economic context, has been suggested as a ceiling for the semi-arid tropics (van Ittersum et al., 2013). In the GYGA approach, one well-tested process-based crop model for a given site is used to simulate Yp and Yw for a certain numbers of years and then compared to Ya (Grassini et al., 2015). Such an approach requires detailed knowledge of local environmental and management factors influencing Yp, Yw and Ya (van Bussel et al., 2015). In addition, Kassie et al. (2014) compared the yield gap between Ya and Yb. Using the improved experimental management practices yield Yb as a ceiling has the advantage that the results are realistically achievable by farmers, but the disadvantage is that such yields are difficult to compare across sites as the definition of Yb depends often on the local socio-economic context, i.e. what is feasible for most farmers. Using bio-physical process-based crop models offers the opportunity to separate biophysical factors from other factors co-determining the maximum attainable yield.

Usually, yield gap studies are restricted to identifying the mean yield gap over time for a given site and not much attention has been paid towards the magnitude of inter-annual variability. Mueller et al. (2012) mapped at a global scale yield gaps, and showed large yield gaps in Africa, and smaller ones in Europe, China and the US. Thus, at this scale, yield gaps can be related to the technology level, which can be defined by amount and type of inputs applied, access to the technologies (availability where it is needed and capital availability to finance these) and the knowledge needed to apply them. However, we argue that it is important to also consider climate-induced risk in studying yield gaps as it can be a major cause for the persistence of the yield gap. This is due to the fact that the variability of attainable yield caused by climate variability and the associated risk are important factors influencing farmers’ decision-making. There is a long-standing debate about farmers’ risk aversion attitudes (Menapace et al., 2013; Rötter and van Keulen, 1997), and indeed farmers tend to be reluctant to intensify under high climate risk (Muchow and Bellamy, 1991; Cooper and Cee, 2011). For instance, combined crop and economic modelling have shown that in low-rainfall southern Australia, where production risk is so high that complete crop failure can occur in some years, higher nitrogen input than applied by farmers would have led to an overall higher profit (Monjardino et al., 2015, 2013). In addition, instead of applying an average fertilizer rate in all seasons, modifying the input according to season-specific water-limited yield as estimated by seasonal weather forecasting in conjunction with soil-crop modelling, could additionally help to better realize the potential for intensification (Asseng et al., 2012).

Utilizing data from ten sites and two crops (wheat and maize) representing some major global food production systems, we investigated the role climate variability might play in determining yield gaps. We hypothesized that: (i) the higher the inter-annual attainable yield variability, the larger the mean yield gap for a given site, (ii) yield gaps decrease along a gradient of technology intensities, (iii) the higher the season-specific maximum attainable yield, the larger the yield gap for this season, (iv) when instead of the yield gap Yw-Ya (Yp-Ya respectively), the yield gap Yw-Yb (Yp-Yb) is analyzed, the influence of seasonal specific attainable yield on the size of the yield gap is smaller in comparison to the attainable yield-Ya gap. The reason might be that...
in well controlled experiments usually higher yields (Yb) are achieved indicating scope for intensification.

2. Material & methods

2.1. Sites

We selected ten sites with contrasting agro-ecological and socio-economic conditions. In each region wheat, or maize, was the dominant crop. For wheat, climatic conditions ranged from temperate with cold, wet winters in the boreal climate of Finland, to tropical highlands at Kulumsa in Ethiopia. For maize, location ranged from a site in a tropical savannah climate in Ghana to a continental temperate climate in Iowa, USA (Table 1).

Soil textural classes varied widely between sites (Table 2). Wheat was cultivated either as winter or spring type according to climate conditions. The most popular cultivar and its associated growth duration were collected for each site (Table 3). Only wheat cropping in Luancheng was completely irrigated, and maize received supplementary irrigation in certain dry years, other sites – maize and wheat - were rainfed systems.

Levels of technology intensity ranged from low input systems as found in many parts of Africa to highly intensive systems as found in China, USA and Europe. The latter ones are backed up by whole

![Global map with study sites (red stars) used for wheat (a) and maize (b) superimposed on actual average regional yields based on Monfreda et al. (2008). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)](image)
agribusinesses for fertilizer, protection measures, machines and crop insurance options. The selected sites are representatives of some major production systems around the globe (Fig. 1).

At each site, Ya representing average farmers’ practices was recorded within the period of 1981 to 2010 (Appendix Table A1). These data were from the district records. In addition, at most sites measured yields from experimental field trials (Yb) were collected (Appendix Table A2). Sources for these data are provided in Appendix Table A1 & 2. Yields are reported at standard commercial moisture content for wheat (13.5%) and for maize (15.5%). Yield gaps were expressed as coefficient of variation (CV%) of attainable yield (water-limited yield (Yw) for rainfed and potential yield (Yp) for the irrigated site (Luancheng, wheat). CV% of attainable yield was calculated for Yb and Ya individually only for the years, where Yb, respectively Ya, was available, which can cause differences in CV% of attainable yield for Yb and Ya for one site. Yb was not available in Nyankpala, Boone, Hays, and Rothamsted. Information on data sources of Yb and Ya are available in the Appendix. Dashed squares are used to illustrate the size of Yb and Ya for a site.

2.2. Model setup

For each site, a regionally experienced modelling group conducted the simulation runs. Yp and Yw were simulated for the years, where Yb and Ya were available, within the period 1981–2010 with process-based crop simulation models (Table 4). Here, we followed the protocol developed for the GYGA: Models have been calibrated and tested for the region and the crop cultivar used. Daily weather data, necessary input to the models, were recorded at a nearby representative weather station. The soil module was parameterized for the dominant soil type (Table 2). A common recent cultivar was chosen and used over the simulation period (Table 3). Setting initial soil water for simulation runs - continuous simulation or re-set every year is still a point of discussion (Grassini et al., 2015; Maltais-Landry and Lobell, 2012; White et al., 2011). Thus, it was left to the experiences by individual modelling groups and is provided for each site in the appendix (Appendix Table B). Management practices defined in the simulation followed yield optimizing strategies for the given region (Appendix Table B). All simulated yields are presented at 13.5% grain moisture for wheat and 15.5% for maize to be consistent with measured yields.

3. Results

3.1. Mean yield gap in relation to attainable yield variability and technology level

The analysis showed that the variability level of Yw, or respectively
Yp, (expressed as coefficient of variation) for a given site did not affect the mean relative yield (Fig. 2). Ya for sites associated with relatively high variability of attainable yield - as found at Hays, Lleida and Boone - reached about two-thirds of Yw, whereas Nyankpala with similar level of Yw variability, and for sites with even lower level of Yw variability (Kulumsa, Awassa), achieved only one-fifth of Yw. This indicated a lack of relationship between the level of variability in Yw and the yield gap expressed as relative Ya and Yb. It appeared that the technology level, rather than the level of variability, determined the mean yield gap. For the African sites (Kulumsa, Awassa and Nyankpala), which can be considered as ‘low input’ sites, the relative yield (Ya) was 20%, while for the European, Chinese and US-American sites yield gaps were about 60% for wheat and about 80% for maize. Interestingly, the ranges of mean relative Ya for the high and low technology level were consistent across crops and regions.

With the exception of Luancheng (maize and wheat), Yb was greater than Ya, especially for Awassa and Kulumsa (Figs. 3 and 4), where Yb was more than double that of Ya; but also for Nossen and Lleida Yb was much greater than Ya (Fig. 3). Highest median Yw values for wheat occurred for Rothamsted (11,800) and Nossen (10,900 kg/ha). Similar high yields were modelled for irrigated wheat (Yp) in Luancheng (10,700 kg/ha). Hays and Lleida had the lowest Yw as a result of low

Fig. 3. Potential (Yp), water-limited (Yw), experimental (Yb) and actual farmer yield (Ya) for wheat for seven selected locations. Yp and Yw are presented only for years where Ya was available. Number of years observed (Yb and Ya) and simulated (Yw and Yp) are given as N. Thick horizontal lines represent the median, boxes delimit the inter-quartile range (25–75 percentiles) and error bars represent ± 1 σ (standard deviation). Outliers are presented as circles.

Fig. 4. Potential (Yp), water-limited (Yw), experimental (Yb) and actual farmer yield (Ya) for maize for four selected locations. Yp and Yw are presented only for years where Ya was available. Number of years observed (Yb and Ya) and simulated (Yw and Yp) are given as N. Thick horizontal lines represent the median, boxes delimit the inter-quartile range (25–75 percentiles) and error bars represent ± 1 σ (standard deviation). Outliers are presented as circles.
precipitation (Table 1).

The most favorable site in terms of median Yw for maize was Boone, which showed very high inter-annual variability (Fig. 4); a similar high Yw was also simulated for Luancheng and Awassa.

3.2. Season-specific yield gap in relation to inter-annual attainable yield variability

The inter-annual variability of the yield gap Yw-Ya showed a significant negative relationship for all rainfed sites between season-specific Yw and relative yield (Figs. 5 and 6) with the exception of maize at Luancheng. In rainfed cropping systems, the higher the Yw in a specific year the larger the yield gap for wheat (Fig. 5) and maize (Fig. 6). For the irrigated wheat site, Luancheng, there was no relationship between Yp and the relative yield.

For Yw-Yb versus Yw this effect was less visible, indicated by the lower R² coefficient for Jokioinen, Kulumsa, Nossen and Awassa (Fig. 5). Only in Lleida, a higher R² value was found for Yb. For Jokioinen, Hayes, Lleida, Boones and Luancheng, relative yields were above 100%, i.e. Yα > Yw in some years (Figs. 5 and 6). This occurred when the model simulated a low Yw due to limited water availability. This could be due to deeper roots and more water access in the actual field than assumed in the simulation. Another important reason might be that the initial water setting underestimated carry-over water affecting yields observed in the field, but not considered in some of the simulations. This could be the case for Hays in years where Yw < Yα; here the simulated attainable yield was low in comparison to simulations for other years, indicating a very unfavorable year.

A significant narrowing of the yield gap over time was observed only in Luancheng (both for maize and wheat), and Rothamsted (Figs. 7 and 8). For other sites, no significant trend was detected.

4. Discussion

4.1. Mean yield gap in relation to attainable yield variability and technology level

There was no relationship between mean yield gap and attainable yield variability. But, China, the US, and Europe had a relative actual yield (Ya) of about 60% of potential for wheat and about 80% for maize in contrast with only about 20% across sites in Africa. Technology level differences appear to be the main determinant of the mean yield gap. Higher input systems which have been possible in China, Europe and the US have reduced the yield gap for wheat and maize, but not for countries in Africa, consistent with Mueller et al. (2012). However, average wheat Ya has not reached the 80% of Yw set as a benchmark (Lobell et al., 2009) in these countries. The GYGA (2017) results for Finland, England and Spain were in line with the gaps presented here, i.e. the 80% benchmark was not reached. Other studies have shown for irrigated rice in Southeast Asia (Papademetriou et al., 2000), irrigated maize in the US (Grassini et al., 2011), and rainfed wheat in Australia (Hochman et al., 2013; van Rees et al., 2014), that the best farmers are getting close to this 80% benchmark. Similar large yield gaps for Africa with relative yields of 20% have also been reported in the GYGA studies (GYGA, 2017) and elsewhere (Kassie et al., 2014; Mueller et al., 2012; Rötter and van Keulen, 1997; Tittonell and Giller, 2012).
4.2. Season-specific yield gap in relation to inter-annual attainable yield variability

A key finding of this study was that the season-specific yield gap increased significantly in the investigated rainfed systems with increasing \( \Delta Y \) with the exception of Luancheng. At this site, as mentioned supplementary irrigation is applied to maize by farmers in case of dry spells. Farmers have not been able to adapt their practices to the specific season, but rather use the same crop management across all seasons. As a consequence, farmers miss many of the high attainable yields in favorable seasons, consistent with reports from high climate risk regions (i.e. low-rainfall southern Australia: Hoffmann et al., 2016; or for semi-arid Kenya: Rötter and van Keulen, 1997). Interestingly, in comparison with \( Y_a \), \( Y_b \) did not have such correlation with season-specific \( Y_w \) with the exception of Lleida, suggesting higher attainable yields are possible with increasing fertilizer inputs at those locations. While higher inputs can increase yields in some seasons, if applied consistently across all seasons, this can also result in no yield gain, or even in reduced yields, due to 'haying-off' (Herwaarden et al., 1998) in dry years with little to no nitrate leaching. Thus, uncertainty with respect to the profitability of season-specific investments into increased input might be a major barrier to narrowing yield gaps.

Finding ways to reduce climate-induced risk might be needed as despite the need to increase production, for most sites (eight out of ten) the yield gaps were not reduced in our study. The yield gap was narrowed during 1981–2010 at Rothamsted and Luancheng. In Luancheng, the maize and wheat yield gaps have been significantly reduced, due to higher inputs of fertilizer, as well as a decrease in \( Y_p \) due to a decrease in solar radiation (Tao et al., 2015; Yang et al., 2013). Thus, crop production in Luancheng and other regions in China increased with increased inputs, resulting in serious environmental concerns (Gao et al., 2014; Qiu, 2010; Sun et al., 2015). Similarly, for Rothamsted, increased fertilizer input has contributed to the narrowing of the yield gap (Dobermann, 2016).

4.3. Exploiting climate variability and shifts in yield ceilings

Climate induced risk can potentially be better managed in rainfed systems with skillful forecasting systems. Seasonal rainfall forecasting and its applications for crop modelling (Cantelaube and Terres, 2005; Capa-Morocho et al., 2016; Landman et al., 2012; Roudier et al., 2014) and how this information is provided to farmers (see, e.g. Patt et al., 2005; Rickards et al., 2014) differs from region to region. A key challenge remains medium and long-term climate forecasting. Nevertheless, this analysis showed that there is a potential benefit from seasonal forecasts to narrow the yield gap in rainfed environments (Asseng et al., 2012; Ramirez-Rodrigues et al., 2014). Another option to reduce risk from variable rainfall is the introduction of irrigation. For instance, expanding irrigation has been explored in Mediterranean countries (e.g. Lorite et al., 2012) and is sometimes considered as an adaptation option to climate variability/change in this region (e.g. see Ruiz-Ramos et al., 2017). Interestingly, contrary to the rainfed sites we could not observe the trend of increasing yield gaps when attainable yield was higher than in normal years for the irrigated site (Luancheng, wheat, and supplementary irrigation for maize) of this study. Thus, a separate analysis for irrigated cropping systems for multiple sites would be helpful to verify whether there is indeed no relationship between season-specific attainable yield and the size of the yield gap.

Potentially, climate variability will play even a greater role in the future (Coumou and Rahmstorf, 2012), thus linking climate-induced risk with yield gap analysis, including the identification of potential adaptation strategies might become more important. In addition, global environmental change can cause trends or shifts in attainable yield, which is, for instance, illustrated by the example from reduced global radiation in China. Long-term increases or declines of attainable yields have also been investigated for various cereals such as wheat (Rötter et al., 1997), rice (Dobermann et al., 2000), wheat (Penning de Vries et al., 1987) or barley (Palosuo et al., 2015). The role of progress in plant breeding over the period and its effect on the size of the yield gap is currently not included in the approach, but might be of interest for

Fig. 6. Each season specific relative (% of attainable yield) actual farmer yield (Ya) and experimental yield (Yb) was plotted against simulated attainable maize yield (water-limited yield). Straight line is the regression for Ya and dashed line is for Yb. R² and p-value are given for each analysis. Significance levels are indicated as *p < 0.05; **p < 0.01; ***p < 0.001; p > 0.05 is not indicated. Note: Squares indicate season where Ya or Yb respectively, was higher than simulated Yw.
Fig. 7. Annual actual farmer wheat yield (Yₐ) expressed as relative yield (% of attainable yield) illustrating the season-specific yield gap within the period 1981 and 2010. Dashed line is the regression between relative yield and year. R² and p-value are given for each analysis. Significance levels are indicated as *p < 0.05; **p < 0.01; ***p < 0.001; p > 0.05 is not indicated.

Fig. 8. Annual actual farmer maize yield (Yₐ) expressed as relative yield (% of attainable yield) illustrating the season-specific yield gap within the period 1981 and 2010. Dashed line is the regression between relative yield-year. R² and p-value are given for each analysis. Significance levels are indicated as *p < 0.05; **p < 0.01; ***p < 0.001; p > 0.05 is not indicated.
further research. From a practical point of view, a key focus should be on developing alternative technology packages to better exploit inter-annual variability of Yw (e.g., fertilizer management based on seasonal forecast) and shifts in yield ceilings. Finally, from a methodological point of view, it is known that crop models differ among each other in terms of complexity and simulated output (Asseng et al. 2013). Thus, in the future it might be of interest to have at least one widely tested model running for all sites for better comparability.

5. Conclusions

In this study we evaluated explicitly the linkage between climate variability and the yield gap. Thereby, we showed that season-specific attainable yield had a significant influence on the magnitude of a yield gap. Further yield gap studies can potentially benefit of implementing this approach to analyse the importance of climate risk for farmer decision making. Overall, our findings underlined the potential for improving season specific farming practices for crop intensification to narrow the overall yield gap.

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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.2017.03.012.

References

Dobermann, A., Dawe, D., Roetter, R.P., Cassman, K.G., 2000. Reversal of rice yield gap. Thereby, we showed that season-specific attainable yield had a significant influence on the magnitude of a yield gap. Further yield gap studies can potentially benefit of implementing this approach to analyse the importance of climate risk for farmer decision making. Overall, our findings underlined the potential for improving season specific farming practices for crop intensification to narrow the overall yield gap.

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References
