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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, CO_2 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.

	Site	Country	Longitude	Latitude	Altitude m a.s.l.	Annual mean temperature °C	Precipitation mm/year
Wheat	Jokioinen	Finland	23°3 E	60°4 N	104	4.6	627
	Kulumsa	Ethiopia	39°1 E	8°2 N	2200	17.0	832
	Hays, Kansas	USA	99°2 W	38°5 N	613	12.3	592
	Lleida	Spain	1°1 E	41°5 N	330	15.0	342
	Rothamsted	UK	0°2 W	51°5 N	128	9.9	712
	Nossen	Germany	13°2 E	51°4 N	255	9.1	653
Maize	Luancheng[a]	China	114°4 E	37°5 N	50	12.2	530
	Awassa	Ethiopia	38°5 E	7°6 N	1710	19.2	1007
	Nyankpala[b]	Ghana	0°6 W	9°3 N	183	27.7	995
	Boone, Iowa	USA	93°5 W	42°2 N	317	8.8	962

[a] For Luancheng both maize and wheat cropping.
[b] 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.

Site	Texture	Clay	Silt	Sand	Rooting depth
Jokioinen	Silty sand	15	35	50	100
Boone, Iowa	Deep silty clay	50	45	5	210
Hays, Kansas	Deep silt loam	NA	NA	NA	205
Luancheng	Clay	53	29	18	190
Awassa	Sandy loam	2	31	67	130
Kulumsa	Clay loam	52	30	18	150
Rothamsted	Medium silty	23	63	14	150
Nossen	Loam	42	38	20	150
Lleida	Silty loam	21	58	21	90
Nyankpala	Sandy clay loam with gravel content between 15 and 50%	28	23	49	100

Table 3
Crop and cultivars used in the study.

Site	Simulated crop	Cultivar name	Avg. growth duration (days)	Main growing season
Jokioinen	Spring wheat	Kruunu	104	May–Aug.
Hays	Winter wheat	Variety 2137	290	Sept.–June
Kulumsa	Wheat	Kubsa	120	June–Oct.
Rothamsted	Winter wheat	Avalon	290	Oct.–Aug.
Nossen	Winter wheat	Batis	186	Oct–July
Lleida	Winter wheat	Soissons	240	Oct–June
Luancheng	Winter wheat	Jimai26	242	Oct.–June
	Maize	Yedan20	197	June–Sept.
Nyankpala	Maize	Obatanpa	110	March–Aug.
Boone	Maize	Mod. DeKalb 611	164	April–October
Awassa	Maize	BH540	145	May–Sept.

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 exploitation by farmers (Lobell et al., 2009; van Ittersum et al., 2013, van Wart et al., 2013). Previous large-scale assessments were based on simple agro-ecological zone-yield relationships (Licker et al., 2010; Mueller et al., 2012). More recently, the research initiative Global Yield Gap Atlas (GYGA; www.yieldgap.org) has developed a protocol for such studies and aims to assess yield gaps across the globe (Grassini et al., 2015; van Bussel et al., 2015; 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 yield 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 Coe, 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