More than the gap: Yield gap extensions, measurement issues and application

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# Introduction

Yield gap is a powerful concept to illustrate the potential to increase future crop yield. It is defined as the difference between potential yield and actual yield observed at the plot, farm or regional level. Despite its abundant use, the yield gap can be defined and measured in a number of ways, which has resulted in lack of consistency in yield gap analysis in the literature (Lobell, Cassman, and Field 2009). Furthermore, in a recent review of the use of yield gap analysis in key policy papers Sumberg (2012) noted that *"there is a tension between the notion of yield gap as developed in crop ecology (although even here there is no single or consistent usage) and micro-economic studies"* [p. 510].

The aim of this paper is to address some of these criticisms by integrating micro-economic and agronomic yield gap approaches into one single framework. The framework follows the reasoning of Tittonell and Giller (2013), who argue that the gap is caused by two main factors: (1) resource use intensity and (2) access and use of technology. It also extends the work of Fischer (2015), who recently reviewed definitions of crop yield and yield gaps and builds on the work of Van Dijk et al. (2016) and Silva et al. (2016), who combine agronomic and economic approaches to yield gap analysis and measurement.

We start by critically reviewing the most common crop yield and yield gap definitions and higlight a number of inconsistencies in their definition and use. We demonstrate that 'actual yield' can be measured in different ways, leading to different yield gaps. Similarly the use of 'attainable yield' is fraught with difficulties and in practice have been used to define conceptually different production levels. We continue by ritically addressing the use of the term 'exploitable yield level (Cassman et al. 2003; Ittersum et al. 2013), sometimes referred to as 'economic yield level' (Fischer 2015). Exploitable yield is normally used to capture the part of the yield gap that will not be closed because of economic constraints and is normally set to 75-85% of potential yield (Cassman 1999; Cassman et al. 2003; Ittersum et al. 2013).

As pointed out by Fischer (2015), these numbers are based on "general experience" [p.11] and mainly represent to situations *"where there is no other competition for the farmers’ resources, and world prices and reasonable transport costs operate"* [p.11]. He also points out that in situtations Where this does not occur, such as Sub-Saharan Africa, which is characterised by poor infrastructure and weak institutions, the exploitable yield gap is expected to be much higher. Despite its weak underpinnings the 75-80% 'rule of thumb' is applied frequently as a 'target' in studies to assess potential to increase future crop production. (Oort et al. 2015; Aramburu Merlos et al. 2015), which can be potentialy misleading, in particular when applied to developing countries. We argue that the definition of (true) economic yield should be rooted in neoclassical economic theory, the dominant paradigm in econimics, and be estimated using information on the prices of inputs and outputs. Analogue to arguments in crop ecology, which stress the localised nature of agroclimatic conditions, we argue that economic yield levels are location specific. It is well-known that in many developing countries (subnational) trade is limited due to poor infrastructure resulting in isolated markets and differentiated market prices (**???**).

To solve some of the inconsistencies with the existing yield and yield gap definitions our conceptual framework introduces three new yield levels that make it possible to decompose the conventional yield gap into a ' technical efficiency', 'economic', 'feasible' and 'technology'. We believe that our framework is able to capture all existing yield gap definitions and reveal the impact of resource intensity and technology on yield gaps.

To demonstrate our framework we present an application using a large nationally representative farm level survey on maize production in Nigeria. [ADD].

The structure of the paper is as follows. Section 2 provides a conceptual framework that integrates varies definitions of yield levels and yield gap. Section 3 briefly discusses the Nigerian farm level maize data set that is used to illustrate the conceptual model. Section 4 computes the yield levels and yield gaps followed by a discussion in Section 5. Finally, Section 6 concludes.

# Background

## Conventional yield levels

For the discussion it is relevant to briefly summarise the convential yield levels that are used in the agronomic literature to estimate yield gaps.

* *Actual yield* also sometimes referred to as (average) farm yield(Fischer 2015; Ittersum et al. 2013), is the average annual yield obtained by farmers in a geographic area for a given crop with a given water regime (Grassini et al. 2015). It is normally expressed in tons per hectare (tons/ha) and expressed relative to harvested land area (Fischer 2015).
* *Potential yield* is defined as *“the yield of a cultivar when grown in environments to which it is adapted, with nutrients and water non-limiting and with pests, diseases, weeds, lodging, and other stresses effectively controlled”* (L. Evans and Fischer 1999). It depends on local climate and weather factors, including atmospheric CO2 emissions, solar radiation, temperature as well as plant characteristics but is independent of soil, which is assumed to be physically and chemically favourable to crop growth (Van Ittersum and Rabbinge 1997; Sadras et al. 2015). Potential yield is the preferred benchmark for irrigated crops, where precipitation is not a constraining factor.
* *Water-limited potential yield* (or just water-limited yield) is similar to potential yield but takes into account that water supply is limited, which is particularly relevant for rainfed crops. It is therefore strongly influenced by the water holding capacity and rooting depth of the soil, which regulate the supply of water. Water-limited potential yield is the reference value to estimate yield gaps for rainfed crops.
* *Exploitable yield.* is defined as 70-85% of (water-limited) potential yield. The 70-85% is used as a 'rule of thumb' to capture the empirical finding that yield levels tend to stagnate at around 70-85 percent of potential yield (Cassman 1999; Cassman et al. 2003; Lobell, Cassman, and Field 2009, Ittersum et al. (2013), Fischer (2015)). The explanation for stagnating yield levels is mainly economic. For most farmers it will not be cost-effective to purchase the large amount of inputs (e.g. fertilizer) that are needed to produce at the potential yield level (Fischer, Byerlee, and Edmeades 2014) nor wil farmers be willing to pay for the additional costs that are needed to 'fine-tune' crop and soil management (Cassman et al. 2003). Fischer (2015), uses exact the same definition but calls it\_economic yield\_.
* *Attainable yield* is used frequently in the yield gap literature but often in a rather ad hoc and inconsistent way, meaning a variety of things. Fischer, Byerlee, and Edmeades (2014); Fischer (2015) equates attainable yield with *economic yield* by defining it as *'the yield attained by a farmer from average natural resources when economically optimal practices and levels of inputs have been adopted while facing the vagaries of weather'* [p.32]. Sadras et al. (2015) use the following definition: *'the best yield achieved through skilful use of the best available technology'* [p. 6]. A similar definition is provided by (Tittonell and Giller 2013), who defined coin the term 'locally attainable yield', which is *the maximum yield achievable by resource endowed farmers in their most productive fields'* [p78]. Clearly, this use of attainable yield differs from the previous definition as it reflects the highest posible yield that can be reached with best available technology, not economic constraints. Finally, several researchers take an empirical approach and refer to attainable yield as the average of the (90 or 95 percentile) highest yield in the sample of observations (A. J. Hall et al. 2013; Mann and Warner 2017). In many cases, the empirically observed attainable yield is used to approximate (water-limited) potential yield when results from crop simulation, the preferred measure (Ittersum et al. 2013), are not available.
* *Highest farmers' yield.* (or best farmers' yield) is average of the top 90 or 95 percentile actual yield observed in a sample of farmers or plots (Laborte et al. 2012; Silva et al. 2016). It is idential to the last definition of attainable yield mentioned above.

## Conceptual framework

Figure ? depicts our conceptual framework to illustrate and disentange the various yield levels that are used in the literature. It shows the observed input and output combinations of a number of agricultural units (e.g. field, farm or region). For purpose of illustration, we assume that the observations are small-scale farms in Africa, who produce a single output (e.g. maize) using one input (e.g fertilizer), agroeconomic conditions are identical for all farms and water is not limited. The *theoretical yield response function* describes the relationship between yield and inputs under perfect crop management and most advanced technology. The maximum of the function is the potential yield level. The *frontier yield response function* is estimated using actual observations from a sample of farmers or plots in a specific country or region. It measures best-practice performance at all input levels and reflects the best management practices and technology that are available in the region. The diagonal line presents the relative input () and output () market price faced by the farmers.

Figure X depicts the two yield levels that determine the conventional yield gap, actual yield () for farm and potential yield () as well as the associated input levels. Similar to Tittonell and Giller (2013), we argue that the yield gap is caused by two main factors. The first is resource use intensity. The relationship between resource use and yield is given by the yield response curve. Intensification will results in higher yields, represented by a movement over the curve to the right. We argue that for the majority of farmers the decision on how much inputs to use depends on economic considerations (i.e. profit maximization behaviour). Under the assumption of perfect functioning agricultural markets and full information, the demand for inputs will solely depend on relative market prices of inputs and output, and production technology (Sadoulet and Janvry 1995). In developing countries, the assumption of perfect markets is not realistic because of high transaction cost, missing credit and insurance markets and lack of information on input and output prices and available technologies (**???**; **???**). Under these circumstances, the demand for inputs tends to be lower than the economic optimum resulting in lower output and yield (**???**). In some cases, farmers the input decision of farmers can be guided by other non-economic objectives such as environmental awareness or output targets [Ref to RUE Rabbinge? - Example] resulting in suboptimal economic input use.

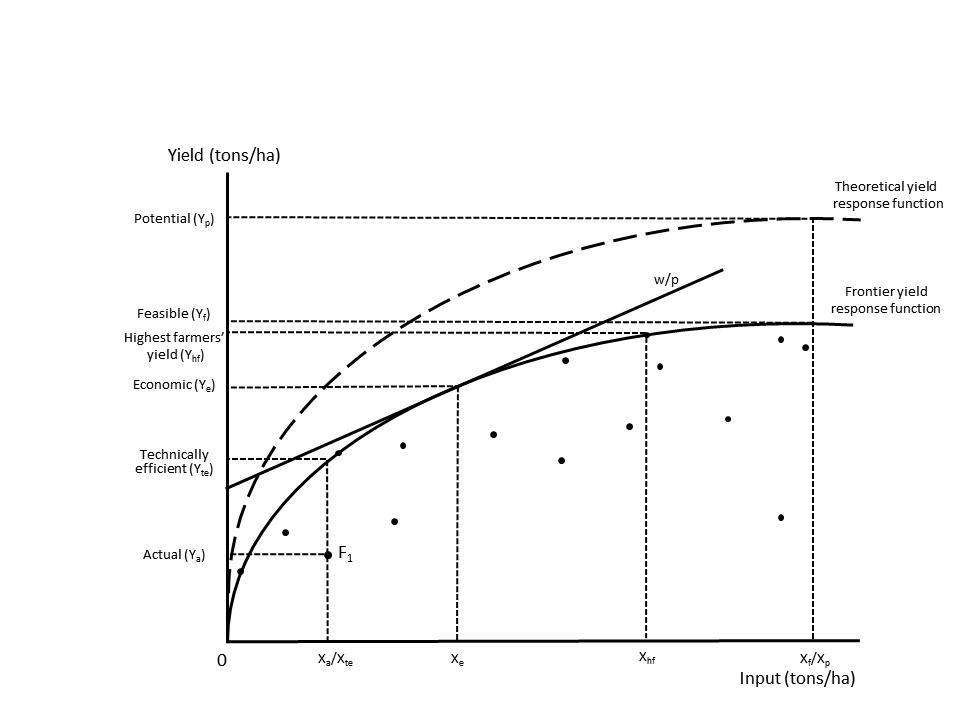
The second major cause of yield gaps is related to the efficient use and adoption of technology. Two different aspects are relevant. The first is technical efficiency, which is defined as the farm’s ability to produce maximum output given a set of inputs and technology (Farrell 1957; Coelli et al. 2005). Best-practice farmers, who are located on the yield response frontier, are considered technically efficient. Farmers below the frontier are considered inefficient because they have a lower yield despite using the same level of inputs and experience the same agroeconomic conditions. Technical inefficiency implies that crop management is suboptimal, referring to differences in establishment dates, and time, space and form of the inputs applied, which, in turn can be related differences in experience and practices, and access to extension services (see Bravo-Ureta et al. 2007; Ogundari 2014 for reviews).

The second technology aspect is the adoption of advanced technologies. As has been poined out by Tittonell and Giller (2013) most small-scale farmers are subsistence farmers with limited access to appropriate technologies. Even if resource availability would not be a problem and farmers would produce at best-practice level, there would still be a gap with the potential yield level. Closing this gap would require the use of advanced technologies such as precision agriculture, advanced crop management and the adoption of the latest varieties (hybrid seeds). The adoption of advanced technologies will help farmers to increase their yield to a level that previously not could be attained. The effect is an upward shift of the frontier yield response curve in the direction of the theoretical yield response curve and a reduction of the yield gap.

Figure X depicts the three yield levels that can be derived on the basis of the economic, technical efficiency and technology constraints discussed above:

* *Technical efficiency yield* measures best-practice performance for a field, farm or region at each input level and reflects the available technology and best management practices in the sample.
* *Economic yield.* is defined as the yield level where profits are maximized (Van Dijk et al. 2016). At this level, the marginal cost of acquiring an additional unit of input (e.g. fertilizer) is equal to the marginal revenue of producing an additional unit of output (e.g. tons of maize). This is a situation of allocative efficiency where Inputs and outputs are distributed in an economic optimal way. This definition of economic yield is consistent with neoclassical economic theory, the dominant paradigm in economics, which postulates that economic actors (e.g. farmers) maximize profits (not production), subject to given output prices, input costs and production technology (Sadoulet and Janvry 1995). *Economic yield* is identified by the point where the relative market price line () is tangent to the frontier yield response function. We prefer this definition over the use of *exploitable yield* and *economic yield* outlined above, which are based on a 'rule of thumb' rather than theorectical assumptions.
* *Feasible yield.* Feasible yield represents the maximum feasible yield that can be reached on a plot with the available technology and best-practice management but without any economic constraints (e.g. inputs are free). This yield level is also sometimes referred to as ‘potential farm yield’ (Datta 1981), ‘maximum attainable yield’ (FAO 2004) and ‘technical on-farm ceiling yield’ (De Bie 2000). It has the same meaning as the definition of *attainable yield* used by Sadras et al. (2015) and Tittonell and Giller (2013).

The figure also depicts the *highest farmers' yield* (for convenience measured as a single observation). In the present situation highest farmers' yield is much higher than economic yield. This implies that, given relative market prices () the farmer with the highest yield is not producing at the economic optimum level. Potential reasons for this behaviour might be [ADD]. Another reason might be that the actual realitive price of the farmer is lower than the market because of (fertilizer) subsidies, which are common practice in many sub-Saharan African countries. Hence, this particular situation demonstrates that the *highest farmers' yield* is not a good proximate for *economic yield*. On the other hand, although resource use differs considerably (the difference between and ) the *highest farmers' yield* is very close to the *feasible yield level*. A well-known observation in agronomy is that the response to inputs is decreasing (or even stagnates or becomes negative) [REF], at high levels of input use. Hence, despite constraints to resource use, the yield of farmers with the highest yield is likely to be close to the feasible yield level [WILL CHECK IF THIS IS THE CASE FOR NIGERIA]. For this reason, we argue that the \_highest farmers\_yield is an accetable indicator if one is interested in having a benchmark for the maximum yield achievable on a field using the best-available technology. It is an emperical question whether actual yield, technical efficiency yield, economic yield and feasible yield are located at or close to the same point. This is further investigated below.



## Yield gaps

The total yield gap () can be decomposed in four parts: the technical efficiency yield gap (), the economic yield gap (), the feasible yield gap ()and the technology yield gap () (Van Dijk et al. 2016). The sum of the economic yield gap and the feasible yield gap has been referred to as the resource yield gap () (Silva et al. 2016). Table 1 summarizes the definitions and potential causes for the the six yield gaps that can be derived from Figure 1. Global studies of the yield gap clearly show that the (total) yield gap is highest in sub-Saharan countries like Nigeria [CHECK] (**???**; **???**; **???**). The decomposition of yield gaps provide a deeper understanding for this finding and its causes. [ADD REF AND CHECK] show that the difference between best-practice and average yield is the same between rich and poor countries [CHECk}. This means that although the technical efficiency gap might be a key cause of yield gaps, is does not explain the large difference in yield gaps between poor and rich countries that are observed [ADD sentence of finding of Silva et al.]. On the other hand, we expect the economic yield gap to be larger in developing countries, such as Nigeria, because of pervasive market failures that characterise (agricultural) input and output markets. Equally, the feasible yield gap is expected to be relatively large in in developing countries because of the unfavourable balance between input and output prices. An example is the high prices for fertilizer in many sub-Saharan countries as a consequence of poor dealer networks, high transportation costs and small market size (**???**). Finally, the technology yield gap is also expected to be large in sub-Saharan countries. [ADD evidence technology use in Africa]. The existence of (agricultural) technology gaps between rich and poor countries has been studied widely (**???**, (**???**), (**???**)) and has been related to the combination of broader institutional, technological, economic and social factors.

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Table 1: Yield gaps

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| --- | --- | --- | --- | --- |
| Yield gap | Estimation | Definition | Measures | Causes |
| Total yield gap (Yg) | Yp - Ya | The gap between (water-limited) potential yield and actual yield | The biophysical potential for farmers to increase actual yield in a specific agroeconomic environment | The combination of all causes below |
| Technical efficiency yield gap (TEYg) | Yte - Ya | The gap between technical efficiency yield and actual yield measured as the distance to the frontier yield response function | The potential for farmers to increase actual yield in comparison with best-practice farmers that use the same level of inputs and operate under the same agroecological conditions. | Suboptimal crop management caused by knowlegde constraints (e.g. differences in experience, practice, management skills and access to extension services) |
| Economic yield gap (EYg) | Ye - Yte | The gap between economic yield and technical efficiency yield | The extent to which farmers can improve allocative efficiency and increase profits, given input and output prices and available technology. | Market failures caused by missing credit and insurance markets and information assymetries on input and output prices. Production objectives other than profit maximization. |
| Feasible yield gap (FYg) | Yf - Ye | The gap between feasible yield and economic yield | The extent to which economic constraints prevent farmers from producing maximum feasible yield with the available technology and best-practice management | Unfavourbale balance between input and output prices farm-gate (including transport costs, taxes, subsidies and other costs associated with the purchase of inputs and sale of outputs). |
| Technology yield gap (TYg) | Yp - Yf | The distance between the frontier and theoretical yield response curve measured by the gap between (water-limited) potential yield and feasible yield | The extent to which the lack of advanced technologies prevent (best-practice) farmers from reaching potential yield. | Various national-level institutional, technological, economic and social factors that prevent the diffusion and adoption of advanced and appropriate technologies to farmers. |
| Resource yield gap (RYg) | Yf - yte | The gap between feasible yield and technical efficiency yield | The extent to which allocative efficiency and economic constraints prevent farmers from producing at maximum feasible yield with the available technology and best-practice management | Market failures, production objectives otherr than profit maximization, and economic constraints. |
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## The definition and measurement of acual yield

Most attention in the literature on yield gaps has been devoted to the definition and measurement of potential yield, while that of actual yield has received relative limited attention although it is a key determinant of the yield gap. Actual yield is defined as:

It is evident that the definition and measurement of the components that make up actual yield have significant impact on estimations of actual yield and the yield gap. The measurement of both quantitay harvested and area is fraught with dificulties (Fermont and Benson 2011; Reynolds et al. 2015) but here we will focus only on the measurement and definition of area for which we have data.

Two potential problems characterise the measurement of area. The first is a measurement problem and deals with how to measure total area in the best way. It has been shown that farmer self-assessed area is not reliable and GPS measurements are preferred (**???**). The second is a question about which definition to use. It is common practice in the yield gap literature to use the FAO definition of actual yield that uses harvested land as denominator (Fischer 2015) although in many cases the definition of area is not even discussed (e.g. in recent reviews on yield gap approaches and data requirements for yield gap analysis (Ittersum et al. 2013, Grassini et al. (2015)), the definition of area is not addressed at all).

In a recent study Reynolds et al. (2015) argue that the use of harvested area leads to a serious overestimation of actual yield because it ignores crop losses that might occur between planting and harvesting. Causes for the difference in area planted and area harvested include crop management factors (e.g. poor germination, damage from pests and diseases) and econonomic constraints (e.g. labor and capital constraints and shortage of market opportunities), which are the same factors that influence yield on harvested area, and hence the yield gap. We argue that there is no fundamental difference between the factors that

## Methods

# Data

* argue that sample is nationally representative and therefore adequately represents all types of farmers, including those that use best-practice technology and crop management.

## Estimation

Boundary lines are often used to estimate yield gaps. Stochastic frontier analysis is somewhat comparable to boundary analysis as it also estimates an envelope curve that represents best-practice yield at each level of input. The advantage of stochastic frontier analysis over boundary analysis is that it simulteaneausly takes into account multiple inputs instead of only addressing one input as is the case in boundary analysis. Depending on the functional form of the yield response curve, inputs can be complementary or substitutes. To keep the estimation tractable we use are relative simple Cobb-Douglas function to estimate the frontier yield response curve. Stochastic frontier analysis is increasingly used to estimate yield gaps (Henderson et al. 2016, Hoang (2013), Silva et al. (2016), Van Dijk et al. (2016))

# Maize yield levels and yield gaps in Nigeria

* calculate different yield gaps, also attainable yield gap and show differences

# Conclusions/Discussion

Main findings

* Reviewed conventional yield levels used in agronomic literature and revealed some inconsistencies in the use and definition of certain yield levels. In particular the use of attainable yield and exploitable yield.
* We present a consistent framework that decomposes the conventional yield gap into four parts that are firmly rooted in neoclassical economics and therefore provide a theoretical framework on explaining why yield falls below potential.
* We also demonstrated how the impact of actual yield definitions on yield gap.

Recommendations:

* We recommend that attainable yield gap is not used as it is a highly confusing term as it can mean: economic yield, technical efficiency yield or . We propsose to use the definitions that actually. We have similar objections to the term exploitable yield, which is based on a rule of thumb. Better to use..
* We recommend that researchers are clear about their definition of actual yield. There is no perfect solution for the definition of area when measuring actual yield. Plot size is probably the best measure if one wants to capture all factors that cause the yield gap (including for example the economic or biophysical reasons, why a farmer did not harvest the full plot) but raises difficulties in situations where multiple crops are grown on one plat. On the other hand, harvest yield [ADD]. In any case researchers should properly explain which definition they used to measure actual yield.

Limitations

* study only covers two years. Recommended number of years is 5(?). Actual yield might be biased because of outliers. Better to use more years, possible in the future when LSMS is repeated.

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