American-Eurasian J. Agric. & Environ. Sci., 23 (2): 52-59, 2023
ISSN 1818-6769

DOI: 10.5829/idosi.aejaes.2023.52.59

Review of Approaches to Yield Gap Analysis in Field Crops

Mebrate Tamrat

Holetta Agricultural Research Center, P.O. Box 2003, Addis Ababa, Ethiopia

Abstract: To ensure the food demand of the fast-growing global population, the reduction of the yield gap is one of the strategies implemented for the improvement of food security. A wide range of yield gaps are observed around the globe, with average yields ranging from roughly 20% to 80% of yield potential. Several methods exist to measure crop yield potential and associated yield gaps, each of which has distinct advantages and disadvantages. Yield gap analyses of individual crops have been used to estimate opportunities for increasing crop production at local to global scales, thus providing information crucial to food security. This paper reviews the approaches used to measure the prevailing yield gaps present in different crops.

Key words: Actual Yield · Attainable Yield · Potential Yield · Theoretical Yield · Water-limited Yield · Yield Gap

INTRODUCTION

Improving crop yields is essential to meet the increasing demand for food driven by the increasing global population, which is expected to be about 9 billion by the year 2050 [1-3]. Population growth leads to a global increase in food consumption patterns, changes in lifestyles and food preferences [4]. Hence, it is now clear that every hectare of existing crop land will need to produce yields that are substantially greater than current yield levels [2]. Meeting food demand on existing cropland, without further encroachment of natural ecosystems such as forests, wetlands and savannahs, is one of the greatest challenges of our time [5]. Furthermore anderson *et al*. [6] examined how the average rate of increase in grain yields of the major rainfed crops has slowed since the 1990s, leading to rates of average yield increase as low as 2 kg/ha/year in some cases, compared to earlier rates that exceeded 100 kg/ha/year in some cases. This levelling or declining of yields may be due to soil degradation and nutrient depletion, climatic changes, failure to adjust management practices to variable seasonal conditions, or farmers' perceptions of risk and diminishing returns. Hence, although trends in grain yield improvement over an extended period in a production area have seldom been smooth or linear, it is appropriate to consider current levels of grain yield relative to some estimate of potential yield and to examine the physical and socio-economic feasibility of various pathways toward further yield improvement [6].

On the other hand, some regions have much greater potential than others to support higher yields in a sustainable manner due to their favorable climate, soil quality and, in some cases, access to irrigation. In some of these favorable regions, current average farm yields are low. Hence, a large exploitable gap exists between current yields and what is theoretically achievable under ideal management [2]. Hence, one strategy that could address this concern is by quantifying the production capacity of farmland to identify ways to increase the yield of major crops [7]. This can be achieved by using high-yielding management practices [8] and closing yield gaps between farmers' actual yield and potential yield [3, 9]. Minimizing yield gaps in major crops by using optimal management practices may lead to improvements in production while offering both environmental benefits and economic value. Assessing the yield gaps in major field crops can help us understand yield variability, yield potential and the input efficiency of major crops and may indicate appropriate pathways for improving agricultural efficiencies [2, 3, 10].

The yield gap, defined as the difference between actual farm yield and potential yield (the most relevant benchmark for irrigated systems) or water-limited yield

Corresponding Author: Mebrate Tamrat, Holetta Agricultural Research Center, P.O. Box 2003, Addis Ababa, Ethiopia.

potential as the benchmark for rainfed systems with good management that minimizes yield losses from biotic and abiotic stresses, is a key biophysical indicator of the available room for crop production increase with current land and water resources [11, 12]. Analysis of yield gaps helps identify opportunities to improve crop yield and assess food security scenarios. At both local and global scales, yield gap analysis has been performed for a number of staple food crops in different regions, but in all these studies, the focus has been on individual crops. However, important improvements in productivity are also likely to come from innovations at the cropping or farming system levels [11]. Lobell *et al*. [13] reported an estimate of a yield gap of 20 to 80 percent across the world's major cropping systems.

Numerous approaches exist to estimate yield gaps. For example, farmer surveys can compare the average yield with the best yield achieved in similar environmental conditions. Additionally, yield gaps can be evaluated through field experimentation, where farmer-level yield data is generated by replicating farmer management practices and attainable yield is estimated by minimizing plant stress to the extent possible via the use of improved technologies and agrochemical inputs. Field experimentation can help to identify site-specific combinations of management practices that are conducive to high yields and low-risk input recommendations [14]. While yield gap analysis is not a new concept in applied agronomy, it has not been adequately applied in many regions of the world. The methods for benchmarking yields and identifying yield-gaps have been reviewed by Van Ittersum *et al*. [2] and FAO and DWFI [10], presenting case studies focusing on relatively similar approaches. The aim of this review is to asses and compiles the existing approaches/methods most frequently used for yield gap analysis.

MATERIAL AND METHODS

Evolution of Yield Criteria: While our ancestors were not unlike other animals, before agriculture, "yield" was the ratio between the energy derived from food and the energy invested in obtaining it FAO and DWFI [10]. According to the review by FAO and DWFI [10], when the sowing of crops was established as a common practice, its definition was shifted from an energy ratio to the ratio between the numbers of seeds harvested and seeds sown [15]. This shift in the definition of yield had a dramatic impact on selective pressures, shifting from the aggressive high-yielding plant (seeds per seed sown) to the less competitive "communal plant" able to produce more yield per unit area. Their review also stated that the next measure of yield, whereby the time dimension is considered explicitly, is yield per hectare per year. This measure is particularly important in the comparison of systems with contrasting cropping intensities, i.e., the number of crops per year. Furthermore, in environments with favorable temperature and water availability, this involves a shift to multiple crops per year. In environments where rainfall or temperature prevents multiple cropping, such as the dry environments of southern Australia, cropping intensity has been increasing at the expense of pastures. Thus, the concept of yield progress based on kg per hectare will become inappropriate in some instances. Increasing cropping intensity could contribute to either stabilization or a decline in yield per crop. Hence, meaningful comparisons of this kind must focus on the whole production system rather than individual crops. Obviously, measuring yield per unit area and time is therefore of increasing importance. In addition, where multiple cropping is prevalent, yield gap analysis should target the system and its components [10].

Yield Definitions: The economic yield of desired plant products such as grain, oilseed, tubers, corms, sugar, fiber, forage, or energy content is considered in this publication, focusing on the definitions of yield relevant for yield gap analysis (Figure 1 and 2).

Theoretical Yield: Is the maximum crop yield as determined by biophysical limits to key processes, including biomass production and partitioning. It can be estimated with models with sound physiological structure and parameters reflecting the biophysical boundaries of key processes (Figure 1). This benchmark is perhaps more useful for breeding [10].

Potential Yield (Yp): Is the yield of a current 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" [15].

Potential yield depends on location as it relates to climate but is independent of soil, assuming that the required water and nutrients can be added through management (which, of course, is not practical or cost-effective in cases where major soil constraints, such as salinity or physical barriers to root proliferation, are difficult to overcome) [2, 10]. The climate factors that

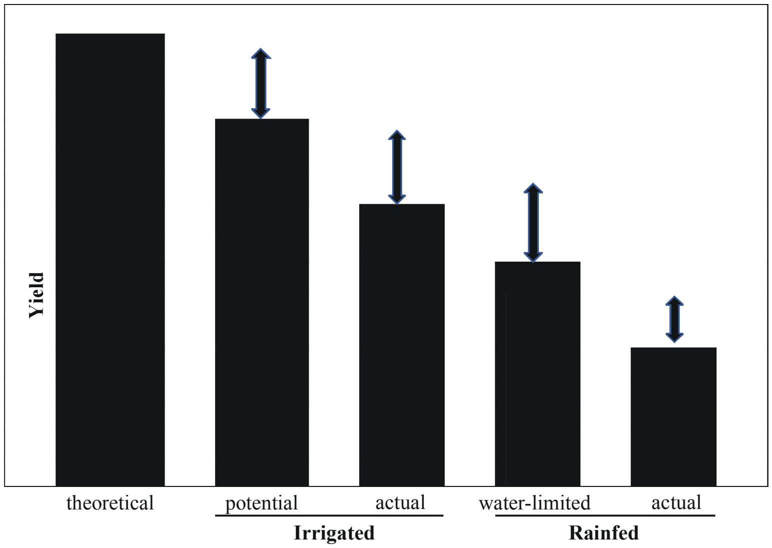

Fig. 1: Definitions of yield relevant to yield gap analysis; arrows illustrate some yield gaps
Source: FAO and DWFI [10]

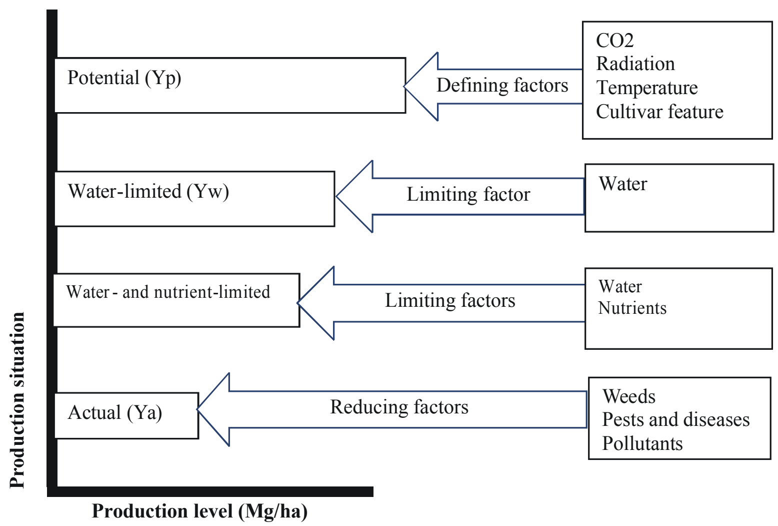

Fig. 2: Different production levels as determined by growth defining, limiting and reducing factors.
Source: van Ittersum *et al*. [2]

influence potential yield are solar radiation, ambient CO_2 concentration and temperature [2, 15]; and genetic traits [2]. That is, when grown under Yp conditions, crop growth rate is determined solely by solar radiation, temperature, atmospheric CO_2 and genetic traits that govern cultivar or hybrid maturity and light interception by the crop canopy (e.g., canopy architecture). In general, maximum potential yields can be estimated using the results of highly controlled on-station experiments or crop models calibrated using the crop characteristics of the latest varieties [16]. The term "yield potential" is used for irrigated systems because it is assumed that an irrigated crop can be provided with an adequate water supply throughout growth [13]. Hence, potential yield is relevant to benchmark crops where irrigation, the amount and distribution of rainfall, or a combination of irrigation and rainfall, ensures that water deficits do not constrain yield [2, 10, 13].

Water-limited Yield (Yw): Is similar to yield potential except that yield is also limited by water supply and hence influenced by soil type (water holding capacity and rooting depth) and field topography [2, 10]. This measure of yield is relevant to benchmark rainfed crops because most rainfed crops suffer at least short-term water deficits at some point during the growing season [13, 2, 10].

For partially (supplementary) irrigated crops, both Yp and Yw may serve as useful benchmarks [2].

Both Yp and Yw are calculated for optimum or recommended sowing dates, planting density and cultivar (which determines growing period to maturity). Sowing dates and cultivar maturity are specified to fit within the dominant cropping system because the "context" of the cropping system is critically important in dictating feasible growth duration, particularly in tropical and semi-tropical environments where two or even three crops are produced each year on the same piece of land. Farmers attempt to maximize production and/or profit for the entire cropping system rather than the yield or profit of an individual crop. Likewise, where machinery and labor are limiting factors or costly, achieving optimal sowing dates may not be feasible for most farms [2, 13]. In addition, van Ittersum *et al*. [2] also argue the relevance of calculating Yp and Yw for current average or median planting dates in addition to optimal dates to overcome the aforementioned cases.

Attainable Yield: Is the best yield achieved through skillful use of the best available technology [10]. Similarly, it is defined as the crop yield grown under optimal management practices (i.e., recommended plant density, non-limiting nutrient condition, effective control of biotic stresses, etc.) in farmers' fields [2].

Actual: (Ya) reflects the current state of soils and climate, the average skills of the farmers and their average use of technology [10]. On the other hand, *actual yield* is defined as the average yield (in space and time) achieved by farmers in the region under the most widely used management practices (sowing date, cultivar maturity, plant density, nutrient management and crop protection) [2].

The Yield Gap Definition: According to FAO and DWFI [10], the yield gap is the difference between two levels of yield. As presented in Fig. 1 and 2, depending on the objectives of the study, different yield gaps are relevant. The difference between yield potential and the actual yield achieved by farmers represents the exploitable yield gap [9]. The exploitable yield gap accounts for both the unlikely alignment of all factors required for achievement of potential or water-limited yield and the economic, management and environmental constraints that impede. For example, the use of fertilizer rates that maximize yield, when growers' aim is often a compromise between maximizing profit and minimizing risk at the whole-farm scale, rather than maximizing the yield of individual crops. To account for this, a factor of less than 1 (one) is used to scale yield potential and water-limited yield. A factor of 0.8 has been used in extensive production systems; higher factors may apply for high-value horticultural crops and smaller factors in other systems depending on technological and economic (e.g., grain price) drivers [10]. The gap between potential and water-limited yield is an indication of the yield gap that can be removed with irrigation. For example, as cited by FAO and DWFI [10], modelling studies in cropping systems of Bolivia compared the yield of rainfed quinoa, from 0.2 to 1.1 t/ha, with yield under irrigation aimed at avoiding stomatal closure during all sensitive growth stages from 1.5 to 2.2 t/ha, thus representing gaps of around 1.2 t/ha.

How Big Are the Yield Gaps?: A survey of the literature on wheat, rice and maize cropping systems revealed a wide range of estimated yield gaps throughout the world. For tropical maize in Africa, where biophysical and management conditions result in frequent nutrient, water, pest and disease stresses, average yields are commonly less than 20% of yield potential. In contrast, average yields in irrigated wheat systems in northwest India can reach 80% of their potential. In general, a range of 20% to 80% includes nearly all of the major cropping systems of the world [13].

Why the Yield Gap Exists?: Hengsdijk and Langeveld [16] identified five production constraints that contribute to the existence of a yield gap, i.e. (i) limited water availability; (ii) limited nutrient availability; (iii) inadequate crop protection; (iv) insufficient or inadequate use of labor or mechanization; and (v) deficiencies in knowledge. On top of this, Lobell *et al*. [13] listed additional biophysical and socioeconomic factors that commonly affect crop growth and yields in farmers' fields (Table 1). These factors include stresses that are biotic in nature and others that are mainly abiotic, factors that are easy to measure and some that are difficult to detect, factors that relate mainly to management and others to soil properties, as well as interactions among these various factors.

The challenges encountered in understanding yield gaps for any given farming system are to identify, among the many possible explanations for yield losses, the few that have the greatest influence and, if possible, to quantify the gains that could be realized if these constraints were removed [13]. For example, water shortages during the growing season can be reduced using irrigation; nutrient limitations can be lifted by

Table 1: Common factors that contribute to yield losses in farmers' fields

Biophysical factors	Socioeconomic factors
Nutrient deficiencies and imbalances (nitrogen, potassium, zinc and other essential nutrients)	Profit maximization
Water stress	Risk aversion
Flooding	Inability to secure credit
Suboptimal planting (timing or density)	Limited time devoted to activities
Soil problems (salinity, alkalinity, acidity, iron, aluminium or boron toxicities, compaction and others)	Lack of knowledge on best practices
Weed pressures	
Insect damage	
Diseases (head, stem, foliar, root)	
Lodging (from wind, rain, snow, or hail)	
Inferior seed quality	

Source: Lobell *et al.* [13]

applying organic or inorganic fertilizers. Yield reductions due to inadequate control of weeds, pests and diseases can be avoided by the introduction of proper crop protection practices, including the use of biocides, phytosanitary methods and crop rotations. Obviously, these production constraints are interrelated and their effects are difficult to separate. For example, weather conditions may limit the accessibility of fields to fertilizer application machinery, resulting in decreased nutrient availability and thus reduced crop yields. It is, however, not possible to identify or account for possible interactions and synergies and the production constraints are treated as independent constraints, each contributing separately to the yield gap in a particular region. The relative contribution of production constraints contributing to the gap between potential and current yields differs among crops and regions [16].

Approaches to Analyzing/assessing Yield Gaps: Yield gaps have been estimated in previous studies with either a global or local focus. Global methods are generally coarse and provide worldwide coverage using a consistent method whereas, local studies are based on location-specific environmental conditions and management, which give local relevance but are hard to compare across locations and studies because of inconsistent terminology, concepts and methods [2].

Local Studies: At least four methods can be distinguished to estimate yield gaps at a local level [13]: (1) field experiments; (2) yield contests; (3) maximum farmer yields based on surveys; and (4) crop model simulations. The first step associated with each method is to estimate yield ceilings as represented by Yp and Yw for a given crop in a given location or region. A yield gap is then calculated as the difference between a farmer's Yp or Yw and Ya.

The most conceptually straightforward (but expensive) way to research on-farm constraints to yields is to conduct controlled experiments that compare alternative management treatments in a series of farmers' fields [13]. Although field experiments and yield contests can be used to estimate Yp and Yw for a given location and under a specific set of management practices, they require well-managed field studies in which yield-limiting and yield-reducing factors are eliminated (e.g., nutrient deficiencies and diseases) and they must be replicated over many years to obtain a robust estimate of average Yp or Yw and their variation [9]. The latter may be a serious limitation in practice because it is difficult to avoid all abiotic and biotic stresses and to do so consistently in a field study lasting several years. Hence, field experiments and yield contests used as a basis for estimating Yp or Yw must use sowing dates and cultivar maturities that are representative of the prevailing cropping systems in the region of interest if they are to serve as benchmarks for these systems [2].

Surveys among farmers to estimate maximum yields from upper percentiles is an alternative but less common approach to estimating Yp or Yw among a sizable sample of farmers in a region of interest [2,13]. Typically, estimates must rely on farmer-reported values rather than direct measurements to achieve large sample sizes and therefore, much care is needed to identify farmers with reliable records for individual fields and to convert all yields to standard moisture content. As an additional step to ensure data quality, one should also obtain independent estimates of yields in a subset of fields, such as by harvesting several small plots within farmers' fields. The use of maximum farmer yields as a proxy for yield potential is only appropriate in intensively managed cropping systems, where farmers apply levels of fertilizer and pest and disease controls that make it possible to approach yield potential [13]. However, if obstacles

Table 1: Desired attributes of crop simulation models

Desired attribute	Explanation
Daily step simulation	Simulation of daily crop growth and development based on weather, soil and crop physiological attributes
Flexibility to simulate management practices	Key management practices include: sowing date, plant density, cultivar maturity
Simulation of fundamental physiological processes	Simulation of key physiological processes such as crop development, net carbon assimilation, biomass partitioning, crop water relations and grain growth
Crop specificity	Should reflect crop-specific physiological attributes for respiration and photosynthesis, critical stages and growth periods that define vegetative and grain filling periods and canopy architecture
Minimum requirement of crop 'genetic' coefficients	The model should have a low requirement of crop-site 'genetic' coefficients, preferably only a limited number of phenological coefficients
Validation against data from field crops that approach Yp and Yw	Comparison of model outcomes (grain yield, aboveground dry matter, crop evapotranspiration) against actual measured data from field crops that received management practices conducive to achieve Yp (irrigated) or Yw (rainfed crops)
User friendly	Models embedded in user-friendly interfaces, where required data inputs and outputs can be easily visualized and with flexibility to modify default values for internal parameters
Full documentation of model parameterization and availability	Publicly available models, published in the peer-review literature, with full documentation and publicly available code and with reference to data sources for internal parameter values

Source: van Ittersum *et al*. [2]

prevent all surveyed farmers from realizing Yp or Yw, then Yg will be underestimated. Such obstacles must operate at the same scale as the yield gap analysis and could include lack of access to inputs, lack of markets and lack of knowledge or access to them [2].

Limitations: While field experiments, yield contests and the highest yields obtained by farmers are useful to determine maximum achievable yields in a specific location or across a population of fields (i.e., best genotype × environment × management interaction, G × E × M), it is difficult to know for certain if all biotic and abiotic stresses were avoided. Therefore, yields from these sources may not be adequate to derive robust estimates of Yp or Yw representative of the dominant weather and soil conditions in a given cropping system or region.

To overcome the limitations of these approaches, crop simulation models are suggested which can be used to estimate Yp or Yw [13, 2]. The simulation models are mathematical representations of our current understanding of biophysical crop processes (phenology, carbon assimilation, assimilate partitioning) and of crop responses to environmental factors and such models have been designed to account for G × E × M interactions [2]. As stated by van Ittersum *et al*. [2] and Lobell *et al*. [13], they require site-specific inputs, such as daily weather data, crop management practices (sowing date, cultivar maturity, plant density), soil properties and specification of initial conditions at sowing, such as soil water availability and a model configuration that ensures nutrients to be nonlimiting. Although specification of weather, soil and management practices in current cropping systems is essential for robust simulations of Yp and Yw, these data are typically not available for most cropping systems with adequate geospatial detail, even in developed countries. Also, models need to be rigorously evaluated for their ability to reproduce measured yields of field crops that received near-optimal management practices across a wide range of environments and management practices. As presented in Table 2, Van Ittersum *et al*. [2] also summarized desirable attributes for crop growth simulation models to be used in yield gap assessment.

Global Studies: As per the review by van Ittersum *et al*. [2], global studies generally use empirical, statistical approaches or generic crop growth models and a grid-based approach using global datasets on climate, soils and sometimes agricultural land use and general crop calendars [see Appendix A in 2]. The statistical methods take the current highest yields within a defined climatic zone or use a stochastic frontier production function. They do not verify whether the highest yields accurately represent the biophysical Yp or Yw limit as confirmed by either a robust simulation model or field studies [2]. The major limitation of this method is that it does not distinguish between irrigated and rainfed crops; thus, many Yg estimates for a given climatic zone are based on irrigated crop yields-even in regions where the crop in question is grown almost entirely under rainfed conditions [to check for more limitations, see 2].

Remote Sensing Approach

Remote Sensing: Is the technology of identifying, observing and measuring an object without coming into direct contact with it. Indirect measurements via satellites have the potential to measure fields and regions to complement and cross-check other sources of data [see Box 4 in 10]. Remote sensing can help in overcoming the limitations of working with point data or individual fields [17, 18]. The use of remote sensing may have historically been restricted by the cost and availability of fine resolution data, but this impediment is rapidly receding [17]. According to the review by Lobell [17], field experiments and simulation models are useful tools for understanding crop yield gaps, but scaling up these approaches to understand entire regions over time has remained a considerable challenge. Satellite data have repeatedly been shown to provide information that can accurately measure crop yields in farmers' fields, either alone or in conjunction with other data and models. The resulting yield maps provide a unique opportunity to overcome both spatial and temporal scaling challenges and thus improve our understanding of crop yield gaps.

CONCLUSION

Improving crop yields is essential to meet the increasing demand for food driven by the increasing global population, which is expected to be about 9 billion by the year 2050. For this purpose, the reduction of the yield gap is one of the strategies implemented for the improvement of food security. Several methods exist to measure crop yield potential and associated yield gaps, each of which has distinct advantages and disadvantages. A wide range of yield gaps are observed around the world, with average yields ranging from roughly 20% to 80% of yield potential. Hence, reduction of the prevailing yield gaps is a priority issue which requires due attention.

REFERENCES

1. FAO (Food and Agricultural Organization), 2011.World Livestock 2011 -Livestock in food security Food and Agriculture Organization of the United Nations (FAO), Rome.
2. van Ittersum, M.K., K.G. Cassman, P. Grassini, J. Wolf, P. Tittonell and Z. Hochman, 2013. Yield gap analysis with local to global relevance: A review. Field Crops Research, 143: 4-17.
3. Chapagain, T. and A. Good, 2015. Yield and Production Gaps in Rainfed Wheat, Barley and Canola in Alberta. Frontiers in Plant Science, 6(990): 1-10.
4. Van Huis, A., 2013. Potential of insects as food and feed in assuring food security. Annu. Rev. Entomol., 58: 563-83.
5. Cassman, K.G. and P. Grassini, 2020. A global perspective on sustainable intensification research. Nat. Sustain, 3: 262-268.
6. Anderson, W., C. Johansen, H. Kadambot and M. Siddique, 2016. Addressing the yield gap in rainfed crops: a review. Agron. Sustain. Dev., 36: 18.
7. Patrignani, P., R.P. Lollato, T.E. Ochsner, C.B. Godsey and J.T. Edwards, 2014. Yield gap and production gap of rainfed winter wheat in the Southern Grain Plains. Agron. J., 106: 1329-1339.
8. Yang, W., S. Peng, R.C. Laza, R.M. Visperas and M. Dionisio-Sese, 2008. Yield gap analysis between dry and wet season rice crop grown under high-yielding management conditions. Agronomy J., 100: 1390-1395.
9. Cassman, K.G., A. Dobermann, D.T. Walters and H.S. Yang, 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annual Review of Environment and Resources, 28: 315-358.
10. FAO and DWFI, 2015. Yield gap analysis of field crops - Methods and case studies, by Sadras, V.O., Cassman, K.G.G., Grassini, P., Hall, A.J., Bastiaanssen, W.G.M., Laborte, A.G., Milne, A.E., Sileshi, G., Steduto, P. FAO Water Reports No. 41, Rome, Italy.
11. Guilpart N., P. Grassini, V.O. Sadras, J. Timsina and K.G. Cassman, 2017. Estimating yield gaps at the cropping system level. Field Crops Research, 206: 21-32.
12. Edreira, J.I.R., J.F. Andrade, K.G. Cassman, M.K. van Ittersum, M.P. van Loon and P. Grassini, 2021. Spatial frameworks for robust estimation of yield gaps. Nature Food, 2: 773-779.
13. Lobell, D.B., K.G. Cassman and B. Christopher, 2009. Field Crop Yield Gaps: Their Importance, Magnitudes and Causes, Annual Review of Environment and Resources, 34: 179-204.
14. Grassini, P., L.G.J. van Bussel, J. Van Warta, J. Wolf, L. Claessen, H. Yang, H. Boogaard, H. de Groot, M.K. van Ittersum and K.G. Cassman, 2015. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Research, 177: 49-63.

15. Evans, L.T. and R.A. Fischer, 1999. Yield potential: its definition, measurement and significance. Crop. Sci., 39: 1544-1551.
16. Hengsdijk, H. and J.W.A. Langeveld, 2009. Yield trends and yield gap analysis of major crops in the world; Wageningen, Wettelijke Onderzoekstaken Natuur & Milieu, WOt-werk document 170 blz. 57; fig. 15; tab. 13; ref. 40; bijl. 2.
17. Lobell, D.B., 2013. The use of satellite data for crop yield gap analysis. Field Crops Res., 143: 56-64.
18. Dehkordi, P.A., A. Nehbandani, S. Hassanpour-bourkheili and B. Kamkar, 2020. Yield Gap Analysis Using Remote Sensing and Modelling Approaches: Wheat in the Northwest of Iran. Int. J. Plant Prod., 14: 443-452.