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Invited Review Paper

Yield potential, potential yield and realized yield at farmer level of cereals with special reference to rice (*Oryza sativa* L.)

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Abstract: Rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are the three main cereals that account for the majority of calories in human diets and they will continue to remain the main sources of human nutrition. In order to meet the food demand of increasing population the only option left to increase production of these crops is to increase crop productivity per unit land area in the existing cultivable lands. Grain production of cereals is largely influenced by their yield potential. However, the terms 'yield potential', 'potential yield' and 'maximum potential yield' are synonymously used in the literature to describe different yield ceilings of crop plants without making a clear distinction among them. These terms have been defined in relation to the realized yield at farmer level. This review discusses the methods of estimating yield potential and potential yields of cereals, their physiological basis, and genetic improvement, with special reference to rice. The role of light interception, radiation use efficiency and harvest index as components of a varietal yield potential in relation to their genetic improvement and importance of improving varietal resistance to biotic and abiotic stresses in relation to improving potential yield have been discussed.

***Keywords*:** Cereals, realized yield at farmer level, potential yield, yield potential

Introduction

Rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) are the three main cereals that account for the majority of calories in human diets and agricultural production. These crops will continue to remain the main sources of human nutrition in the foreseeable future (Cassman, 1999). The 'green revolution', which began in late 1960s with the development of improved varieties in wheat, rice and maize having high yield potentials resulting in greater yield per unit land area averted the impended shortfall in food supply worldwide (Cassman, 1999).

World population is projected to increase by 35 % and reach around 9 billion by 2050, requiring 70-100 % increase in food production (Bruinsma, 2009: Rosegrant *et al*., 2009). Global rice demand is estimated to rise from 676 million tons in 2010 to 852 million tons in 2035 with an overall increase of 26 % or 176 million tons in the next 25 years (Khush, 2013). Global wheat and maize demand is estimated to be 882 and 916 million tons, respectively, by 2027 (Cassman, 1999). As opportunities for greater cropping intensity and expansion of irrigated area are limited, the only option left to increase food production is to increase

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crop productivity per unit land area in the existing irrigated and the favorable rainfed lands to meet the food demand of increasing population (Cassman, 1999). Crop productivity per unit land area at farmer level is mainly dependent on the 'yield potential' of crop varieties as increase in the varietal yield potential will pull the realized yield at farmer level further up, irrespective of the magnitude of existing gap between them (Abeysiriwardena, 2000). Yoshida (1981) stated that the estimation of 'maximum potential yield' is important as it indicates how far human beings can attempt to increase crop yields.

Grain production of rice is largely influenced by the yield potential of cultivated varieties so that improvement in the yield potential of rice varieties is the major strategy to increase world rice production (Khush, 2013). Studies on yield potential of crop plants can assist in identifying the production constraints in any cropping system (Constable and Bange, 2015). Estimates of yield potential have been used as yard sticks to assess progress in plant breeding programs and to analyze the relative contribution of plant breeding and agronomic advances towards past increases in crop yields (Evans and Fischer, 1999). However, the terms 'yield potential', 'potential yield' and 'maximum potential yield' are synonymously used in the literature to describe different yield ceilings of crop plants without making a clear distinction among them.

In crop improvement and plant breeding programs, scientists are compelled to estimate or predict the expected yield levels of crop varieties before actual yields are obtained, based on yield components and related vegetative characteristics, climatic factors, management practices, etc. In such occasions, those predicted yield values are interchangeably presented as yield potential or potential yield values. Further in crop variety evaluation for yield, scientists may identify certain elite breeding lines to show a higher yield potential or higher potential yield than certain others, based on their yield performance with no uniform terminology of expressing different yield ceilings. Thus, the present paper attempts to make a clear distinction among the terms 'yield potential', 'potential yield' and the 'maximum potential yield' and to define and discuss how they could be quantified and increase in relation to realized yield at farmer level, with special reference to rice. Such distinction is expected to measure and estimate yields effectively and objectively in crop improvement programs towards realizing greater productivity of crop varieties in a given environment.

Definition and Distinction

Evans (1993) defined crop yield potential 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 are effectively controlled. Although this definition appears straight forward, measuring yield potential under actual field conditions is difficult as it is impossible to eliminate all biotic and abiotic stresses (Cassman, 1999). Thus, the same author gave a comparatively more functional definition of yield potential as the yield obtained when an adapted cultivar is grown with the minimum possible stress that can be achieved with the best management practices. However, there is certain degree of imprecision in the specification of minimal possible stress and best management practices. In addition, estimating yield potential under actual field conditions is unlikely. Constable and Bange (2015) defined the yield potential as 'the yield that can be obtained with current cultivars under ideal conditions in the absence of poor weather, diseases, soil or nutritional constraints with management and genetics optimized'. Further, Dawe and Dobermann (1998) defined yield potential of rice in a different context as the 'maximum grain yield of a given variety in a given environment without water, nutrient, competition or disease constraints, which will be different in environments differing in temperature and solar radiation regimes'. According to this definition, yield potential is not measured under ideal climatic environment so that yield potential may vary from region to region or environment to environment. Reynolds *et al*. (2011) used the term potential yield instead of yield potential and defined it as 'the maximum yield of a given species or cultivar possible achievable under existing conditions of solar radiation flux density with all the other environmental factors considered to be optimal'. Thus, the potential yield is determined by the biological properties of the species or cultivar and radiation resources available for utilization.

In all the above definitions, no distinctions have been made among the terms 'yield potential', 'potential yield' and the 'maximum potential yield', instead all the terms are used in the same context. Bingham (1967) distinguished between the potential and realized yields of a cultivar in farm cultivation where potential yield is achieved when cultivar was free from lodging, winter killing, pests and diseases and realized yield is obtained with the indicated stresses. However, Evans and Fischer (1999) made a distinction between yield potential as defined by Evans (1993) and potential yield, which was defined by them as the maximum yield that could be reached by a crop in a given environment as determined; for example, by simulation models with plausible physiological and agronomic assumptions. Then Evans and Fisher (1999) indicated that yield potential can be used mainly for measured comparisons of cultivars and potential yield can be used for comparisons between different crops and different environments as well as for estimating plausible future limits to crop yields. Emitiyagoda *et al*. (2010) also made a clear distinction between yield potential and potential yield, and defined yield potential as 'the maximum yield that a variety can reach under the best environment and potential yield as the maximum yield that can be realized by a variety × environment combination under best management'. Yoshida (1981) used the term 'maximum potential yield' in an exercise to estimate yield potential of rice. Obviously the ultimate maximum of potential yield should be the yield potential, so that both maximum potential yield and yield potential are representing the same yield ceiling.

Yield potential is the genetic potential, which is dependent on biological or plant factors under the ideal environmental conditions and crop management practices, having one definite yield level for the species or variety. One definite yield level is because there is only one ideal environment and set of crop management practices. Potential yield is the yield of a variety × environment combination under the best crop management and will be different in environments differing in temperature and solar radiation regimes for a given variety. Most of the time, environment restricts the variety yield potential so that potential yield of the variety × environment combination is the value mostly estimated. Evans and Fischer (1999) indicated that there are 'yield genes' (genes governing yield components) and 'stress-resistance genes' and that a yield potential measurement attempts to measure only the effects of the former. Stress-resistant genes can help only to sustain a given yield potential value. However, potential yield would measure the combined effects of both yield genes and stress-resistance genes. Thus by definition, resistance to biotic and abiotic stresses have no direct effect on yield potential but have a direct effect on potential yield. Potential yield varies from place to place depending on the level of environmental restrictions and varieties used so that if a region or zone is considered, potential yield varies among specific environments within the region or zone eventually requiring the estimation of maximum, minimum and average potential yields for the region or zone. Similarly a given variety will have varying potential yield levels depending on where it is grown and different varieties will have similar potential yield values depending on the differences in environments in which they are grown.

Realized yield at farmer level is clearly distinguishable from yield potential and potential yield. Realized yield which is the actual farmer yield at farmer or production level is often lower than the potential yield and highly variable over space and time as it is influenced by not only the varying physical and biological environments but also by the crop management practices which is highly variable among farmers. Actual farm yield reflects farmers' natural resource endowment, their access to technology and their skills and exposure to real market economics (Evans and Fischer, 1999). Realized yields at farmer level are measured and recorded as district, regional, zonal, national and seasonal or yearly averages taking into consideration of cultivation systems such as rain-fed, minor or major irrigation. Varietal aspects that influence sustainable increase in realized yield at farmer level are increasing in variety yield potential and reduction in gap between potential and realized yields by improving variety adaptability over diverse environments (Abeysiriwardena, 2000).

Yield potential

Quantitative estimation

Yield potential (YP) can be expressed in its simplest form as a function of the light intercepted (LI) and radiation use efficiency (RUE), whose product is biomass and the partitioning of the biomass into grain yield; that is the harvest index (HI) (ratio of grains : above ground biomass): YP = LI × RUE × HI (Reynolds *et al*., 2011). Thus, estimation and the genetic enhancement of yield potential of crops are dependent on three basic parameters of LI, RUE and HI.

Estimation of yield potential in rice is presented as an example. Different scientists (Evans, 1972; Murata and Matsushima 1975; IRRI, 1977) used different methods of estimating the yield potential of rice as the product of net photosynthesis per day and the number of effective days for grain production per given area. In these exercises the assumptions stipulated were i) sink size was not limiting ii) the contribution of carbohydrate stored before flowering to grain yield was negligible and iii) all the photosynthates are carbohydrate and contribute to grain carbohydrate. All these assumptions appear reasonable.

Murata and Matsushima (1975) estimated the gross production by examining the efficiency of component processes in the energy flow of canopy photosynthesis and subtracted the respiration losses to obtain the net photosynthesis. However, IRRI (1977) used the recorded maximum photosynthetic efficiency of the rice crop. This method is comparatively more empirical and simpler Yoshida (1981).

The assumptions of the method of Murata and Matsushima (1975) are (i) period for yield production is 40 days after heading, (ii) the average daily solar radiation is 400 cal. day^{-1} $(cm^2)^{-1}$ of which only 45% is Photosynthetic Active Radiation (PAR), (iii) 5.5 % of PAR is lost by reflection at the canopy surface and another 10 % through absorption by inactive tissue, (iv) eight photons are required to reduce one molecule of carbon dioxide corresponding to an efficiency of 26 % in energy conversion, (v) the loss due to light saturation in the upper leaves is 17 % at 400 cal. day^{-1} $(cm^2)^{-1}$, (vi) the conversion factor for dry matter is 3900 $cal.g^{-1}$, (vii) the respiration loss is the sum of 1.5% of dry weight day^{-1} (1.5 Kg $(m^2)^{-1}$ in this case) and 25 % of the gross photosynthesis and (viii) the ratio of husk weight to the dry grain weight is 20 %. Based on these conditions the theoretical yield potential estimated was 19.1 tha^{-1} brown rice and 23.8 t ha^{-1} rough rice at 14 % grain moisture. The theoretical yield potential estimated by the method proposed by IRRI (1977) was 23.2 tha^{-1} of rough rice when effective grain filling period was assumed to be 40 days. Thus, estimations of both methods were almost similar. Long effective grain filling periods around 40 days are expected only in temperate regions due to low temperature and this is the achievable maximum grain filling period for rice. However, many varieties will not take more than 35 days from heading to maturity in temperate environments. If grain filling period is assumed to be 35 days, the estimated yield potential would be 20.4 t ha^{-1} (IRRI, 1977). Hanson *et al*. (1982) reported that the estimated theoretical yield potential of wheat is 20 t ha^{-1}, which is marginally lower than that of rice.

Physiological basis

As yield is a function of total biomass and HI, increase in one of those or both will increase yield potential of crop plants. The largest contribution to increase in yield potential of modern rice and wheat varieties came from the increase in HI. HI has been increased up to 0.50 to 0.55 in modern rice varieties (Peng *et al*., 1999) in comparison to 0.2-0.3 in traditional varieties. However, scope for further increase of HI is limited by the need to maintain sufficient leaf area and stem biomass for interception of solar radiation, physical support and storage of assimilates and N used in grain filling (Cassman, 1999). Adequate partitioning among plant organs is crucial to ensure that plants with comparatively heavier grain weight have strong enough stems and roots to avoid structural failure (Berry *et al*., 2007). However, among current elite materials of wheat, HI varies in the range of 0.40-0.55 (Sayre *et al*., 1997) and lower limit of the range is relatively low so that further increase in HI in combination with other desirable characteristics that determine yield might be feasible. In maize, any marked reduction of crop height or increased HI has contributed little to the increase in yield potential of hybrids (Tollenaar *et al*. 1994; Duvik, 1992). However, the main factor contributed to increase in yield potential of maize was its increased tolerance to closer planting that made possible to have high plant densities (Evans and Fischer, 1999).

Although increases in HI have been successfully achieved in the post-Green revolution period, their physiological and genetic basis has not been well established. Poor adaptation can result in very low yield despite the expression of a significant crop biomass. The photosynthetic capacity of contemporary germplasm of wheat may not even be utilized efficiently if spike fertility is not optimized (Reynolds *et al*., 2011). Spike fertility of wheat can be improved by increasing the availability of assimilates to the developing spike (Fischer, 1985), thereby reducing the early abortion of grains (Miralles and Slafer, 2007) or by increasing grain weight (Duggen and Fowler, 2006).

In order to achieve a quantum boost to cereal crop yield potential, a major improvement in photosynthetic capacity and/or efficiency will be required. In rice, 'source' limitation is indicated by insufficient provision of photosynthates at key developmental stages as only 40 % of the florets are fertilized and filled to become grains though potential spikelet number per panicle has increased markedly in new rice types (Reynolds *et al*., 2011). However, in wheat, while the 'sink' strength of grain and photosynthetic capacity may be more in balance, historic gains in wheat yield potential have been associated with increased photosynthesis (Fischer *et al*., 1998). Basic research has confirmed that substantial improvements in photosynthesis are theoretically possible in cereals (Long *et al*., 2006: Parry *et al*., 2007; Zhu *et al.,* 2010).

Plant characteristics that contribute primarily to improvement of photosynthesis at the whole canopy level or crop photosynthesis in the field are photosynthetic rate per unit leaf area, leaf area index (LAI) and leaf orientation. Larger the LAI higher the intercepted incident solar radiation but size of LAI needed to obtain maximum crop photosynthesis depends on the leaf orientation of the canopy. A LAI of 4-8 is needed for good rice crop photosynthesis (Yoshida, 1981). A combination of erect upper leaves and droopy lower leaves in a plant canopy gives the maximum crop photosynthesis (Duncan, 1971). Improvements in whole canopy level photosynthesis has made a substantial increase in yield potential of cereals, particularly in rice (yoshida, 1981) through breeding for improved plant type (Kush, 2013). Need for further improvement in light interception and photosynthesis at whole canopy level for enhanced yield potential in rice was stressed by Kush (2013).

Reynolds *et al*. (2011) reported two approaches for increasing total crop biomass through increasing the photosynthetic efficiency and capacity for which genetic variation exists in C_3 cereals like wheat and rice by targeting the first step of CO_2 fixation, catalyzed by 'Rubisco'. The first approach would be to enhance catalytic properties of Rubisco which is possible and considerable progress has been made in identifying natural variation in the catalytic properties of Rubisco and in developing the tools for introducing both novel and foreign Rubisco genes into plants. Genetic manipulation can be used to engineer RuBP, the co-substrate for Rubisco, regeneration and Rubisco activase or to introduce Rubisco subunits with enhanced catalytic properties. Under conditions of low light and elevated CO_2 the regeneration of RuBP limits photosynthetic carbon assimilation. Increase in the duration of photosynthetic activity of leaves allowing them to 'stay green' for a comparatively longer period in maize (Duvick, 1977) and a comparatively slower decline in the canopy photosynthetic activity in rice (Sasaki and Ishii, 1992) through slowing down the degeneration of Rubisco have been reported.

The second approach would be to mimic systems present in nature which concentrate CO_2 in the compartment where Rubisco is located, eliminating photorespiration and ensuring Rubisco operates close to its catalytic optimum. These systems are present in C_4 plants where a biochemical CO_2 concentrating mechanism capable of elevating CO_2 at the site of Rubisco up to 10 fold over atmospheric level (von Caemmerer and Furbank, 2003). However, the complexity of the biochemical and anatomical traits necessary for this mechanism to operate is unclear and thus the minimal set of gens necessary is unknown. Price *et al*. (2008) reported that in many algae and cyanobacteria, CO_2 in the form of bicarbonate is pumped across membrane to elevate CO_2 to even higher levels than those observed in C_4 plants. If this mechanism could be introduced to chloroplast membrane of wheat and rice, substantial increase in photosynthetic efficiency may be expected.

Genetic improvement

The LI, RUE and HI are components of yield potential. Genetic improvement basically focuses on improving all three of these components (Reynolds *et al*., 2011). Physiological traits (PTs) based breeding approaches are needed for combining PTs to achieve cumulative gene action. The responsible PTs that will optimize LI, RUE and HI and their limitations in current gene pools have to be identified to help determine new target levels of expression. Hybridization schemes have to be designed to combine PTs in such a way that the main drivers of yield potential are improved systematically (Reynolds *et al*., 2011). Conventional hybridization and selection is still a widely used strategy for developing crop varieties with high yield potentials. This strategy has made an increase in yield potential by about 1% per year in cereals such as wheat, rice and barley (Peng *et al*., 2000). Braun *et al*. (2010) indicated that genetic progress in yield has been achieved mainly through the innovative use of both the germplasm and crossing strategies followed by empirical selection for grain yield at multi-locations. However, there is little evidence to show that the yield potential ceiling has increased during past 33 years in maize and rice (Cassman, 1999; Duvick and Cassman, 1999; Peng *et al*., 1999) and in wheat (Graybosch and Peterson, 2010).

Jakson *et al*. (1996) concluded that the impact of crop physiology on plant breeding programs has so far been modest. Introduction of the crop 'ideotype' (ideal plant type or a model plant) concept is an example of contribution of crop physiology to plant breeding efforts. Donald (1968) was the first to define the crop ideotype with a specified set of characteristics in wheat. In this approach, a plant type is defined which is theoretically more efficient than existing varieties on the basis of physiological and morphological traits and breeders begin to select directly for the ideotype within segregating populations rather than the grain yield at the end (Peng, *et al*., 1999). Thus, in most cereal breeding programs, ideotype traits such as plant height, tiller and panicle number, leaf color and orientation and grain weight have been the selection criteria (Rasmuson, 1991).

Ideotype breeding aimed at modifying the plant architecture is time-tested strategy to increase the yield potential and selection for short-statured cereals such as rice, wheat and sorghum resulted in doubling their yield potential (Khush, 2013). The first short-statured rice variety, IR8, developed at the International Rice Research Institute (IRRI) had a combination of other desirable traits such as profuse tillering, dark green and erect leaves for good canopy architecture and sturdy stems for lodging resistance, which have also been included in the ideotype. This plant type was widely accepted by plant breeders. Subsequently to further increase yield potential, IRRI scientists proposed a new plant type (NPT) with reduced tillering and no unproductive tillers, 200-250 grains per panicle, dark green and erect leaves, vigorous and deep root system, comparatively higher HI and growth duration of 110-130 days (IRRI, 1989). Many NPT lines with a comparatively higher yield potential have been developed through a crossing program between Tropical Japonica varieties and a semi-dwarf japonica breeding line to date and several of them out yielded the best improved varieties which had been developed earlier by as much as 1.0–1.5 t ha^{-1}. These breeding lines have also contributed to increased genetic diversity through introduction of japonica germplasm into indica breeding materials (Khush, 2013).

Another breeding approach to increase yield potential is the development of hybrid varieties. Hybrid breeding exploit the increased vigor or heterosis in F_1 generation of a cross between two inbred lines, which is translated to grain yield through improving one or more components of yield potential. In maize, major yield improvement has been associated with the introduction of F_1 hybrids on commercial scale and average yield advantage of hybrids vs. varieties is approximately 15-20 % (Tollenaar, 1994). The proposed idoetype for hybrid rice should have the characteristics of moderate tillering, heavy and droopy panicles at maturity, plant height comparatively taller (around 100 cm), HI of 0.55 and narrow, V shaped, thick and dark green top three leaves above panicle height remaining erect until maturity with LAI of 6 (Yuan, 2001). Rice hybrids were introduced in China during mid-1970s and are now planted to about 50 % of the rice area in that country. The average yield advantage of hybrids over inbred varieties is about 10-15 %. Development of rice hybrids of this ideotype with high yield potential is being continued by Chinese breeders. Rice hybrids adapted to tropical conditions have been developed at IRRI (Virmani, 2003) and by the national programs of many other countries in tropical Asia but have met with limited success (Khush, 2013). Thus, the issue is that whether the hybrid rice increase potential rice yield in tropical environments. However, under controlled experiments, increase in potential yield of indica hybrids by about 9 % compared with the best inbred indica varieties under tropical conditions has been observed (Peng *et al*., 1999).

The yield advantage of hybrid rice has been attributed to greater dry matter production, which results from higher LAI and a greater crop growth and an increased HI, which results from greater spikelet number and sometimes an increase in single grain weight (Ponnuthurai *et al*., 1984; Akita *et al*., 1986; Agata, 1990; Song *et al*., 1990a; Patnaik *et al*., 1991; Peng *et al*., 1996). However, Hybrid IR64616H had a lower single-leaf photosynthetic rate due to comparatively lower leaf N concentration than the inbred variety IR 72 at any time during the growing season (Peng, *et al*., 1999).

Widening the crop gene pools through hybridization of crop varieties with wild species, weedy races as well as intra-subspecific, inter-specific and inter-generic crosses can also be used to increase yield potential of cereals.

Inter-specific and inter-generic crosses within *Triticeae* have already been made in wheat breeding (Trethowan and Mujeeb-Kazi, 2008). Introduction of chromatin from C_4 species into wheat is possible although so far not proven to be successful (Reynolds *et al*., 2011). In rice, Xiao *et al*. (1996) reported that some backcross derivatives from a cross between *Orysa rufipogon* accession and cultivated rice out yielded the recurrent parent by as much as 18% and two QTL from wild species, that contributed to yield increase were identified.

Completion of rice genomic sequence has facilitated the identification and cloning of genes and QTL for yield traits (Khush, 2013). These QTL can be pyramided in elite varieties through marker-assisted selection to increase their yield potential (Xing and Yang, 2010). In addition, genomic approaches have allowed the identification and cloning of genes/QTL for some of the sink traits in rice (Sakamoto and Matsuoks, 2008). Genome-wide marker-trait association has become feasible as an empirical selection tool for complex traits such as yield (Bernardo and Yu, 2007). On the other hand, advances in genome sequencing offer opportunities to identify potentially new sources of allelic variation for the purpose of widening the gene pool available for hybridization (Reynolds *et al*., 2011).

Enhanced photosynthesis through incorporation of 'stay green' trait in several crop species including rice has been a major achievement of breeders and this approach appears to have great potential in improving crop yield potential through improving the canopy photosynthesis (Khush, 2013). Attempts have been made to enhance photosynthesis through incorporation of C_4 photosynthetic pathway into C_3 plants like rice (Matsuoka *et al*., 2001; Furbank *et al*., 2009) and wheat (Reynolds *et al*., 2011) and based on the experimental evidences available at present this approach can be considered possible. However, if incorporation of C_4 photosynthetic pathway becomes successful there will be major improvement in the yield potential of rice and wheat.

Potential yield and realized yield at farmer level

Estimation

Accurate estimates of potential yields are needed to interpret yield trends in regions and countries where aggregate yield data over time indicate yield stagnation (Wart *et al*., 2013) and to study and narrowing the yield gaps. Potential yield of a variety × environment combination under the best crop management will be determined by the yield potential of the variety and the environmental conditions under which the crop is grown. Environment can de mainly divided into irrigated and rain-fed environments. Potential yield is determined in the irrigated systems whereas relevant measure in the rain-fed systems is termed water-limited potential yield. Potential yield in the irrigated system is determined by temperature regime and the solar radiation in a given area or region during the cropping season. In order to determine water-limited potential yield in the rain-fed systems, rainfall data are also used in addition to temperature regime and solar radiation (Wart *et al*., 2013).

Wart *et al*. (2013) reported that well documented models validated in field experiments with optimal management using long term weather data and genotype-specific coefficients to determine crop phenological development and final maturity depending on whether the crop is wheat (Jones *et al*., 2003; Ritchie *et al*., 1985), rice (Bouman *et al*., 2001) or maize (Yang *et al*., 2004) are available to estimate crop potential yields. They also suggested improved protocols to obtain robust, transparent and reproducible estimates of potential yields and water-limited potential yields at local regional and national scales for countries in which crops are grown in areas with relatively homogeneous topographies. These authors estimated, using their improved protocol, potential yield of rice in China and maize in US under irrigated system as 7.8 and 15.1 tha^{-1}, respectively, and maize in US and wheat in Germany under rain-fed system as 13.2 and 9.5 t ha^{-1}, respectively.

As limitations in access to accurate long term daily weather data and unavailability of appropriate crop models that have been validated against field data in which crops have been grown to produce yield data that approach potential yield, maximum yields achieved in the field are frequently used as potential yields of cereals. Record yields and winning yields if genuine, represent potential yield at some favorable confluence of genotype, radiation, temperature and management (Evans and Fischer, 1999).

The highest rice yield recorded or the maximum potential yield of rice achieved so far under sub-tropical environment is 17.113 t ha^{-1} (Yuan, 1998). The maximum potential yield in rice recorded in Australia to date again under sub-tropical environment is 14.700 t ha^{-1} (Horie *et al*., 1994). The maximum potential yield of rice recorded under sub-tropical environment in Japan is 13.2 t ha^{-1} (Yoshida, 1981) and at Lower Nile River Valley in Egypt is 11.070 tha^{-1} (Badawi, 1998). The highest recorded or maximum potential yield of rice at IRRI, Philippines under tropical climate is 11.0 t ha^{-1} (Yoshida, 1981). However, DeDatta (1981) also reported a yield level of 10.3 t ha^{-1} in rice at IRRI. In Sri Lanka, maximum potential yield of rice with the present day varieties in the Low Country Dry and Intermediate Zones is 11.73 t ha^{-1} and in the Low Country Wet Zone is 9.38 tha^{-1} (Emitiyagoda *et al*., 2010).

If potential yield for a crop growing environment, zone, region or country is reported, it has to be an average for the whole area but not the maximum potential yield recorded at a location within that area. Similarly the realized yield at farmer level is reported as zonal, regional, seasonal or annual and country averages. The average potential yield for a given environment can be estimated by conducting a representative set of yield tests under the best management practices within that environment. Average yield of these yield tests would estimate the average potential yield and the maximum yield obtained would estimate the maximum potential yield for that environment. Realized yields at farmer level for different environments are obtained through crop cut surveys conducted in farmers' fields. Abeysiriwardena (2000) reported average potential yields and realized yield at farmer level for rice in different rice growing environments of Sri Lanka (Table 1). The average potential yield of 8.5 t ha^{-1} and the realized yield of 5 t ha^{-1} at farmer level by year 1999 have been reported in Asia's irrigated rice lands (Peng *et al*., 1999; Cassman, 1999).

Table 1. Average potential grain yield and average realized grain yield at farmer level by year 2000 for rice in major rice growing environments of Sri Lanka.

Rice growing environment	Average grain yield (t ha^{-1})*	
	Potential	Realized at farmer level by year 2000
Dry Zone		
Major Irrigation Wet Season	9.0	4.1
Major Irrigation Dry Season	8.0	3.9
Minor Irrigation Wet Season	8.0	3.3
Minor Irrigation Dry Season	7.0	3.2
Rain-fed Wet Season	6.0	2.5
Intermediate Zone		
Minor Irrigation Wet Season	8.0	3.4
Minor Irrigation Dry Season	7.0	2.8
Rain-fed Wet Season	6.0	3.1
Rain-fed Dry Season	6.0	2.7
Wet Zone		
Rain & Spring fed Wet Season	6.0	2.9
Rain & Spring fed Dry Season	6.0	2.4

*With present day varieties. (Source - Abeysiriwardena, 2000).

Physiological basis and genetic improvement

Potential yield, defined as the yield of crop variety × environment combination, is dependent upon the yield potential of the crop variety and the climatic, edaphic and biological environment where the crop is grown. It is not restricted by crop management. The grower has no direct control over climatic, edaphic and some biological factors that vary across environments influencing the grain yield. However, grower may have indirect control over climatic, edaphic and biological environment within limits through selecting the proper variety to fit into the environment where the crop is grown (Emitiyagoda *et al*., 2010). This is where the notion that the 'yield genes and stress-resistance genes' (Evans and Fischer, 1999; Cassman, 1999) becomes important so that improving variety resistance to biotic and abiotic stresses would obviously contribute to improve in potential yields.

Physiological basis and genetic improvement of yield potential equally apply to potential yield as well because potential yield is a function of yield potential. Cassman (1999) indicated that much of the observed genetic gain in yield in cereals during the thirty year period prior to 1999 could be attributed to greater stress resistance rather than an increase in yield potential. Same author also reported that for tropical rice and temperate maize, there had been no detectable increase in yield potential although steady progress has been made toward improving stress tolerance. Tollenaar (1994) also reported that by that time resistance to multiple stresses has contributed most to genetic yield gain of temperate maize hybrids grown in southern Canada and only wheat has shown a genetic gain in both yield potential and stress resistance. Among the small grain cereals, the introduction of the dwarfing genes immediately improved resistance to lodging making the Green Revolution possible though it also caused parallel increase in yield potential due to progressive increase in HI (Evans and Fischer, 1999).

Progress made in increasing potential yield of crop varieties has been assumed to be a significant component of the progress made in actual farm yield (Evans and Fischer, 1999). However, rice yields have been stagnant in Japan and China, maize yields have been stagnant in China, Italy and France and similarly wheat yields are stagnating in northern Europe and India (Brisson *et al*., 2010; Cassman *et al*., 2010). One explanation for yield plateaus is that average farm yields have approached potential yield (Wart *et al*., 2013). The average regional and national yields can be predicted to plateau when they reach 70-90 % of potential yield (Cassman, 1999; Cassman, *et al*., 2003; Grassini, *et al*., 2009) because 100% farmers cannot achieve the perfection of crop and soil management required to reach potential yield and crop response to additional inputs exhibits a diminishing marginal yield benefit as yield approaches the potential yield ceiling (Wart *et al*., 2013).

Once the realized yield at farmer level reaches the potential yield, sustaining it over time with the same variety has been difficult. For example, in IRRI, the rice variety IR8 produced 9.6 t ha^{-1} in the late 1960s but the maximum yield produced by IR8 in 1998 at the same site was 7.2 t ha^{-1} (Peng *et al*., 1999). However, with other newly released varieties, grain yield of 9-10 t ha^{-1} has been often recorded in agronomic trials conducted at the experimental station farm at IRRI (Kropff *et al*., 1993; Peng *et al*., 1996). This also suggests that the yield potential of varieties developed at IRRI and/or potential yield of rice at IRRI have not changed during the period from 1960s to 2000. Another example can be drawn from Sri Lanka. At a site at Mapakada, Mahiyanganaya in Sri Lanka, rice yields obtained in 1998/1999 wet, 1999 dry, 1999/2000 wet and 2000 dry seasons were 10.3, 10.45, 8.5 and 8.75 t ha^{-1}, respectively and at present the yield level in the same site has stabilized around 8 t ha^{-1}.

Conclusions

Clear distinction among the terms 'yield potential', 'potential yield', 'maximum potential yield' and 'realized yield at farmer level' in relation to cereals has been made. Yield potential is the genetic potential, which is dependent on biological or plant factors under the ideal environmental conditions and crop management practices, having one definite yield level for the species or variety. Potential yield is the yield of a variety × environment combination under the best crop management and will be different in environments differing in temperature and solar radiation regimes for a given variety. Thus, if a region or zone is considered, potential yield varies among specific environments within the region or zone eventually making to estimate maximum, minimum and average potential yields for the region or zone. Realized yield which is the actual farmer yield at farmer or production level is often lower than the potential yield and highly variable over space and time as it is influenced by not only the varying physical and biological environments but also by the crop management practices, which is highly variable among farmers. Yield potential and potential yields of cereals can be estimated or measured and genetically improved. To-date there is no evidence to judge the limit to yield potential in cereals. Even if the yield potential is reached, potential yields and realized yields at farmer level could still continue to rise as plant breeders continue to improve variety capability through incorporating resistance to biotic and abiotic stresses and as crop management improves.

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References

Abeysiriwardena, D.S. de Z. (2000): Rice varietal improvement for future challenges. Rice Congress 2000. pp 87-99. Department of Agriculture, Peradeniya, Sri Lanka.

Agata, W. (1990): Mechanism of high yielding achievement in Chinese F_1 rice compared with cultivated rice varieties. *Jpn. J. Crop Sci*., 59: 270-273.

Akita, A., Bianco, L. and Virman,i S.S. (1986): Physiological analysis of heterosis in rice plant. *Jpn. J. Crop Sci.*, 65: 14-15.

Badawi, A.T. (1998): Sustainability of rice production in Egypt. Paper presented at 19th Session of the IRC, 7-9 September. Cairo, Egypt.

Bernardo, R. and Yu, J. (2007): Prospects for genomewide selection for quantitative traits in maize. *Crop Sci.*, 47: 1082-1090.

Berry, P.M., Sylvester-Bradly, R., and Berry, S. (2007): Ideotype design for lodging-resistant wheat. *Euphytica* 154: 165-179.

Bingham, J. (1967): Breeding cereals for improved yielding capacity. *Ann. Appl. Biol*., 59: 312-315.

Bouman, B.A.M., Kropfff, M.J., Tuong, T.P., Wopereis, M.C.S., Ten Berge, H.F.M. and van Laar, H.H. (2001): Oryza2000: Modeling Lowland Rice. International Rice Research Institute, Los Baños, Philippines.

Braun, H. J., Atlin, G. and pain, T. (2010): Multi-location testing as a tool to identify plant response to global climate change. In: Climate change and crop production (Ed: Reynolds, M.P.) pp 115-138. Wallingfoed, UK: CABI Publishers.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F. X. and Huard, F. (2010): Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. *Field Crop Res.*, 119:201-212.

Bruinsma, J. (2009): The resource outlook to 2050: by how much do land, water and crop yields need to increase by 2050? FAO expert meeting on how to feed the world in 2050; 2009/06.

Cassman, K. G. (1999): Ecological intensification of cereal production systems; Yield potential, soil quality and precision agriculture. *Proc. Natl. Acad. Sci. USA,* 96: 5952-5959.

Cassman, K.G., Dobermann, A.D., Walters, D. and Yang, H. (2003): Meeting cereal demand while protecting natural resources and environmental quality. *Ann. Rev. Environ. Res*., 28: 315-358.

Cassman, K.G., Grassini, P. and van Wart, J. (2010): Crop yield potential, yield trends and global food security in a changing climate. In: Handbook of climate change and Agroecosystems (Eds: Rosenzweig, C., Hillel, D.). p 37. Imperial College Press, Londen.

Constable, G.A. and Bange, M.P. (2015): The yield potential of cotton (*Gossypium hirsutum* L.). *Field Crop Res*., 182: 98-106.

Dawe, D and Dobermann, A. (1998): Defining productivity and yield. Discussion paper series No. 33. International Rice Research Institute. Los Banos, Philippines.

De Datta, S.K. (1981): Principles and practices of rice production. Wiley and Sons.

Donald, C.M. (1968): The breeding of crop ideotypes. *Euphytica,* 17: 385-403.

Duggan, B.L. and Fowler, D.B. (2006): Yield structure and Kernel potential of winter wheat on the Canadian prairies. *Crop Sci.*, 46: 1479-1487.

Duncan, W.G. (1971): Leaf angle, leaf area and canopy photosynthesis. *Crop Sci.*, 11: 482-485.

Duvick, D.N. (1977): Genetic rates of gain in hybrid maize yields during the past 40 years. *Maydica* 22: 187-196.

Duvick, D.N. (1992): Genetic contribution to advances in yield of U.S. maize. *Maydica* 37: 69-79

Duvick, D.N. and Cassman, K.G. (1999): Post-green-revolution trends in Yp of temperate maize in the north-central United States. *Crop Sci.*, 39: 1622-1630.

Emitiyagoda, G.A.M.S.S., Abeysiriwardena, D.S. de Z. and Silva S. (2010): Grain yield and yield variability of rice under high management in different Agro-climatic Zones in Sri Lanka. *Annals Sri Lanka Dep. Agric*., 12: 63-77.

Evans, L. T. (1972): Storage capacity as a limitation in grain yield. In: Rice Breeding. pp 499-511. International Rice Research Institute, Los Banos, Philippines.

Evans, L.T. (1993): Crop Evolution, Adaptation and Yield. Cambridge University Press, Cambridge.

Evans, L.T. and Fischer, R.A. (1999): Yield Potential: Its Definition, Measurement and Significance. *Crop Sci*., 39(6): 1544-1551.

Fischer, R. A. (1985): Number of kernels in wheat crops and the influence of solar radiation and the temperatures. *J. Agric. Sci*., 105: 447-461.

Fischer, R.A., Rees, D., Sayre, K.D., Lu Z-M, Condon, A.G. and Saavedra, A.L. (1998): Wheat yield progress associated with higher stomatal conductance and photosynthetic rate and cooler canopies. *Crop Sci.*, 38: 1467-1475.

Furbank, R. T., Caemmerer S., Sheehy, J. and Edward, G. (2009): C_4 rice: a challenge for plant phenomics. *Functional Plant Biol.*, 36: 845-856.

Grassini, P., Yang, H.S., and Cassman, K.G. (2009): Limits to maize productivity in Western Corn-Belt: a simulation analysis for fully irrigated and rainfed conditions. *Agric. For. Meteorol.*, 149: 1254-1265.

Graybosch, R.A. and Peterson, C.J. (2010): Genetic improvement in winter wheat yields in the Great Plains of North America: 1959-2008. *Crop Sci.*, 50: 1882-1890.

Hanson, H, Borlaug, N. E. and Anderson, R. G. (1982): Wheat in the third world. Westview Press,
Colorado.

Horie, T., Ohnishi, M., Angus, J.F., Lewin, L.G. and Matano, T. (1994): Physiological characteristics of high yielding rice inferred from cross-location experiments. Proc. First Temperate Rice Conference. 21-24 February. pp. 635-663. Yanco, NSW, Australia.

IRRI (1977): Annual Report for 1976. International Rice Research Institute, Los Banos. Philippines. P 418.

IRRI (1989): IRRI Towards 2000 and Beyond. International Rice Research Institute, Los Banos, Philippines.

Jakson, P., Robertson, M., Cooper, M. and Hammer, G. (1996): The role of physiological understanding in plant breeding; from a breeding perspective. *Field Crop Res.,* 49: 11-37.

Jones, J.W., Hooganboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J. and Ritchie, J.T. (2003): The DSSAT cropping system model. *Eur. J. Agron.*, 18: 235-265.

Khush, G.S. (2013): Strategies to increase yield potential of cereals: case of rice as an example. *Plant Breeding,* 132: 433-436.

Kropff, M.J., Cassman, K.G., van Laar, H.H. and Peng, S. (1993): Nitrogen and yield potential of irrigated rice. *Plant Soil*. 155/156: 391-394.

Long, S.P., Zhu X-G and Ort, D.R. (2006): Can improvement of photosynthesis increase crop yields? *Plant Cell Environ*., 29: 315-330.

Matsuoka, M., Fukayama, H., Ku, M.B.S. and Miyao, M. (2001): High level expression of C_4 photosynthetic genes in transgenic rice. In: Rice Genetics IV (Eds: G.S. Khush, D.S. Brar and B. Hardy). pp 439-447. International Rice Research Institute, Los Banos, Philippines.

Miralles, D. J. and Slafer, G. A. (2007): Sink limitations to yield in wheat: how could it be reduced? *J. Agric. Sci*., 145: 139-149.

Murata, Y. and Matsushima, S. (1975): Rice. In: Crop physiology (Ed: L.T. Evans). pp 73-99. Cambridge University Press. London.

Parry, M.A.J., Madgwick, P.J., Carvalho, J.F.C. and Andralojc, P.J. (2007): Prospects of increasing photosynthesis by overcoming the limitations of Rubisco. *J. Agric. Sci.*, 145: 31- 43.

Patnaik, R.N., Pande, K., Ratho, S.N. and Jachuck, P.J. (1991): Consistent performance of rice hybrids. *Crop Res*., 4: 272-279.

Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Vispersa, R.M. and Cassman, K.G. (1996): Increased N-use efficiency using a chlorophyll meter on high yield irrigated rice. *Field Crop Res*., 47: 243- 252.

Peng, S., Cassman, K.G., Virmani, S.S., Sheehy, J. and Khush, G.S. (1999): Yield potential trends of tropical rice since the release of IR8 and the challenge of increasing rice yield potential. *Crop Sci*., 39: 1552-1559.

Peng, S., Laza, R.C., Visperas, R.M., Sanico, A.L., Cassman, K.G., and Khush, G.S. (2000): Grain yield of rice cultivars and lines developed in the Philippines since 1996. *Crop Sci*., 40: 307-314.

Ponnuthurai, S., Virmani, S.S. and Vergara, B.S. (1984): Comparative studies on the growth and grain yield of some F1 rice (*Oryza Sativa* L.) hybrids. *Philipp. J. Crop Sci.*, 9: 183-193.

Price, G.D., Badger, M.R., Woodger, F.J. and Long, B.M. (2008): Advances in understanding the cynobacterial CO2- concentrating-mechanism (CCM): functional components, Ci transporters, diversity, genetic regulation and prospects for engineering into plants. *J. Exp. Bot.*, 59: 1441-1461.

Rasmuson, D.C. (1991): A plant breeder's experience with ideotype breeding. *Field Crops Res.,* 26:191-200.

Reynolds, M., Bonnett, D., Chapman S.C., Furbank, R.T., Manes Y., Mather D.E. and Parry M.A.J. (2011): Raising yield potential of wheat. 1. Overview of a consortium approach and breeding strategies. J. Exp. Bot., 62(2): 439-452.

Ritchie, J.T., Godwin, D.C. and Otter-Nacke, S. (1985): CERES-Wheat: A User Oriented Wheat Yield Model: Preliminary Documentation. Michigan State University, MI.

Rosegrant, M. W., Ringler, C. and Zhu, T. J. (2009): Water for agriculture: maintaining food security under growing scarcity. *Ann. Rev. Env. Resour*. 34: 205-222.

Sakamoto, T. and Matsuoks, M. (2008): Identifying and exploiting grain yield genes in rice. *Curr. Opin. Plant Biol*., 11:209-214.

Sasaki, H. and Ishii, R. (1992): Cultivar differences in leaf photosynthesis of rice bred in Japan. *Photosynthesis Res*., 32: 139-146.

Sayre, K.D., Rajaram, S. and Fischer, R.A. (1997): Yield potential progress in short bread wheat in northwest Mexico. *Crop Sci*., 37: 36-42.

Song, X., Agata, W. and Kawamutsu, Y. (1990a): Studies on dry matter and grain production of F_1 hybrid rice in China. II. Characteristics of grain production. *Jpn. J. Crop Sci*., 59: 2933.

Tollenaar, M. (1994): Yield potential of maize: impact of stress tolerance. In: Braking the Yield Barrier (Ed: K.G. Kassman), pp. 103-109. International Rice Research Institute, Los Banos, Philippines.

Tollenaar, M., McCullough, D. E. and Dwyer, L. M. (1994): Genetic Improvement of field crops (Ed. Slafer, G A.) pp. 183-236. Dekker, New York.

Trethowan, R. M. and Mujeeb-Kazi, A. (2008): Novel germplasm resources for improving environmental stress tolerance of hexaploid wheat. *Crop Sci*., 48: 1255-1265.

Virmani, S.S. (2003): Advances in hybrid rice research and development in the tropics. In: S. S. Virmani, C. X. Mas and B. Hardy (eds.), Hybrid Rice for Security, Poverty Alleviation and Environmental Protection. Proc. 4th Int. Symp. Hybrid Rice. May 2002, pp 14-17, Hanoi, Vietnam.

Von Caemmerer, S. and Furbank, R. J. (2003): The C_4 pathway: an efficient CO_2 pump. *Photosynthesis Res*., 77: 191-207.

Wart, J. V., K. Christian Kersebaum, S. Peng, M. Milner and K. G. Cassman. (2013): Estimating crop yield potential at regional to national scale. *Field Crop Res.,* 143: 34-43.

Xiao, J., Grandillo, S., Ahn, S. N., McCouh, S. R. and Tanksley, S. D. (1996): Genes from wild rice improve yield. *Nature.* 384:1223-1224.

Xing, y. and Yang, Q. (2010): Genetic and molecular bases of rice yield. *Ann. Rev. Plant Biol*., 61: 421-442.

Yang, S.H., Doberman, A., Lindquist, J.I., Walters, D.T., Arkebauer, T.J. and Cassman, K.G. (2004): Hybrid-maize-a maize simulation model that combines two crop modeling approaches. *Field Crop Res*., 87: 131-154.

Yoshida, S. (1981): Estimation of maximum potential yield. In Fundamentals of Rice Crop Science. pp. 90-94.

Yuan, L. (1998): Hybrid rice development and use: Innovative approach and challenges. Paper presented at the 19th session of the IRC, 7-9 September. Cairo, Egypt.

Yuan, L. (2001): Breeding of super hybrid rice. In: S. Peng and B. Hardy (eds), Rice Research for Food Security and poverty alleviation, pp 143-149. International Rice Research Institute, Los Banos, Philippines.

Zhu X-G, Long, S. P. and Ort, D. R. (2010): Improving photosynthetic efficiency for greater yield. *Ann. Rev. Plant Biol*., 61:235-261.