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Definitions and determination of crop yield, yield gaps, and of rates of change

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ABSTRACT

Given the importance of crop yield and yield progress, this review endeavours to clearly define the different representations of yield, discuss their measurement, and elucidate some controlling factors in yield change. For a field, farm, district or region, average farm or actual yield (FY) is central, but potential (and water-limited potential) yield (PY, PY_w) is also an important yardstick. PY is defined here as the measured yield of the best cultivar, grown with optimal agronomy and without manageable biotic and abiotic stresses, under natural resource and cropping system conditions representative of the target area. Economic yield, governed by considerations of profit and risk, and record and theoretical yield, complete the picture. Yield gap is defined as the difference between PY and FY under the same environment. Across most crop-region combinations in the last 2 to 3 decades, FY progress has been associated with both PY progress and yield gap closing, and a simple model, based on linear regression against time, is proposed for understanding this. PY advance is the result of plant breeding and new agronomy (and their interaction, usually positive), while yield gap closing arises with the adoption by farmers of known innovations faster than new ones are invented. Unravelling the true technological component in apparent progress in PY, and especially in FY, is not necessarily simple, and confounding factors are listed and discussed.

1. Introduction

Crop yield is of fundamental importance in agriculture, as is yield increase through new technology for world food security (Fischer et al., 2014). Despite the rich published literature on measures of yield, these have often been poorly defined, while the role of technology in yield change over time can be confounded by other influences. As a prelude to the crop-specific papers which follow, this review proposes some clear definitions and yield measurements along with a simple model of yield change, while attempting to unravel the general factors behind yield change. The review relies largely on Evans (1993), van Ittersum and Rabbinge (1997), Evans and Fischer (1999), Connor et al. (2011), van Ittersum et al. (2013), and follows Fischer et al. (2014). The last-mentioned two references, in particular, represent the culmination of much deliberation on the subject by crop scientists; where significant differences in definition remain these are pointed out. Different crops and regions are used to illustrate the subject, and are largely drawn from Fischer et al. (2014), as are some summary numbers on yield change. The reader is referred to this reference for a comprehensive look at yield change and prospects across more than 20 crops.

2. Yield definitions

2.1. Crop yield

'Crop yield' is the weight of grain or other economic product, at some agreed standard moisture content, per unit of land area harvested per crop (usually metric tons per hectare[1], or here abbreviated to t/ha). Standard moisture content varies between crops but is 8–16% in grains. This is usually the maximum limit for marketing of grain and may also vary slightly between countries: typical values are wheat (12–15%), paddy rice (14%), maize (15.5%), soybean (13%) and canola (8%). In all cases, grain moisture content is calculated on a fresh weight basis[2].

[1] A metric ton (1000 kg or 1 Mg) is sometimes referred to as a "tonne"; an Imperial ton is 2240 lbs (1017 kg).

[2] Grain dry weight is given by grain fresh weight multiplied by (100 − '% moisture')/100. Zero percent moisture is determined in a standard manner, which varies somewhat between commodities.

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Complications abound with yield measurements. Thus rice yield is usually reported as paddy or rough rice (husk attached), but in Japan it is common to use brown rice yields (husk removed, weight about 80% of paddy), and in India milled rice yield (white grain after milling to remove seed coat, weight about 67% of paddy weight). Barley is normally hulled, with the floral glumes closely adhering to the grain, but hulless varieties, from which the glumes are removed at harvest, also exist; the hull weighs about 10% in a hulled variety. Peanut yield is normally reported as in shell, the seed weigh comprising 67% of the in-shell weight. Sugarcane and root crops are reported as fresh weight yields, with various proportions of useful product (around 7 to 14% extractable soluble sugars in sugarcane and ~18% for sugar beet), or dry matter contents for cassava (~30%) and potato (~20%).

Energy, protein, oil, vitamin and microelement contents of yield products are also of importance in yield studies when nutritive, energetic or economic values are to be considered. Suffice here to point out that energy contents reflect the cost of biosynthesis of the major product constituents: the grams of glucose needed to synthetise 1 g of product are 1.3 g (carbohydrate), 1.6 g (protein with reduced N), 2.5 g (protein with nitrate N), and 2.7 g (lipid) (Connor et al., 2011). Thus cereals have a total energy content of ~15 MJ/kg, while soybean, with around 40% protein and 20% oil, contains ~24 MJ/kg[3]. To compare product yields between commodities these different energy costs need to be considered.

2.2. Farm yield (FY)

The central yield figure for agriculture is the field, farm, district, regional or national average yield given in kilograms or metric tonnes per hectare (kg/ha and/or t/ha). This figure is reported from farmers' yield measurements, nowadays in modern farming often measured directly from the harvester (but commonly poorly calibrated), from surveys and/or local or national statistics, and is referred to here as 'farm yield' (abbreviated to FY as in Fischer et al., 2014). Some call this actual yield (e.g. Connor et al., 2011), while van Ittersum et al. (2013) use average farm yield (abbreviated to Ya). Ya is considered ambiguous, and FY is preferred here.

FY and many related crop statistics for all countries are collated annually by governments and then by the Food and Agriculture Organization of the United Nations (FAO), and are disseminated via the publically accessible database FAOSTAT[4]. FY is expressed relative to harvested land area, noting that this area can fall well below planted area in some situations (e.g. after winter kill or spring freeze in winter wheat, or salvation grazing or hay making under drought).

Although FY is quoted and used widely, it may not be as accurate as it appears due to poor data collection, uncertain grain admixtures or moisture contents, and other complications with data processing. With survey data, sampling error and bias can also arise. Nevertheless some countries publish very accurate FY numbers as Lobell et al. (2014) attest for maize in USA when they compared official USDA county survey yields with county aggregate yields from yields of farmers' fields monitored for insurance purposes. This is confirmed by Sadras et al. (2014) for both maize and soybean in USA, but these authors found worrying discrepancies between two reputable sources for crop yields in Argentina.

In warm climates, more than one crop may be grown each year. Crop area and yield is still always reported by FAO on a per crop basis, being an area weighted average if the same crop which is repeated (e.g. double rice in the Philippines), but yield per year or per day can be more important than individual crop yield. For example, Indonesian rice systems may produce up to three crops per year, a situation in which 'cropping intensity' (defined as the harvested area of all crops each year as a per cent of the cultivated area) is given as 300%.

In the last decade FY data estimated from satellite images has become available, including the yield of various crops at a resolution of 1 arcmin × 1 arcmin (about 2 km × 2 km) across the whole globe (Monfreda et al., 2008). While these may be calibrated to exactly match regional or national statistics, they lack the accuracy needed to unravel most causes of yield changes. More accurate estimations combine high-resolution satellite imagery, crop modelling, and local weather inputs with ground truthing (Lobell, 2013; van Ittersumet al., 2013). This can deliver FY values for all fields in a region, revealing many useful statistics on the FY population (e.g., normality, standard deviation, quantiles, skewedness) and its mesoscale distribution (e.g., as a function of distance from road or irrigation canal), previously only available in a more limited manner from expensive ground surveys.

2.3. Potential yield (PY)

At the high end of the yield scale it is critical to define 'potential yield' (abbreviated here as PY) which is the yield to be expected with

(i) the best adapted variety (usually the most recent release),
(ii) the best management of agronomic and other inputs,
(iii) the absence of manageable abiotic and biotic stresses, but
(iv) otherwise with the same natural resource base and cropping system as has the region to which the particular PY refers.

This definition is provided by Evans and Fischer (1999), although in that case using the term 'yield potential'[5]. van Ittersum et al. (2013) define potential yield similarly (which they abbreviate to Yp). Many complications are hidden within this apparently simple definition but PY remains a key yardstick for understanding yield change. It may be difficult to measure, but PY and its surrogates are frequently reported in the crop science literature—although often without adequate attention to complications.

One complication is the sowing date when there are multiple crops of the same commodity; for example in the tropics, the PY of irrigated dry season rice is greater than that of irrigated wet season rice. Also the optimal sowing date may be constrained in multiple cropping systems (van Ittersum et al., 2013); PY from sowings both with and without this constraint need to be considered (e.g. in Argentina, with double cropping, soybean planted after wheat harvest has a lower PY than soybean planted at the earlier optimal date in sole cropping).

PY is usually determined in plots, but to be applicable to the surrounding district, the natural resource base (climate, soil type, topography) of the plots needs to be comparable (not superior) to the district, and this includes consideration of any long-term management improvements (e.g. irrigation or liming or tile drainage) and the sampling of a reasonable number of seasons. Water supply must be adequate for PY to be determined, otherwise it is necessary to instead consider 'water-limited potential yield' (PY_w), which is described further below. Adequate water can come from well distributed in-crop rainfall sufficient to satisfy most or all of crop potential evapotranspiration (ET_p = crop water use from sowing to harvest without water limitation), or from full or supplemental irrigation. Complete fertilization may be needed to insure lack

[3] Note that food and feed energy are less, depending on digestibility.
[4] http://faostat3.fao.org/home/index.html.
[5] Here 'yield' is retained as the noun, and 'potential' as adjective, to avoid confusion with the term 'yield potential' which appears often in published literature with various meanings.

of nutrients. Similarly pests, weeds and diseases must be held at negligible levels, through use of biocides if necessary. Finally crops experiencing relatively rare weather damage (such as crop lodging or unseasonal frosting) are excluded from PY measurement.

Since PY is usually measured in plots, sampling errors will occur. Also edge effects arising from extra solar radiation reaching border plants – or extra soil moisture in the case of PY_w – must be avoided, ideally by discarding the plot edges (up to a width of 25 cm to 100 cm, depending on crop height) (Rebetzke et al., 2014). If adjacent plots are harvested without discarding longitudinal edges, at the very least the inter-plot path area must be included in the yield calculation.

PY as defined here is obtained from two sources: comparative variety trials and single variety experiments, in each case covering a fair sample of years. Typically variety trials are well managed experiments for the purpose of comparing new varieties against previously leading varieties (usefully called 'vintage trials') and all varieties may be present in all locations and/or years (termed a 'balanced trial'). Alternatively, multiyear unbalanced trials in which varieties gradually change over time – the situation for many breeding programs and national variety testing schemes – are another source of PY information. Trials for variety testing usually have the major advantage of being sensibly distributed across the target region. A most useful example is the comparative trials conducted by the UK Home Grown Cereals Authority (e.g. HGCA, 2011), in the case of wheat varieties at some 30 sites across the wheat growing region of the UK, and which additionally are split for fungicide protection. Yields from variety trials can only be considered as a true measure of PY where protection has been used, but around the world fungicide protection is not yet a common treatment in such trials. However visible disease levels are usually reported, and (if not negligible or too serious) this information can be used to correct yield to give PY.

The second source of PY data comes from careful field experiments conducted by crop physiologists, often to calibrate and/or validate crop simulation models. Compared to most variety trials, these experiments run the risk of not adequately representing the natural resource base of the region of interest. But such experiments should have good enough management to eliminate all manageable stresses, something variety trials may not achieve (e.g. even in humid regions there can sometimes be significant rainfall deficiencies)

Crop modelling is then commonly used to predict PY in other environments (e.g. different sowing dates, years and/or locations within, or with care, beyond the region of interest) and is especially useful for estimating PY across a relevant sample of seasons. Modelling accuracy has steadily improved for such purposes, but simulation is often extended into environmental factor spaces beyond those used in calibration, and significant errors are still revealed when different models are compared (e.g. Palosuo et al., 2011). Ensembles of crop models are however showing a surprising improvement in accuracy (Asseng et al., 2013). Models need to be updated for the latest varieties every few years, since breeders are steadily altering varieties (e.g. changing phasic development and improving PY). Fischer et al. (2014) favoured measured PY, but it is noted that in a recent review van Ittersum et al. (2013) opt strongly for PY determination using thoroughly and locally validated simulation modelling, and site-specific weather, soil and agronomic inputs. They illustrated the strength of this approach by the simulation of PY for 123 individual fields of irrigated maize in Nebraska, incorporating the field level data on soil, weather (rainfall) and management.

Lobell et al. (2009) used either measurement, modelling or expert opinion to estimate PY across cereals in many key growing regions of the world, with the last two mentioned methods tending to give higher values of PY. Finally, various types of frontier analysis can be used to identify the top yields reached by farmers (Fischer et al., 2014), but these are not likely to be potential yields as defined (see below).

2.4. Water-limited potential yield (PY_w)

Much of the global grain crop is grown in rainfed situations where water supply from stored soil water at the start of the crop season, plus precipitation during the crop season, falls well below ET_p. These circumstances are so different to non-water limited ones that it is useful to define a water-limited potential yield (PY_w)[6] when average actual ET is less than about 70% of ET_p. This is the yield obtained with no other manageable limitation to the crop apart from the water supply. Obviously crop yield will depend on the amount of available water, so PY_w is usually plotted relative to water supply (or actual evapotranspiration, ET_a). The PY_w for a location or region becomes the value of PY_w at the average expected water supply. The slope of this relationship (e.g. across different water supplies in a region) is considered to be reflective of potential 'crop water use efficiency' (or 'water productivity'), commonly reported in kilograms of grain yield per harvested hectare per millimetre of water (kg/ha/mm). Care is needed to distinguish water use efficiency thus calculated from that more readily obtained from dividing yield by ET_a, which is the definition of water productivity in van Ittersum et al. (2013).

Complications can arise due to variation in rainfall distribution with respect to crop development stages, but PY_w (defined as a linear function of the water supply) is a valuable and simple benchmark as argued in a recent in-depth review of the subject by Passioura and Angus (2010). Simulation modelling has been especially useful in understanding expected deviations in PY_w due to variation in the distribution of water supply (e.g., Sadras and Connor, 1991).

2.5. Economic yield (EY)

In any given region, between FY and PY (or PY_w), there is another important yield benchmark, namely 'economic yield' or EY. This is defined here as the yield attained by farmers with average natural resources when economically optimal practices and levels of inputs have been adopted while facing all the vagaries of weather. Recently van Ittersum et al. (2013) defined this as exploitable yield, and Fischer et al. (2014), and several others before, as attainable yield. It is here suggested that the adjective "economic" better captures the sense of this important definition.

Since risk of financial loss almost always forms part of a farmer's decision to invest in increased inputs, the economic yield definition must temper 'optimum level' with 'prudent attention to risk'. As an example this could mean input investments must be expected to return a risk premium over and beyond the cost of the inputs and the capital. This premium is usually low in developed countries and/or when water supply is assured, but is higher in developing countries and under rainfed conditions.

Of course EY will reflect the economic circumstances of the crop and region—particularly grain prices relative to input costs, all measured at the farm gate. Although it is not easy to establish an appropriate EY to which farmers aspire, general experience suggests that it will lie ∼20–30% below PY in situations where there is no other competition for the farmers' resources, and world prices and reasonable transport costs operate (e.g., van Ittersum et al., 2013; Fischer et al., 2014). Where this does not occur – for example, in much of Sub-Saharan Africa where infrastructure and

[6] van Ittersum et al. (2013) similarly define a water-limited potential yield, abbreviated to Yw.

institutions are weak – EY may be much lower relative to PY. Alternatively, where inputs and grain prices are heavily subsidised, it could more closely approach PY.

Another reason why EY doesn't reach PY is because of the inevitable minimum time lag taken for the latest varieties (and any accompanying novel agronomy) to dominate in farmers' fields. Even in the best situations this lag time probably equates to around 5 years: if PY progress is 1% p.a., this would inevitably lead to an FY deficit of 5%. For many reasons, and especially in developing countries, the lag in new variety adoption can be much longer – as is also common for the adoption of new agronomy – and this can partly explain exploitable yield gaps (see below).

2.6. Record and contest winning yields

Sometimes crop contest winning yields or record crop yields are considered in the scientific literature to be synonymous with PY. Even if verified independently, these yield values need to be treated with caution because they refer to very favourable circumstances (e.g. soils, weather, and/or management) relative to the district or regional average conditions, and thus exceed PY notably. With cautious interpretation, record and contest winning yields can provide useful information, but they do not measure PY as defined here.

2.7. Theoretical yield

Models, both simple and complex such as dynamic crop simulation models, are also used to calculate yields which would result if certain physiological processes could be altered favourably within realistic bounds: such yields are here called 'theoretical yields'. Argument surrounds what are the realistic bounds, and it is likely that some such assumptions, like radiation use efficiency equivalent to leaf photosynthetic efficiency at low light, are not realistic for field crops.

3. Defining and measuring yield gaps

Because of the uncertainties surrounding EY, it is easier to discuss the yield gap in terms of that between FY and PY, as have van Ittersum et al. (2013)[7]. Also when it comes to discussion of food security, it is more appropriate to express yield gap as a percentage of FY, because desirable increases in actual world grain yields are inevitably expressed as a percentage of current FY, not current PY. Most other researchers express the yield gap relative to PY (or PY_w), readily calculated from the gap figure defined here, but one which in a sense hides the huge yield gaps to be found in parts of the developing world (e.g. 400% for maize in sub-Saharan Africa).

Published literature and experience support the notion of a minimum yield gap when FY equals EY (as defined above) depending largely on prices. Assuming that future prices will be reasonably favourable for the farmer and close to world prices, as mentioned earlier it is suggested that this minimum yield gap is 30% of FY, meaning EY is 23% below PY. van Ittersum et al. (2013) opted for a minimum yield gap of 15 to 25% below PY, and define the amount by which a yield gap is larger than this as an economically exploitable yield gap.

Calculated as the difference between FY and measured PY and expressed as a percentage of FY, the yield gap across around 40 important commodity–region combinations around the world in 2010 was found to range from 25% to as high as 400% (Fischer et al., 2014). The results also supported the notion of a minimal gap of 30%. These results agree well with an earlier review of cereal yield gaps around the world (Lobell et al., 2009). Recently a useful global yield gap atlas was initiated, showing country yield gaps as a percentage of modelled PY (http://www.yieldgap.org/).

Some researchers have attempted to derive the yield gap from study of the distribution of FY across fields, or farms, or even units of lower resolution (e.g. 1 arcmin × 1 arcmin areas across the earth's surface, or across US counties). van Ittersum et al. (2013) reviewed the low resolution top-down approaches and concluded that they are all probably too general, simplistic and idiosyncratic to be useful, certainly at any detailed level. Focus on fields or farms in a defined region, however, would seem realistic, a bottom-up approach according to these authors. For example FY was determined by high resolution satellite imagery in the several thousand irrigated wheat fields in the Yaqui Valley of north-west Mexico over three years by Lobell et al. (2003)[8]. FY distribution showed a negative skew, and Fischer et al. (2014) estimated that the 90th percentile value of FY in this data set was 25% above the average FY (5.7 t/ha) but below measured PY, by an amount equal to 34% of average farm yield; thus it may be close to EY yield for the Valley. Grassini et al. (2011) reported irrigated maize FY for 777 fields across three counties in central Nebraska. The coefficient of variation was only 8%, meaning that the 90 percentile yield was only about 10% above the average FY (13 t/ha), while PY (modelled in this case)[9] was 35% above the average FY; again the 90th percentile FY may be a reasonable estimation of EY. Under rainfed conditions in developed countries, FY plotted against crop water use reveals EY as the upper frontier bounding the data plotted, and identifies yield gaps as the distances the many other FY values lie below this frontier (e.g., French and Schultz, 1984; Passioura and Angus, 2010; Patrignani et al., 2014).

With small holder farmers, however, FY distributions may not indicate EY or point towards PY. Thus Laborte et al. (2012) studied rice FY in surveys of farmers in central Luzon (Philippines), reporting that the mean of yields within the top decile of yields (somewhat more than the 90 percentile yield) was more than 50% (of average FY) below modelled PY. Similarly Affholder et al. (2013) found the 90 percentile FY across four small holder samples engaged in tropical cropping to be only around one half of the modelled PY, similar to that reported for rainfed maize farmers in Kenya by van Ittersum et al. (2013).

4. Measuring progress in farm yield (FY) and potential yield (PY)

4.1. Measuring farm yield (FY) progress

It is common to plot FY, the dependent variable, against year for given regions, states or nations. Economists look at exponential or compound rates of change (or the linear fit of log FY versus time) expressed as annual per cent change. In contrast, crop scientists tend to calculate the linear fit of FY versus time, coming up with a slope in kilograms (or tons) per hectare per year (kg/ha/yr or t/ha/yr). As change in FY over time in most cases resembles a linear relationship more closely than an exponential one (Grassini et al., 2013; Fischer et al., 2014), the recent linear slope is suggested as the best basis for reporting the current annual rate of FY progress, and for making future projections.

Over the last century bilinear fits were adequate for major grain crops in most countries (Evans, 1993; Calderini and Slafer, 1998; Hafner, 2003), meaning slow or zero initial FY gains were replaced

[7] These authors abbreviate yield gap to Yg, an abbreviation not deemed necessary here.

[8] They actually worked with 30 × 30 m^2 pixels, but on average many were sampled per field and within field variability was small.

[9] This modelled PY ignores the increased risk of frost damage when seeking higher PY with longer season maize hybrids.

by rapid linear increases that often commenced in the 1950s or 1960s with the onset of modernization of agriculture (e.g. the Green Revolution in rice and wheat yields in Asia). Lately many rising yields have slowed and some have even shown another break—to lower linear rates of increase, or even zero FY improvement. This has occurred with wheat yields in parts of Western Europe (Lin and Huybers, 2012; Grassini et al., 2013) including France (Brisson et al., 2010). And in the case of maize in the Argentina and parts of USA, there has been a recent acceleration in the FY growth such that an exponential model fits well (Grassini et al., 2013).

The question of which is the best description of current FY change is an important one. Clearly current progress must be calculated only over recent times but given the noise arising largely for interannual weather variation, at least 20 years is needed to do this (or 30 years if the data is very noisy, as with rainfed crops and/or small growing regions); even then slopes are notably affected by small changes in start (and end date) of any yield series and for comparative studies decisions should be made before inspecting the data! Choosing 20 or 30 years largely avoids the previous 'Green Revolution' period of most rapid yield improvement, but also reduces the chance of detecting significant changes in slope.

The 'recent' linear slope can be expressed as a percentage of the current FY predicted by the linear relationship, being the most appropriate means of comparing rates of change across regions and crops. Calculating the slope relative to recent yield should also prove far more relevant to the future than a rate of progress inflated by a smaller denominator, such as the average yield of a time series or, worse still, the yield in its first year. Note however that if linearity continues into the future, the calculated relative slope (% p.a.) will decline with time, as distinct from a constant exponential slope referred to above.

Fischer et al. (2014) reported scores of examples of linear FY rates of change, measured over the last 20 to 30 years, and ranging from slightly negative to as high as 2.0% p.a. In no case were quadratic relationship significantly better, and few relationships had non-significant slopes ($P > 0.10$), examples being wheat in France and Switzerland, maize in Italy and parts of Africa, and sorghum in several countries, being the most notable cases.

A typical situation for FY progress, in this case rainfed wheat yields across 5 Mha of semi-arid and sub-humid wheatlands in Western Australia, is illustrated by the lower points and line in Fig. 1 adapted from Fischer et al. (2014). Recent droughts were notable but nevertheless FY slope is 18 ± 7 kg/ha/yr and significant ($P < 0.05$). Using this slope and the FY in 2011[10] of 1.8 t/ha as the appropriate denominator, gives a current rate of FY progress is 1.0% p.a.

Slope calculations can make allowance for outliers or heteroskedasticity in fitting the data, as have some authors (e.g. Finger, 2010). Heteroskedasticity in this case refers to changing variance of yield with year, which is likely to be small over a period 20–30 years; not allowing for it should not bias the determination of slope.

4.2. Measuring potential yield (PY) progress

PY (or PY_w) is plotted not against year (as for FY), but against year of variety release, being the first year in which farmers could avail themselves of the potential offered by the variety[11]. This is seen in the upper points and line in Fig. 1, referring to PY_w because of the dry rainfed climate. The linear slope of PY_w versus year of release is calculated (14 ± 4 kg/ha/yr, $P < 0.01$), with the rate of PY_w progress given by this slope expressed as a per cent of estimated PY_w in the latest year of variety release, which ideally should be close to the present. A long residence time for advanced lines and varieties in the trials makes for accurate progress measurement in this example. In Fig. 1, estimated PY_w from the trend line was 2.6 t/ha in 2008 and the rate of progress is thus 0.5% p.a.

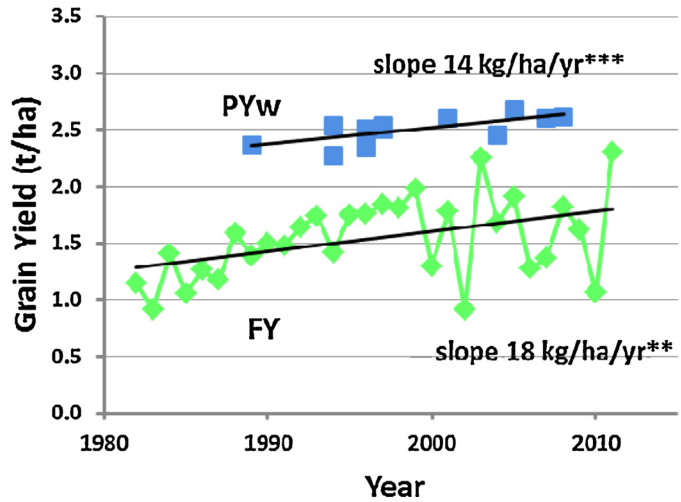

Fig. 1. Typical plot of progress in farm yield (FY) and water-limited potential yield (PY_w) using the example of spring wheat yields in Western Australia. FY is plotted against year. Note that PY_w is plotted against year of variety release, and uses 8-year average yields from the 2000 to 2007 rainfed National Variety Trial sites in Western Australia (adapted from Fischer et al., 2014). *Note* ** $0.01 < P < 0.05$, *** $P < 0.01$.

Note that in the example of Western Australia, recent trial data have been sought (variety releases during the last 20–30 years) so that rates of PY_w progress are as current as possible. Over longer periods one might expect diminishing returns to have affected breeding progress such that rapid early PY progress was followed by slower progress. There is evidence that this has been the case over the last 60 years of breeding for low latitude spring wheat and of tropical rice which, early on, included the relatively easy benefits of introducing semi-dwarfing genes. However Mackay et al. (2011), using UK national trial data, found that the rate of PY increase in winter wheat varieties was close to linear between 1948 and 2007, a result confirmed for French winter wheat by Brisson et al. (2010).

As previously described, balanced vintage trials – in which newer varieties are compared alongside older ones – represent the simplest situation in which to measure PY progress. Unbalanced multiyear trials have also been used to measure rate of progress, relying on recurrent control varieties which appear every year and against which the yields of non-recurrent varieties are expressed as ratios or percentages. These ratios are then regressed against year of release, converted to kg/ha/yr using the control yield, and then expressed relative to the PY of the latest releases. Both approaches assume that the older varieties, or the recurrent control varieties, always react in the same manner to any environmental changes over time (e.g. new disease races in unprotected trials). Obviously if varieties become more susceptible to disease with time, the rate of progress will be overestimated. This was not the case in the Western Australia data (Fig. 1), but Sayre et al. (1998) offer an excellent example when yield progress across irrigated Mexican

[10] Note that when FAO Crop Statistics refer to a given year, it is the year of harvest for all crops everywhere, with the exception of the southern hemisphere where it is the year of sowing of autumn-sown crops whose harvest can spill into January to February of the following year. In the US Department of Agriculture (USDA) and Australian system, (year n to $n+1$ notation), the first year (n) is the year of harvest of all crops except: (1) again for some late harvested southern hemisphere autumn-sown crops, and (2) for southern hemisphere summer crops, when the second year ($n+1$) is the year of harvest.

[11] Sometimes researchers use year of first entry in widespread trials, perhaps 2–3 years before official variety release.

spring wheats was 0.5% p.a. with leaf rust protection, while apparent progress was over 2% p.a. without.

More recently, new statistical techniques can calculate effects from the unbalanced multiyear data sets now more common with breeders and national testing authorities. With regular variety turnover (old varieties replaced by newer ones) over long time series, very few of the potential number of pairwise comparisons are present (e.g. <10% in Mackay et al. (2011) using 1948 to 2007 HGCA data in the UK). Using linear mixed model regression statistics, a coefficient for year of release can be directly fitted (e.g. Nalley et al., 2008; Rijk et al., 2013), or variety effects can be separated from year effects and then regressed against year of release in a two-step process (e.g. Mackay et al., 2011). Again, some authors in this situation have allowed for heteroskedasticity (e.g. Nalley et al., 2008) but others do not consider this to be a significant issue (I. Mackay, pers. comm. 2012).

Using whichever above method was most appropriate, Fischer et al. (2014) studied current rates of progress in PY and PY_w in almost 60 commodity–region combinations of global importance. These authors found the rate of progress over the last 20–30 years, and expressed relative to 2010 PY values, to range from 0.3% to 2.0% p.a., with averages of 0.6% (wheat), 0.7% (soybean), 0.8% (rice), 1.1% (maize) and 1.4% p.a. for canola.

Interpretation of progress in PY is not necessarily straightforward. The procedures described do not eliminate the risk in unprotected trials of upwards progress bias due to breakdown of disease resistance with age. In winter wheat in Western Europe both Mackay et al. (2011) and (Pheipo et al., 2014) found marked effects of variety age (year of trial less year of release) in unprotected trials. Obviously bias is lessened as the residence period of varieties in the trials shortens, and fortunately there are now trial series with good disease protection. Sometimes there are detailed disease scores and yields can be corrected back to zero levels of disease.

PY trials need to be performed under recent optimal conditions representative of the target region, although this is more critical for determining the actual level of PY rather than the relative rate of progress. PY trials should receive the best agronomic practices of the day. Advancing agronomic practice as well as breeding has generally contributed to PY progress, and a positive interaction between the two has often delivered a major part of the progress (de Wit, 1992; Evans, 1993; Evans and Fischer, 1999; Fischer, 2009). For example, to cover two of the major interactions in modern agriculture, the interaction between genetic progress in spring wheat and increased level of N fertiliser is shown in Fig. 2(a) and that between genetic progress in maize and increased plant density in Fig. 2(b).

Overall PY progress is given in each case by the blue line AD, but most commonly vintage trials compare varieties under modern agronomy and thus measure PY progress as the black line BD, an underestimation for wheat (Fig. 2(a), and an overestimation for maize (Fig. 2(b). Fortunately the maize interaction with density is unique in that the older variety responds negatively to a modern level of inputs (density); mostly older varieties respond less but nevertheless positively. The response of the older variety to the improved agronomy (the distance A to B in Fig. 2(a)), which is also part of PY progress, representing a lift in the yield of all varieties, is missed in the modern vintage trial (but is picked up as part of the yield gap closing, see below).

In the analysis of long term unbalanced variety trials such as those considered by Mackay et al. (2011), both varieties and agronomic management are changing steadily, trial management presumably keeping up with any new agronomic technologies. In the statistical model, the management effect is presumed to be contained in effect of year (along with any other year related effects e.g. weather trends). Just as a trend in the variety year of release term is sought, there may also be trends in the year effect, positive as a result of better agronomy but in either direction if there are weather trends over the study period. Thus the Mackay et al. (2011) study of UK winter wheats found both variety and year (agronomic) progress between 1949 and 1981 when nitrogen levels increased notably, and in this case the likely positive interaction would be contributing to the estimates of both components of progress. However after 1982 there was still a highly significant variety vintage trend but no significant year trend; this suggests no agronomic progress after 1982, if as some studies suggest, there were no trends since 1982 in weather of significance for wheat yield in the UK.

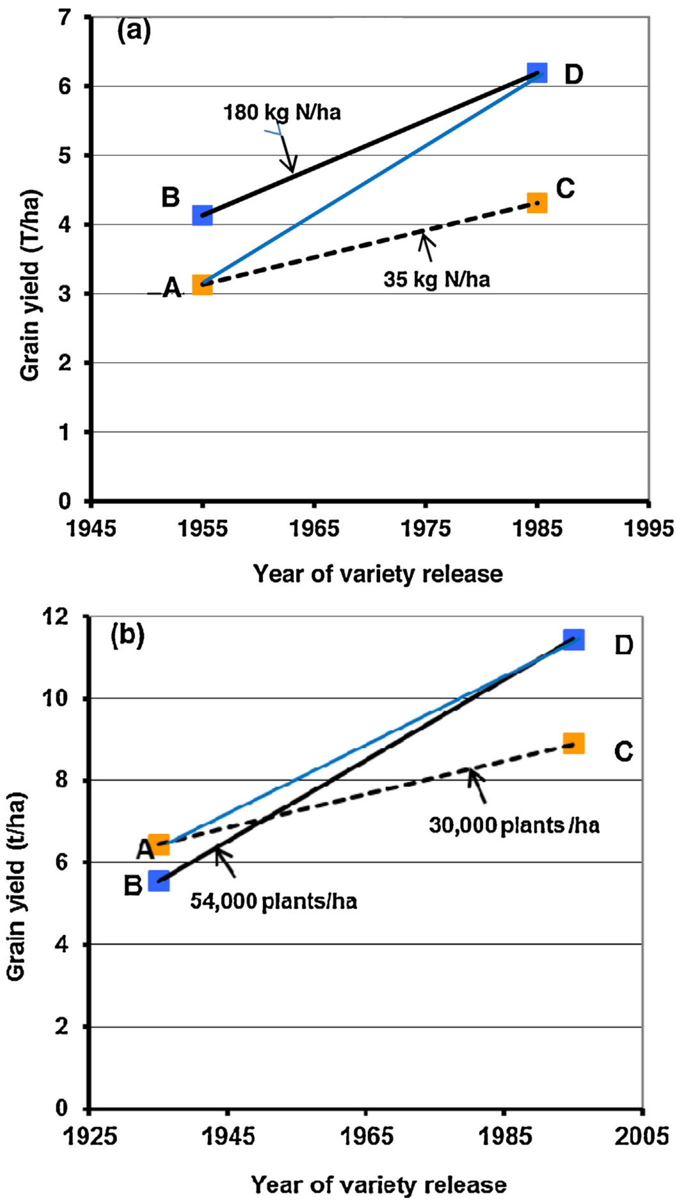

Fig. 2. (a) Wheat potential yield (PY) progress at two levels of nitrogen per hectare, and (b) Maize PY at two plant population densities. In each case an old and a modern variety is shown, point A representing the old variety at the old level of agronomy, B the old variety under modern agronomy, C the modern variety under old agronomy and point D the modern variety with modern agronomy. Source (a) Ortiz-Monasterio et al. (1997) (b) Duvick (1997), both adapted from Fischer et al. (2014).

To date linear mixed-model regressions have not been attempted to determine if there is PY progress due to a trend in the variety vintage × management interaction. The effect of such an interaction would not however be lost in current analyses, it is simply partitioned into the vintage and year main effects, at some cost

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to model fit; overall PY progress due to breeding and new agronomy is correctly given by the sum of the vintage and agronomy trends.

It should also be noted that it is impossible to separate mathematically the breeding and agronomic contributions in interactions, an important point often overlooked in the attribution of progress to one or other of these routes. However, the research effort taken to breed higher PY is clearly more than that required to raise the level of an agronomic input as with the nitrogen or seed rate increase in Fig. 2. In contrast, an entirely new agronomic intervention, like conservation agriculture which usually brings the benefit of a higher yield through greater moisture supply to the crop, was an endeavour requiring substantial research.

Finally, some researchers have used the change in competition winning yields over time as a type of index of PY progress (e.g. Duvick and Cassman, 1999). This would seem to be valid where the sample is large and yields are properly verified, as in annual yield contests of the National Corn Growers Association in USA, which up to 2008 were showing around 1.5% p.a. progress (Butzen, 2010).

5. New technology, farm yield (FY) progress and yield gap closing

Many factors can be involved in the change in FY over time, and the actual importance of each factor will change with region and crop. The premise here is that the main driver of FY progress is the adoption of steadily improving technologies, namely new varieties, new agronomic or management techniques, and better timeliness and decisions by the farmer, as assumed by many others (e.g. Cardwell, 1982; Feyerherm and Kemp, 1988; Bell et al., 1995). It is also assumed that PY trials, conducted under the best current management, measure the latest technical progress in varieties and agronomy.

The estimated current values of FY and PY form the basis of the calculation of the yield gap by difference (gap = PY − FY), which in the case of Fig. 1 is 0.8 t/ha, or 45% of the current FY (or 15% below the likely EY). The changing yield gap with time is also evident in Fig. 1 as the changing gap between the two regression lines; in this case the gap was 1.0 t/ha 20 years ago or 70% of FY at the time. It is also proposed here that the rate of change of the yield gap relative to farm yield is more meaningful than the absolute rate of change.[12] This is given by the difference between the relative rate of change in PY (0.5% p.a.) and that in FY as measured in Fig. 1 (1.0% p.a.), giving −0.5% p.a., noting that yield gap closing will be reflected in a negative rate of gap change. It is better understood as gap closing at 0.5% p.a.

An important assumption here is that PY progress leads to the same relative progress in FY when the new technologies involved in the progress are fully adopted by farmers. There is plenty of evidence to support this, at least where farmers are not operating at a substantially lower yield level than potential. For example new varieties usually express their relative advantages in farmers' fields unless there is heavy weed competition.

Of the scores of cases studied along the lines of Fig. 1 by Fischer et al. (2014), there was always significant PY progress. Also the vast majority show FY progress associated with both PY progress and yield gap closing (as in Fig. 1), the latter averaging 0.7% p.a. but reaching as high as 1.8% p.a. In a few instances, however, PY progress exceeded FY progress, which was sometimes zero, and obviously in these cases the yield gap was widening (up to 0.8% p.a.). This reminds us that PY progress doesn't automatically lead to FY progress, the latter being linked by the adoption of the technologies contained in PY progress: yield gaps only close when innovations are adopted faster than they are invented. Also several factors at the farm level can counter or reinforce the changes expected from innovation (see below).

The inevitable minimum time lag involved in adoption, even with new varieties and innovative farmers, was mentioned earlier as part of the minimum likely yield gap. The yield gap with respect to delayed and variable variety adoption has been incorporated into some analyses of progress. For example, Silvey (1981) and Bell et al. (1995) took the breeding yield progress contained in each variety grown (measured in variety trials relative to a standard control variety), then weighted that by the proportion of the region grown to the variety. In this way these authors built a variety weighted index of PY for the mix of varieties in farmers' fields in any year. The index was then plotted against time to estimate the relative progress that might be expected at the farm level from variety change alone. This process required statistics on which varieties are grown – data that are not often available – but the method does eliminate uncertainty arising from assuming that the best varieties are always adopted (after an inevitabe but variable lag).

6. Confounding factors in farm yield (FY) change

Besides the major role of the discovery, development and uptake of new technologies, the following potentially-confounding factors need to be considered when examining change with time in FY.

6.1. Change in crop area, location, and cropping system within a region

Over decades the area of a particular crop may change, thereby changing its location within the region; location can change also without area change. Such changes bring the possibility of crop shifts to poorer or better natural environments. These changes arise as land is newly cropped, or old land retired, or when one crop replaces another. A key land use change which can confound yield is the adoption of irrigation, and it is often impossible to disaggregate official yield data into rainfed versus irrigated yields. In New Zealand, for example, national wheat yields have doubled in the last 20 years but the main cause has been a shift from zero to 80% irrigation of wheat over the period. The adoption of irrigation is better considered a land use change, not a technology for yield gap closing. The disadoption of irrigation, as water supply declines or costs rise, is another complication, although the high fixed costs of cropping suggests crops will either be reasonably well irrigated or not at all. For example, declining ground water in the North China Plain is seeing a shift from irrigated wheat-summer maize double crop to irrigated sole crop spring maize with a higher PY.

A major cropping system change has been the adoption of conservation agriculture, for example in the rainfed Great Plains of North America. This has so improved soil moisture storage that one year "summer" fallow as a precursor to wheat has declined and cropping intensity increased (Lyon et al., 2004); wheat PY_w and FY may suffer because there is less water per crop but overall productivity has increased. Also wheat suffers high levels of crop failure in this region (harvested area can be as low as 70% of sown area); since failure is greater in lower yielding years, reported average yields (based on harvested area) are somewhat buffered by this phenomenon (e.g. Patrignani et al., 2014). Yield trends may also be influenced if there are trends in failure rates, or if as has happened in USA, crop insurance reduces the financial risks of dryland cropping.

[12] Again this is justified by the fact that future production for world food security is commonly estimated relative to actual production. This might seem inappropriate when, as is the case in sub-Saharan Africa, yield gaps are several hundred percent of FY, but this serves to emphasize the scale of the gap. Also it has yet to be shown that closing these large gaps in terms of % FY p.a. is any easier than closing the more common smaller ones in developed countries.

Farmers switching to earlier maturing varieties can increase cropping intensity (crops grown per year), and although individual crop yield may not increase or may even decrease, productivity may benefit (e.g. many Asian paddy rice systems). Sowing dates may shift, with PY and FY consequences, in order to accommodate desirable overall cropping system changes. Farmers who abandon intercropping practices would record higher yields for the main crop without any other change in technology. This has happened with wheat–mustard intercropping in northwest India because of rising labour costs, and may happen for cowpea–cereal intercropping in West Africa.

6.2. Weather and atmospheric gas changes

Variation in weather causes deviations from any yield trend. Seasonal variations can also change the slope of the FY trend line if the weather variation correlates with year, and this effect can be critical for understanding the impact of technical innovation on FY. For example a number of cropping regions have registered significant warming trends over the last few decades (Lobell et al., 2011) and at least one significant and beneficial cooling trend (Lobell et al., 2005). Crop simulation models or simple empirical relationships can permit correction for such weather changes in order to improve estimates of the true technological effects on FY slope. Such weather trends may or may not persist or be associated with human-induced climate change, but the predominance of warming trends (Lobell and Field, 2007) is likely a reflection of the latter.

At least two atmospheric gases, CO_2 and ozone may cause yield change over time. The concentration of CO_2 is steadily increasing, and over the last 20 years has risen at ~2 ppm/yr or 0.5% p.a. The influence of increased CO_2 on yield has been widely studied and, although the crop yield response depends somewhat on growing conditions (moisture, temperature, nitrogen) and the method of measurement, it is reasonable to assume that due to CO_2 rise the yield of crops with C3 photosynthesis is currently increasing at ~0.2% annually (Horie et al., 2005; Tubiello et al., 2007). The yield of C4 crops is generally assumed unaffected but the CO_2 rise does reduce stomatal conductance in such crops and may be beneficial to yield where it is water limited.

It is useful to consider how the rise in CO_2 impacts on the approach adopted here, as represented by Fig. 1. Increased CO_2 level now compared to 20 or 30 years ago adds a positive trend to both PY and FY (at least for C3 crops), but in Fig. 1 the effect on PY is not revealed since all variety and other technology comparisons to determine PY progress are carried out in the case of vintage trials under the same modern higher CO_2 levels, even if PY is plotted against year of release. This means the FY progress seen in Fig. 1 and the gap-closing progress (FY change less PY change) must be discounted by 0.2% p.a. to determine the true impact of technical progress at the farm. In multiyear variety trials, as analysed for example by Mackay et al. (2011), the effect of increased CO_2 becomes part of the year effect.

Ozone concentrations in the lower atmosphere are variable in time and space, but can be high enough to reduce crop yields in some locations where industrial activity is intense. Increasing ozone over time could have the opposite effect to increasing CO_2, leading to a lower apparent FY progress and yield gap closing due to adoption of new technology than the reality. Alternatively, reducing ozone levels (e.g. with pollution control as has happened in USA) could boost FY trends over those due to true on-farm technology change alone.

In the face of gradual environment change, either favourable change like increased CO_2, or unfavourable like increased ozone (or gradual warming mentioned earlier or steady salinization mentioned below), it is possible that plant breeding has unwittingly adapted varieties to these changes. In the approach used here this effect is simply lumped into other positive variety-by-environment or management interactions contributing to genetic progress. It is possible that this is the explanation of puzzling PY measurements with inbred indica rice varieties at the International Rice Research Institute, which reveal a decline in PY of old varieties even in the absence of pests and disease (S. Peng personal communication). This is exemplified by IR8 for which the dry season PY was around 10 t/ha when released in the mid 1960s but which around 35 years later only yielded 8.5 t/ha, while PY for the most recent varieties was about 10 t/ha (Peng et al., 2010). Thus there was PY breeding progress, but it arose largely from a vintage × year interaction with the most modern varieties maintaining PY due to greater resistance to some gradual negative change in the environment. This change limited the yield of older varieties roughly in proportion to their age, with the most extreme case being the oldest "modern' variety, IR8. One suggested negative factor is rising night temperature (Peng et al., 2010) and another could be rising ozone levels.

6.3. Natural resource base of cropping

Gradual change in the natural resource base of cropping in a region can influence FY change. This is commonly the result of soil deterioration due to erosion, fertility or structural decline or salinization, but equally, cropping soils can be gradually improved (e.g. through liming, phosphorus applications in excess of removal or fixation, and/or reduced tillage). Availability and quality of irrigation water can decline with overuse or poor system maintenance. Pressure from weeds, disease and pests can change due to new arrivals or pest evolution or changes in farming practice (e.g. the appearance of herbicide-resistant weeds). These changes are by definition gradual and their occurrence is often invoked as indicators of sustainability of the natural resource base of cropping when no other explanation for yield change is evident. The possibility of such impact should not be ignored, but definitive proof of such change is hard to secure. By the definitions used here, these are causes of exploitable yield gaps and therefore manageable by proper use of technology. Often, however, the time period of poor management has been decades, in which case management to reverse degradation may take more than one year. In addition the poor management may not be a problem that an individual farmer can deal with alone (e.g. aquifer overuse, exotic pest invasion).

6.4. Policy and regulations

Farm yield can also be influenced by change in government policy directly impacting farm practices such as regulations and/or incentives. Removal of grain price subsidies, limitations on the use of nitrogen fertiliser, and subsidies for low-input farming, are examples now found in Western Europe which may be contributing to apparent FY stagnation with wheat, and hence to increased yield gaps (although these gaps are still generally small, being around 30% or less). Policies may favour some crops over others, such as price policy favouring wheat and rice in India; favoured crops will tend to have both higher rates of FY progress, especially relative to unfavoured crops, due to both higher PY progress and greater yield gap closing. Crop insurance subsidies are likely to favour investment in inputs in risky environments such as low rainfall ones and boost both FY and its variability.

6.5. Costs and output prices

Farmer decision to adopt a new technology or practice is generally slow but can be strongly influenced by input costs and grain prices (both calculated at the farm gate) and also by availability and cost of credit. However the allocation of already-in-use inputs by farmers responds most quickly to price shifts at the farm gate.

Economists refer to this as the price elasticity of yield which Hertel (2011) estimates to be 0.2 for maize in USA, meaning that a 1% rise in prices would lift yield by 0.2% through greater input use. Elasticity may be greater if input use is lower.

The importance of grain quality, through price signals to the breeders and farmers, means there can be progress in economic output with relatively less (or even without) FY progress. Economists consider this a "product mix" contribution to productivity growth. This often arises because of the common negative relationship between PY and several aspects of grain quality that originate from either genetic (e.g. inverse yield versus protein concentration relationships in wheat) or agronomic (e.g. rice eating quality in Japan is not favoured by high nitrogen) influences. The recent rate of breeding progress for starch potatoes in the Netherlands was three times that for ware or food ones, presumably because of the importance of quality traits in the latter case (Rijk et al., 2013).

7. Conclusion

Definitions and simple procedures are proposed which should clarify the presentation and understanding of the role of technical innovation in PY and FY progress and change in the gap between these two measures. This is aided by the preponderance of linear relationships with time of the last 20 to 30 years, and the assumption that relative FY progress is the sum of the relative changes in PY and in the yield gap. While simulation modelling has the power to more easily deliver PY values, the situations reviewed here suggest that reasonable measures of PY can be obtained with well managed and distributed trials, which if varieties of various vintages are included, can also provide useful estimates of PY progress. It has also been shown that FY change can reflect more than the invention and adoption of new technologies.

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