Field Crops Research 182 (2015) 9–18

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

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

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ARTICLE INFO

Article history:
Received 7 October 2014
Received in revised form 1 December 2014
Accepted 9 December 2014
Available online 30 December 2014

Keywords:
Yield definitions
Farm yield
Potential yield
Yield gap
Economic yield
Yield progress

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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http://dx.doi.org/10.1016/j.fcr.2014.12.006
0378-4290/

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.