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REVIEW ARTICLE

Addressing the yield gap in rainfed crops: a review

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Abstract The problems and challenges of rapidly increasing world population, global climate change, shortages of water suitable for irrigation and degradation of agricultural land are increasing the demand to improve grain production from rainfed arable lands. Specific challenges include estimating the size and thus the value of the yield gap, identifying the factors limiting current average production and designing profitable remedial strategies for a range of agro-ecological regions. This review of the rainfall-limited potential yields and the gap between actual or average yields of cereal and legume crops and the rainfall-limited potential indicates that there is still substantial room to increase the average yield of crops in rainfed systems in both developed and developing regions. The review has indicated that (1) the size of the gap between average and potential yields varies according to the agro-ecological zone and the available technologies from about 0.5 to over 5 t/ha, leaving considerable scope for future yield improvement; (2) there is relatively less information applicable at the farm or field scale that assesses the spatial and temporal variability of the yield gap, the reasons for the gap and the possible methods to close the gap; (3) there is also limited information on the feasibility and profitability of applying various approaches to close the gap, including tactical and strategic management practices and plant breeding; (4) the evidence of the impact of the components of conservation agriculture on crop yields in a wide range of agro-ecological regions supports the adoption of zero tillage and crop rotation but is less clear in support of residue retention; (5) objective identification and testing of factors that limit production can lead to a rational sequence of amelioration that is specific to each agro-ecological or field situation and can close the yield gap in winter-dominant rainfall environments; and (6) farmer-participatory varietal selection, including breeding for specific adaptation can make a substantial contribution to closing the gap in a range of environments. A common observation from the reports reviewed here is that sustainable yield improvement will need to employ a range of methods that are appropriate to specific agro-ecological conditions—previous approaches based on single inputs, practices or genotypes can only be partial solutions.

Keywords Yield · Grain · Crop management · Constraint diagnosis

Contents

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1 Introduction

The average rate of increase in grain yields of the major rainfed crops has slowed from about the 1990s, leading in some cases to rates of average yield increase as low as 2 kg ha^{-1} $year^{-1}$ compared with earlier rates that have exceeded 100 kg ha^{-1} $year^{-1}$ in some cases (Ladha et al. 2003; Brisson et al. 2010; Stephens et al. 2011; Grassini et al. 2013; van Wart et al. 2013; Kirkegaard et al. 2014). It has been suggested that this levelling or declining of yields may be due to soil degradation and nutrient depletion (Ladha et al. 2003; Zika and Erb 2009), climatic changes (Stephens et al. 2011), failure to adjust management practices to variable seasonal conditions (Simpson et al. 2007; Tokatlidis 2014) or farmers' perceptions of risk and diminishing returns (e.g. Anderson 2010; Hochman et al. 2012; van Rees et al. 2014; Siddique et al. 2012). Although trends in grain yield improvement over an extended period in a production area have seldom been smooth or linear (e.g. de Wit and van Heemst 1976; Donald 1981; Freebairn et al. 2006; Kirkegaard et al. 2014), it is appropriate to consider current levels of grain yield relative to some estimate of potential yield and to examine the physical and socio-economic feasibilities of various pathways toward further yield improvement.

The grains required to feed the approximately nine billion people that are projected to be living on the planet by 2050 ('10 billion by 2100', United Nations 2015) must rely on intensification on existing crop lands as opportunities for sowing new agricultural lands are rapidly diminishing (Montgomery 2007). However, there is often a surplus of food grains in developed countries and a deficit in developing countries. For example, over 80 % of the wheat produced in the major grain-producing states of Australia is exported to countries such as Indonesia, Iraq, Korea, Iran and Vietnam (Nguyen et al. 2015). Given that consumers in developing countries probably cannot afford to pay the prices that farmers in developed countries can profitably accept, the problem of food security becomes one of distribution rather than production. This leads to the conclusion that research on yield improvement will deliver a greater contribution to food security if the focus is on regions where food supplies are in deficit. A particular example is that of grain legumes in South Asia, where demand is ongoing or increasing but cannot be met by local production and thus imports, mainly from developed countries, are required (Nedumaran et al. 2015).

As the supply of suitable water and land for irrigation are also nearing their global limits (Montgomery 2007; Solomon 2010), increased grain production will need to rely on increasing yields in rainfed cropping regions. We will consider rainfed farming in both commercial, mechanised agriculture as well as in resource-poor small-holder farming systems, where there is a particular urgency to narrow the prevailing large yield gaps.

The aim of this review is to explore some of the existing methods to assess potential grain yield, the size of the gap between average and rainfall-limited potential yield and to suggest pathways for future gains in crop yields in the presence of soil degradation, climate change and seasonal variability of rainfall. We focus mainly on cereal and grain legume crops but recognise that oilseed crops such as canola and mustard play an important role in many rainfed cropping systems (Figs. 1 and 2).

2 Methods relating to the yield gap

2.1 Estimation of potential grain yield

It is widely recognised that some objective estimate of potential yield for the crop of interest in the study area of interest is useful in estimating the target amount of grain that can possibly be produced in the future. Any estimate of the rainfall-limited potential grain yield is of necessity governed by current knowledge and so could change as our understanding of genetics, physiology and agronomy improves. Since there is no objective way of assessing the accuracy of these estimates, the choice of method has been largely a matter of perceived relevance for each particular purpose (van Ittersum et al. 2013). All methods aim to provide some sort of target yield that might be achieved as an indication of the additional grain that might be produced and the resources needed to close the gap between actual or average yield and the theoretical potential. Since we are here discussing the opportunities for yield improvement under rainfed conditions, our definition of potential yield implies yield under the limitations set by the seasonal rainfall. Some recent papers that have addressed the questions of potential yields and the gap between actual or average grain yield and potential yield are summarised in Table 1.

There have been three main methods for estimating potential grain yield:

The 'yield of an adapted cultivar grown with best management in the absence of natural hazards and biotic limitations' ('yield of adapted cultivar' in Table 1) has been used in reviewing rates of yield progress of several crops in favourable environments (Cassman 1999; Evans and Fischer 1999; Fischer and Edmeades 2010). The assumptions of this method are that the agronomic practices appropriate for potential yields have been met in the experiments, that they are equally valid for all genotypes (e.g. genotype × management interactions as discussed by Cooper et al. 2001 are not a factor), and that there are no unrecognised limitations to yield.

If these assumptions can be satisfactorily addressed then the method is likely to be useful for favourable environments. Plant breeders and physiologists have used this method in assessing genetic progress and likely future gains in cereal

Fig. 1 Farmers inspecting cultivars and agronomic treatments in a yield potential trial on wheat in Western Australia. Farmer participation can be an important step in designing field experiments and in assessing responses. Yield advances must be statistically and economically significant and practical to apply on a broader scale. (Photo credit: Kadambot Siddique)

yields (e.g. Loss and Siddique 1994; Evans 1987; Richards 1991; Qin et al. 2015). However, there have been some suggestions that there may be a need in the future to extend the current, known estimates of potential yield (Passioura 2006; van Rees et al. 2014). It is axiomatic that agronomic practices appropriate to support new genotypes will need to be researched concurrently.

Fig. 2 Maize is an important food crop in Timor-Leste where yields have benefitted greatly from introduction of new cultivars and assessment of performance by local farmers. Here, the improved cob size and fertility are demonstrated as part of the process of yield improvement. (Photo credit: Seed of Life Project Timor-Leste)

In environments that are normally water limited, a simple water balance calculation ('modified water balance' in Table 1) has also been used, often a modification of the parameters suggested by Slatyer (1956), Fitzpatrick and Nix (1969) and later by French and Schultz (1984). This method has been widely employed by Australian farm advisers to estimate for their clients the ratio of actual to potential yield (management efficiency). Seasonal rainfall, with or without an estimate of stored water as appropriate, is taken as a surrogate for water use. It is assumed that the distribution of seasonal rainfall does not affect the calculation, an assumption challenged by Asseng et al. (Asseng et al. 2001) and Oliver et al. (2009). Water stored before sowing is not always accounted for by this method. The transpiration use efficiency and the average amount of water lost to the crop (assumed to include soil evaporation, surface run-off and drainage below the root zone where applicable), the only two parameters required for the calculation, need to be locally derived for this method to have practical relevance. However, the ease of calculation has made this method convenient in many practical situations, especially in winter-dominant rainfall regions, and it appears to be useful provided its limitations are recognised.

More sophisticated crop simulation models ('crop simulation model' in Table 1) have been favoured by some researchers as they take account of most growth factors likely to be linked to crop growth and yield, including radiation use efficiency and crop phenology (e.g. APSIM, Keating et al. 2003). Although their availability to field agronomists and farmers has increased (e.g. van Rees et al. 2014), their use at the practical crop management level is still evolving, especially since the data required for their operation are not available in all situations (e.g. Stephens et al. 2011; Hochman et al. 2012; Oliver and Robertson, 2013). There is also a requirement for field verification of model outputs under the target conditions (van Ittersum et al. 2013).

Chauhan and Rao (2014) used the APSIM model to better characterise seasonal soil water status for mungbean in the northern grain region of Australia. From historical rainfall records, they simulated yields over time and could thus estimate risk of drought stress at different crop growth stages. Cluster analysis identified different target production environments within the region, based on local climate and soil water holding capacity. They proposed that this should help refine specific genotype and agronomic requirements for the different target production environments. However, substantial temporal shifts in rainfall pattern resulting from climate change, as now apparent in cropping areas of Australia (Stephens et al. 2011) limit the practicality of this assessment for risk of drought stress.

Simulation models have also been combined with data from satellite images to assess the potential for yield improvement at the regional or national scale (Lobell and Ortiz-Monasterio 2006; Neumann et al. 2010; Hochman et al.

Table 1 Summary of recent publications that discuss yield potential and the gap between average or actual farm yields of grain crops and estimates of potential yield

Reference	Aims and target environments	Definition of potential yield	Yield 'gap' (t/ha) and % average of potential
Cassman et al. (2003)	Prospects for conserving natural resources and meeting demand for major cereal crops.	Yield of adapted cultivar.	When average yields reach ~80 % of potential grown with best management.
Anderson et al.(2005)	Contribution of management to wheat yield improvement in Western Australia.	Modified water balance.	State average wheat yield ~2 t/ha or 67 %, of potential of well-managed crop, ie.gap is 1 t/ha.
Simpson et al.(2007)	Contribution of nutrition in achieving potential yield of wheat and barley in the high rainfall zone of Western Australia.	Modified water balance.	Rainfall-limited potential reached at <350 mm using fertilisers but not at rainfall >500 mm. Gap in farm yields 3.5–5.5 t/ha, average yields ~36 % of potential.
Fischer and Edmeades (2010)	Review of rates of yield progress in wheat, rice and maize in favourable environments.	Yield of adapted cultivar.	For wheat in the UK, the yield gap was 3.1 t/ha, and average yield was 73 % of potential.
Anderson (2010)	Contribution of management to closing the gap between average and potential yield of wheat in a rainfed environment.	Modified water balance.	Estimates of the gap vary according to rainfall zone ~0.4–2.7 t/ha, average yields about 65 % of potential.
Stephens et al. (2011)	Analysis of changes in crop productivity and water use efficiency in Australian grain crops and specific barriers to yield improvement.	Crop simulation model and water balance equation.	Average gap ranged from 0.5–1.3 t/ha or 35–65 % of potential. Yield plateau for wheat was approximately 1.8 t/ha.
Oliver and Robertson (2013)	Quantifying spatial pattern of the yield gap in a low rainfall environment. Analysis of a farm at Bodallin, WA.	Crop simulation model and water balance equation.	Estimated gap was 0.6–1.5 t/ha depending on season, average yields 50–60 % of potential.
Hochman et al. (2012)	Quantifying the variation in yield gap in wheat in Australia. Example given for Wimmera district in Victoria.	Crop simulation model, remote sensing and Global Positioning Systems mapping.	Estimated average gap of 2 t/ha, average yields ranged from 26 to 78 % of potential.
van Ittersum et al. (2013)	Comparison of methods of yield gap analysis, from local to global.	From local measurement to crop simulation.	Examples of average yield as % of potential: 31 % for rainfed maize in Kenya; 89 % for irrigated maize in Nebraska; 73 % for rainfed wheat in Victoria.
van Wart et al. (2013)	Estimating crop yield potential at regional to national scales (irrigated rice in China, maize in United States of America and rainfed wheat in Germany).	Crop simulation model.	For rainfed wheat in Germany yields plateau-ed at 75–85 % of potential.
Lobell (2013)	Use of satellite data with crop models to assist understanding of magnitude and causes of yield gaps.	Crop simulation model plus satellite data.	Maximum yields in irrigated fields used for comparisons.
Anderson et al. (2014)	Diagnose and treat limiting factors for crop yield in a high rainfall area of Western Australia.	Modified water balance.	Average yield achieved using farmer treatments was 88 % of highest experimental plots of canola and 78 % for barley.
van Rees et al. (2014)	Potential of modelling to develop new practices to assist in closing the yield gap in wheat. Analysis of three leading farms.	Crop simulation model.	Gap was 0.48–0.77 t/ha, farm yield of wheat on leading farms was 74–82 % of potential.

2102; Lobell 2013; Oliver and Robertson 2013; van Wart et al. 2013). These assessments may well be useful for planning strategies for yield improvement on the broad scale but potentially less relevant at the farm level unless followed up by local diagnosis of limiting factors (Dore et al. 1997, 2008; Siddique et al. 2012: Anderson et al. 2014). The potential errors associated with such methods have been outlined by Neumann et al. (2010).

In any average yield for a farm, a district, a region or a country there will be a spread of yields that possibly approximates a normal distribution. This assumption can seldom be tested except possibly at the whole farm level since statistical data are seldom presented in a sufficiently disaggregated form. However, an implication for much of the work summarised in Table 1 is that average or better yields should and could be improved. The implication of the simple water balance method for estimation of potential yield is that yields produced at seasonal rainfalls below about 250 mm are at or close to the estimated potential (data summarised by Anderson 2010). However, low yields produced at higher seasonal rainfall that is at very low transpiration efficiency, can also influence the average yield and may represent an opportunity for substantial improvements (Anderson et al. 2014). In contrast to the findings from field experiments quoted above (e.g. Fischer and

Edmeades 2010), the largest gaps when average farm or simulated data are considered appear to be in the more favourable areas or in the higher rainfall seasons.

Uncertainties associated with calculating yield potential in rainfed and irrigated environments, using the abovementioned variety of methods have been discussed by van Ittersum et al. (2013). They concluded that simulation modelling grounded in site-specific data is likely to be the most robust methodology and refer to the Global Yield Gap Atlas project (www.yieldgap.org), which promotes this approach. Generally however, estimates of potential yield remain nebulous.

There have been very few studies of the reasons why yields are less than some measure of potential, other than lack of rainfall. Temperature, radiation, position in the landscape, unidentified soil constraints, pests and diseases and crop management (including supplementary irrigation management, where applicable) can also contribute to the yield gap between actual or average yield and potential yield, however estimated (e.g. Anderson et al. 2014).

2.2 Management efficiency and the yield gap

Actual or average grain yield expressed as a percentage of the estimated potential grain yield (management efficiency) is subject to errors that depend on the rigour of measurement at the field level and the degree of regional aggregation (van Ittersum et al. 2013) as well as the error associated with the estimation of potential yield. Thus the actual size of the estimated yield gap (t/ha), and the management efficiency, are related concepts that are both subject to unknown error. This is particularly so for rainfed environments where the extent of environmental variability is high. The papers summarised in Table 1 refer largely to winter cereals and range from about 25 to more than 85 % efficiency. The higher efficiencies are mainly reported from studies on crops in higher-yielding conditions (Fischer and Edmeades 2010; van Rees et al. 2014; Fischer et al. 2014) or where the major limiting factors have been determined experimentally (Anderson et al. 2014). Studies that report variation related to agro-ecological regions vary from about 30 to 75% (Anderson et al. 2005; Anderson 2010; Stephens et al. 2011; Hochman et al. 2012; Oliver and Robertson 2013; van Wart et al. 2013). The range is similar for data derived from experiments examining various agronomic treatments (Simpson et al. 2007; Anderson et al. 2014).

The gap between achieved and estimated potential grain yield ranges from less than 1 to over 5 t/ha (Table 1). These findings, almost entirely from developed countries, show considerable scope for improving grain yields. The yield gaps are mostly less where average grain yields are less, although the extent to which this generalisation applies to areas that are low yielding due to low rainfall, compared with those that are low yielding due to low inputs, is not apparent.

Estimates of yield gaps in grain legumes are fraught with uncertainty as they are, in general, more sensitive than cereals to a range of biotic and abiotic stress factors, increasing the spatial and temporal variability of yield (Srivastava et al. 2010). This particularly applies in developing countries where resource-poor farmers may be unable to implement established measures that would alleviate these constraints. For example, in the case of chickpea (*Cicer arietinum* L.) in South Asia, where most of the world production occurs, national average yields are in the order of 0.5–0.9 t/ha (FAO 2015). Uncertainties occur in the ‘crop cutting’ methodology used to quantify yields and reporting of national statistics, which possibly overestimate yields. Potential yields of chickpea at particular sites in that region have been reported at 2.5–3.5 t/ha (Khanna-Chopra and Sinha 1987). These are usually derived from field experiments and are also likely to be overestimated due to small plot size and sampling bias (Gomez and Gomez 1984). It can only be concluded that there is an unsatisfactorily large gap between realised and potential yields. Established technology is available to narrow that gap but its implementation in resource-poor farming communities faces many constraints in addition to technical ones—local availability of information, timely input availability, risk management, economic, social and markets to name a few.

Despite the recognised limitations in quantifying potential and actual yields for specific situations it is agreed that their future refinement, for example through initiatives like the Global Yield Gap Atlas project, will guide prioritisation of future research into grain yield improvement. It may be that transfer of existing knowledge to low-yielding areas in developing regions, especially where the yield gap is quite large, may pay greater dividends in terms of future food security than research in areas where food supply is already adequate, regardless of the size of the yield gap. Seasonal variability, potential yields and the size of the yield gap aside, the best that researchers, farmers and their advisers can aim for in water-limited environments is to maximise water use efficiency each season in order to maximise profits.

2.3 Relative contributions—management and breeding

It is arguable that the discovery and adoption of innovative technologies has interacted with the prevailing economic conditions to produce changes in cropping practices that have improved grain yield in the past. It is generally agreed that both breeding and agronomy have contributed to yield advances although the relative contributions of each have varied according to the crop species and environment (Fischer and Wall 1976; Byerlee 1994; and summarised in Anderson et al. 2005).

Average rates of genetic yield improvement in cereal crops grown under non-limiting conditions have been estimated at less than 1 % (e.g. Fischer and Edmeades 2010). This could represent from 10 to about 70 kg ha^{-1} year^{-1} or even more, depending on the average yield in various parts of the world and assuming that the rate applies across regions. An earlier study (Perry and D'Antuono 1989) found a rate of yield improvement due to genotype in dryland wheat of 5.8 kg ha^{-1} year^{-1} during a period in Western Australia when average farm yields increased at 20.2 kg ha^{-1} year^{-1} and the state average yield of wheat was about 0.8 t/ha. For South Australian wheat cultivars released between 1958 and 2007, Sadras and Lawson (2011) reported an average rate of yield increase of 25 kg ha^{-1} year^{-1}. The rate of genetic yield increase is likely to have been influenced by both spatial and temporal factors such as agro-ecological zone and season in all of these studies.

At the agro-ecological scale in Australia, Stephens et al. (2011) showed that average commercial wheat yield increases from 1982 to 2000 ranged from 11.4 to 108.1 kg ha^{-1} year^{-1} (average 44.5 kg ha^{-1} year^{-1}) but fell to 1.9 to 50.1 kg ha^{-1} year^{-1} (average 19.9 kg ha^{-1} year^{-1}) in the period 1990–2008. The seasonal variability of yield was greater in the second period, but the average water use efficiency was also greater. This probably suggests that the skills of farmers in responding to environmental variability, including tactical management and choice of cultivars, improved in the second decade (Fig. 1).

3 Future yield improvement—where and how?

There are three broad areas for yield improvement in rainfed grain crops in the future.

a. Breeding, genetics and physiology. The methods for assessing advances attributable to both genetic and management factors are subject to errors and assumptions that can distort the proportions of each (Anderson 2010), but it seems that the genetic potential of most modern cultivars of wheat (for example) far exceed the seasonal potential set by rainfall. This implies that breeding for yield stability through disease resistance, and for profit stability through improved quality, should be the main focus for breeders rather than increasing the genetic yield potential.

Suggestions for yield improvement through breeding and associated physiological research have a long history with respect to the rainfed environment for wheat. Fischer and Wall (1976), Evans (1987) and Passioura (2006) have discussed physiological characters such as developmental patterns in relation to sowing times and length of season, Reynolds et al. (2012) and Semenov et al. (2014) assessed physiological and biochemical traits in relation to radiation and nitrogen use efficiency in some detail, and others placed emphasis on the synergies that exist between breeding and agronomy or management (Hochman et al. 2009; Passioura and Angus 2010; Richards et al. 2014; Sadras and Lawson 2011). Improved transpiration efficiency (Evans 1987; Passioura and Angus 2010), competitive ability against weeds (Lemerle et al. 2001; Palta and Peltzer 2001), nutrient use efficiency (Anderson and Hoyle 1999) and suitability for dual purpose use (grazing and grain recovery, e.g. Anderson 1985; Virgona et al. 2006) have also been suggested as traits likely to contribute to yield increases.

In rainfed systems, grain legumes face a heterogeneous and variable environment, where widely adapted cultivars, an objective of most conventional breeding programmes, are likely to be less than optimum in any particular environment. To adequately exploit environmental niches, a range of specifically adapted cultivars is required (Sperling et al. 1993). Thus, to test whether cultivar replacement can alleviate identified constraints, or just increase local yield potential, participatory varietal selection methods are recommended (Joshi and Witcombe 1996). Essentially, these are simple varietal evaluations in large plots across many farmers' fields within a specified target region. Entries can be existing cultivars or progeny from a breeding programme. Farmers' usual inputs are used rather than research station recommendations. Evaluation is primarily by farmer assessment according to their prioritisation of criteria (e.g. yield, phenology, grain quality, market value).

In addition to carrying out the varietal evaluation process under their own conditions, it is possible for farmers to be directly involved in the varietal improvement process itself for specified regions, through such methodologies as participatory plant breeding, also known as client-oriented breeding (Witcombe et al. 2005). Farmer involvement in parental selection and progeny selection and evaluation (via Participatory Varietal Selection) ensures a better match of breeding outcomes to the target production environment and farmer requirements.

Further, farmer involvement in the entire genetic improvement process ensures farmer 'ownership', and hence more likely adoption, of resultant improved varieties. A client-oriented breeding approach is considered necessary for heterogeneous environments, such as rainfed environments, where spatial and temporal yield variability is the norm (Witcombe et al. 2005). A centralised breeding approach is better suited to more homogeneous target environments, such as irrigated environments. Successful examples of the use of participatory varietal selection and participatory plant breeding/client-oriented breeding are collated in Ceccarelli et al. (2009), as well as in more recent publications (e.g. vom Brocke et al. 2010; Joshi et al. 2012) (Fig. 2).

b. Tactical management. Decisions regarding choice of cultivar, sowing date, plant population or seed rate, fertiliser rates and application strategies, weed and pest control methods are considered fundamental to modern crop production (Siddique et al. 2012). Their contributions to yield improvement have changed and evolved over time in relation to changes in varieties (Anderson and Smith 1990), improvements in cultivation techniques (Schmidt and Belford 1993; Serraj and Siddique 2012; Ward and Siddique 2014), earlier sowing in relation to opening rains (Sharma et al. 2008) and changes in the agronomy of cropping systems (Anderson 1992). Variations in seasonal conditions in rainfed areas, largely related to rainfall, continue to influence management decisions of farmers in both developed and developing regions. In fact seasonal variation is almost always the major influence on responses to tactical management practices such as plant population and N fertiliser (e.g. Anderson et al. 2011). It is thus suggested that future agronomic research is aimed in part at improving the ability of farmers to adjust tactical management according to seasonal conditions.

c. Strategic management. This largely revolves around soil improvement although decisions regarding the cropping sequence are often made in advance of sowing time in response to market conditions. Soil improvement may involve strategic practices such as amelioration of acidity (Dolling et al. 1991), soil compaction (Hamza and Anderson 2005), sub-surface water-logging (raised beds, Bakker et al. 2001), non-wetting (Carter et al. 1998) and low SOC reserves that are often associated with other soil physical deficiencies (Verhulst et al. 2010).

It may be assumed that measures taken to alleviate soil constraints to crop growth that may take some years to be fully effective, may contribute to longer-term production stability (see section below on diagnosis of soil constraints). Whether and to what extent treatment of soil constraints removes or ameliorates seasonal variability of grain yield deserves further investigation (see also comments on conservation agriculture below).

Recent techniques related to remote sensing and global positioning systems such as yield mapping, variable rate technology, auto-steering and controlled traffic (which may be a combination of both tactical and strategic management) have shown promise for greatly reducing production costs and improving precision (e.g. Kingwell and Fuchsbichler 2011; Robertson et al. 2012). It is yet to be clearly shown through field experiments that such techniques will contribute to future yield advances or yield stability in developed agriculture. Their contribution in less developed agriculture, where the problems of food security are greatest, is also yet to be established.

Components of the conservation agriculture system—zero or minimum tillage, residue retention and crop rotation—might also be considered, wholly or partly, as strategic management. Given the widespread adoption of conservation agriculture, and the continuing debate on the capacity of the conservation agriculture components to increase yield through improved soil fertility, it is discussed separately below.

4 Impact of conservation agriculture—water storage, organic matter and crop yield

Conservation agriculture is often credited with contributing to soil improvement including increased soil organic matter (and soil organic carbon) and associated physical characters such as water infiltration and aggregate stability (Hamza and Anderson 2002; Scott et al. 2010; Verhulst et al. 2010). The yield benefits of crop rotation, especially of cereals with legumes, have been accepted in practice by farmers in many dryland systems for a very long time, and recently reaffirmed from long-term experiments in northern Syria (Christiansen et al. 2015) and Western Australia (French et al. 2015). However, published reports do not always support the claim that soil and yield improvements come from the retention of crop residues (Scott et al. 2010).

In the West Asian and North African regions, there is some evidence that no-till systems with stubble retention have increased soil organic matter and wheat yields more often than not in field experiments compared with the conventional systems (Mrabet et al. 2012; Loss et al. 2015). In a study on stony hillsides in Morocco however, only small increases in grain yields and water use efficiency were measured (Schwilch et al. 2013). Evidence in Australian rainfed crops that soil organic matter increases in a range of soil types using direct drilling with residue retention indicates that even after 10 years or more there may be no increase unless annual rainfall exceeds about 500 mm (data summarised by Chan et al. 2003). This is likely due to the lower levels of crop yield and residue produced under lower rainfall conditions, or to the likelihood of higher soil temperatures in low rainfall areas which can prevent accumulation of soil organic matter (Hamza and Anderson, 2010).

Verhulst et al. (2010) have concluded that conservation agriculture systems that include residue retention can have a positive effect on soil properties other than organic matter percentage. Where green material is added to the soil, other soil physical properties such as water stable aggregates and soil bulk density may also improve (Hamza and Anderson 2010; Krull et al. 2012). The relative benefits for soil improvement of adding green and dry stubble material to the soil is a question that needs clarification.

In higher rainfall areas (>500 mm annual rainfall) and where perennial pastures are part of the dominant farming system, soil organic matter tends to accumulate more across a range of soil types than where continuous cropping is practised (Hoyle et al. 2014). In any case organic matter largely accumulates in the top 10 cm of soil in a zero tillage system such that, even if the topsoil is saturated with respect to the soil organic carbon level, the content below that depth may still below.

The review by Pannell et al. (2014) concluded that the impact of residue retention (mulching) on crop yields in central Africa and South Asia has been largely positive over the longer term. In contrast, a review of stubble retention in cropping systems in southern Australia (Scott et al. 2010) concluded that "the effects on grain yield of stubble retention are largely negative, using current technology". In a further review Scott et al. (2013) again concluded that in the dominant cropping systems of southern Australia there is little compelling evidence that retention of crop residues has lead reliably to economic benefits.

In addition, Farooq et al. (2011) found that the impact of conservation agriculture(both zero tillage and residue retention) on crop yields was mostly positive, especially at lower rainfall, but suggested that where the yield of conservation agriculture crops did not exceed those of conventional systems, factors such as weeds and diseases may have been responsible. However, the impact of crop residue as distinct from the tillage effect is not reported in many of the experiments described in these reviews. In any case, the evidence that soil organic carbon percentage is closely related to crop yield is not always apparent in field studies across a wide range of experiments (Howard and Howard 1990; Fettell and Gill 1995).

The apparent lack of a robust relationship, or set of relationships, between soil organic matter percentage and crop yield may be due to some other factor or factors limiting yield such as water or nutrient availability. In general there seems to be some agreement that soil organic matter and crop yields are more or less linearly related up to about 2 % organic carbon (Howard and Howard 1990; Janzen et al. 1992) even if there is less agreement that a critical level exists across soil types and environments (Loveland and Webb 2003). However, the variability in these relationships appears to indicate that the slope of any increase below 2 % is quite wide. More precise data are needed for a range of cropping and farming systems that can be used to isolate the anticipated impact of soil organic matter on grain yield in the absence of other limiting factors. The potential impact of changes in soil physical and chemical properties due to plant roots and the return of animal wastes, other than changes due to soil organic matter, also need to be separately assessed.

Given the variability among various authors and reviewers as to the benefits of conservation agricultural practices including retaining crop residues, it seems likely that local climatic, edaphic and technological situations should be accounted for when attempting to extrapolate from experimental evidence to commercial farms. This variability in responses to the various components of the conservation agriculture system has likely lead to partial adoption by farmers in the various Australian environments as discussed by Kirkegaard et al. (2014). It appears that the variable conclusions reviewed above could be related to extrapolation beyond the local conditions under which the efficacy of stubble retention has been tested.

5 Diagnosis of constraints

Much past research on agronomic practices has focussed on one or two factors assumed to be limiting production (examples given in Anderson et al. 2011; Siddique et al. 2012). Often, responses due to tactical and strategic management practices are additive such that improvement in one is not dependent on application of the other (Anderson 2010). This gives farmers some scope to adjust management according to seasonal conditions and available resources. Identifying the factors most likely to be limiting in any particular paddock by objective means (diagnostic research as reported in Dore et al. 1997, 2008; Anderson et al. 2014; Sharma and Anderson 2014) suggests a hierarchy of practices that can be tested and applied according to available resources, perceived risk and farmer convenience. An example is given in Table 2 for two farm sites where both zero tillage and partial stubble retention were standard practices in mixed farming systems based on barley, canola, oats, pasture and grazing by sheep.

Table 2 shows that no single factor-limited production at either site as the responses varied from season to season. However, major yield responses could be identified as due to K and tactical N application at the first site and gypsum and tactical N at the second site. Extension of results such as these should be achieved through further testing or demonstration plots when extrapolating to similar situations in the same agro-ecological zone.

Increasing internet accessibility, even to remote, resource-poor rural regions (James 2010), increases the scope for identifying possible remedies for constraints found in farmers' fields. Agronomic and genetic options may be apparent but these would require on-farm evaluations as to their practicability for specific on-farm situations. For agronomic options, simple on-farm trials, farmer managed but with advice from research or extension personnel, can evaluate the efficacy of a particular treatment and assess the rate at which an input should be applied.

Attempts based on surveys of opinions of researchers have been made to better identify yield constraints of chickpea and other crops across global regions, with the aim of sharpening research priorities (e.g. Waddington et al. 2010; Kelley et al. 1995). This methodology does not account for spatial and temporal variability of particular constraints or potential biases of those surveyed, or the survey takers, so it seems prudent to use such information to support field experimentation rather than to replace it.

Table 2 Summary of yield responses of canola (*Brassica napus*), barley (*Hordeum vulgare*) and oats (*Avena sativa*) to experimental treatments at two sites in the high rainfall zone of Western Australia over five years

Year and crop	Seasonal rainfall (mm)	Best treatment	Ya/Ypot[b] (%)
Camp paddock			
2004 canola	245	Lime (2.5 t/ha)	102 (1.64 cf. 2.01)[c]
2005 barley	397	K (50 kg/ha) + tactical N[a]	98 (3.33 cf. 4.47)
2006 oaten hay	177	Tactical N[a]	106 (7.70 cf. 7.81)
2007 pasture	359	K (50 kg/ha)	–
2008 canola	245	K + lime + clay (100 t/ha) + tactical N[a]	102 (1.42 cf. 2.55)
One tree paddock			
2004 canola	225	Deep ripping to 20 cm + gypsum (2.5 t/ha)	119 (2.07 cf. 2.33)
2005 barley	467	Deep ripping + raised beds + gypsum	129 (3.90 cf. 5.63)
2006 pasture	222	Not measured	
2007 canola	290	Gypsum	110 (2.45 cf. 2.80)
2008 barley	382	Gypsum + tactical N[a]	122 (4.92 cf. 5.42)

Yield of 'Best' treatments always significantly greater, P=0.05, than the control treatment. After Anderson et al. (2012)

[a] Nitrogen applied one third at sowing then in two applications after heavy rain (>20 mm in one fall). K is potassium applied at sowing

[b] Average yield (Ya) as a percentage of calculated potential yield (Ypot)

[c] Actual yields of control and highest treatment in tons per hectare in parentheses

Another method of constraint diagnosis, particularly suited to resource-poor farming systems, is a more co-ordinated deployment of 'participatory rural appraisal' (Chambers et al. 1989). This approach directly gathers the farmers' perspectives of yield-constraining factors but does not necessarily permit specific identification and quantification of causal factors. On-farm diagnostic trials are needed to pinpoint causal factors and to suggest possible alleviatory treatments. However, not all possible remedies would be feasible in resource-poor farming situations and thus close farmer involvement with researchers in on-farm experimentation is required to identify remedies that may, or may not, work in a given farmer's field. Examples of on farm experimentation used to diagnose constraints faced by resource-poor farmers growing chickpea in Bangladesh include diagnosis of molybdenum deficiency (Johansen et al. 2007) and diagnosis and treatment of *Botrytis* grey mould disease (Johansen et al. 2008).

Where average farm yields are low relative to seasonal rainfall in developing agriculture, it may be irrelevant to focus on potential yield, but equally inappropriate to assume that management and genetic inputs as applied in developed agriculture can be used to bridge the yield gap. The diagnostic approach as described above, used in collaboration with farmers, may be more appropriate.

In rainfed areas farmed by resource-poor communities, crop yield increases resulting from genetic or agronomic improvements are not always apparent in regional yield data, which are often due to incomplete or non-existent statistical records. Further, farmers may attribute 'crop improvement' to factors additional to increases in grain yield including improved grain quality, yield stability in a stress-prone environment, value of other crop products beside grain (e.g. straw for building material, fuel or animal feed) and contribution to a total cropping system. Fitting an extra crop into a cropping sequence would increase the productivity of that cropping system even if the yield of the introduced crop is constrained by a sub-optimal growing period (e.g. fitting lentil or mungbean into rice–wheat cropping systems; Kumar Rao et al. 1998; Malik et al. 2015). Adding an extra crop as an intercrop may improve system productivity even though the yield of both crops is necessarily reduced by competition from the main crop (Ali 1990).

The relevance of protecting the natural resource base for agricultural production has been emphasised by Cassman et al. (2003). The general importance of soil improvement as part of conservation agriculture systems has also been emphasised (Serraj and Siddique 2012). The maintenance or improvement of soil fertility in modern crop production systems must form a vital part of long-term yield improvement in addition to the much-reported aspects of crop tactical management and genetic improvement. There is an increasing need to assess the impact of all methods of yield improvement on yield stability in our changing environments. A future focus on the vulnerability of grain production systems to diminishing supplies of fossil fuels and opportunities for their replacement with renewable energy is also needed if the world is to feed the projected population increase.

6 Conclusion

Yield gaps in rainfed crops remain large enough to suggest considerable scope for increasing prevailing yields. The size of the yield gap varies according to the region under study, but it appears to be greater in general in higher rainfall areas and in developing agriculture where it may be difficult to deploy known remedies. Although measurement of potential and actual yield are associated with uncertain errors there is general agreement among the various methods used that average grain yields achieved by farmers are considerably less than estimates of the biological or rainfall-limited potential.

The risks associated with closing the yield gap and the profitability of doing so under rainfed conditions have not been thoroughly addressed in the papers reviewed. Addressing this aspect of the potential yield and yield gap questions is likely to lead to clearer guidelines for farmers.

The greatest human benefits from increasing grain yields and closing yield gaps potentially come from addressing the problem in developing countries given that the largest deficiencies of grain supply are in those countries and not in developed countries where grain production is often in surplus. In developing agriculture, there is scope for relatively well-established genetic and agronomic means of yield improvement but more emphasis can be given to strategic means (soil improvement) to ensure sustainability of yields. Land degradation continues to increase and concepts of conservation agriculture can be applied when appropriate. There is evidence that conservation agriculture, especially zero tillage, has contributed to soil improvement, and in particular to cost reduction, but the contribution of the residue retention component to increased yields has been positive in some conditions, and uncertain in others. Objective, on-farm diagnosis and verification of the factors limiting crop production is a priority for closing the gap between average and rainfall-limited potential grain yield. The current methods require wider testing, especially where grain yields are low due to inadequate inputs rather than due to insufficient seasonal rainfall.

References

Ali M (1990) Pigeonpea: cropping systems. In: Nene YL, Hall SD, Sheila VK (eds) The pigeonpea. CAB International, Wallingford, UK, pp 279–301. ISBN 0-85198-657-9

Anderson WK (1985) Production of green feed and grain from grazed barley in Northern Syria. Field Crops Res 10:57–75. doi:10.1016/0378-4290(85)90006-1

Anderson WK (1992) Increasing grain yield and water use of wheat in a rainfed Mediterranean type environment. Aust J Agric Res 43:1–17. doi:10.1071/AR9920001

Anderson WK (2010) Closing the gap between actual and potential yield of rainfed wheat. The impacts of environment, management and cultivar. Field Crops Res 116:14–22. doi:10.1016/j.fcr.2009.11.016

Anderson WK, Hoyle FC (1999) Nitrogen efficiency of wheat cultivars in a Mediterranean environment. Aust J Exp Agric 39:957–965. doi:10.1071/EA98045

Anderson WK, Smith WR (1990) Increasing wheat yields in a high rainfall area of Western Australia. Aust J Exp Agric 30:607–614, http://www.publish.csiro.au/?act=view_file&file_id=EA9900607.pdf

Anderson WK, Hamza MA, Sharma DL, D'Antuono MF, Hoyle FC, Hill N, Shackley BJ, Amjad M, Zaicou-Kunesch C (2005) The role of management in yield improvement of the wheat crop—a review with special emphasis on Western Australia. Aust J Agric Res 56:1137–1149. doi:10.1071/AR05077

Anderson WK, van Burgel AJ, Sharma DL, Shackley BJ, Zaicou-Kunesch CM, Miyan MS, Amjad MC (2011) Assessing specific agronomic responses of wheat cultivars in a winter rainfall environment. Crop Pasture Sci 62:115–124. doi:10.1071/CP10142

Anderson WK, Flower KC, Siddique KHM (2012) Increasing crop yields in rainfed agriculture through better agronomy and soil improvement. Indian J Agron 57:40–47

Anderson WK, McTaggart RM, McQuade NC, Carter D, Overheu TD, Bakker D, Peltzer S (2014) An approach to crop yield improvement through diagnostic systems research in a winter-dominant rainfall environment. Crop Pasture Sci 65:922–933. doi:10.1071/CP14065

Asseng S, Turner NC, Keating BA (2001) Analysis of water- and nitrogen-use efficiency of wheat in a Mediterranean climate. Plant Soil 233:127–143. doi:10.1023/A:1010381602223

Bakker DM, Hamilton GJ, Houlbrooke D, Spann C (2001) Improved soil management and cropping systems for waterlog-prone soils. In: Resource management technical report no. 194, Agriculture Western Australia, South Perth

Brisson N, Gate P, Gouache D, Charmet G, Oury FX, Huard F (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res 119:201–212. doi:10.1016/j.fcr.2010.07.012

Byerlee D (1994) Technology transfer systems for improved crop management: lessons for the future. In: Anderson JR (ed) Agricultural technology: policy issues for the international community. Commonwealth Agricultural Bureaux International, Cambridge, UK, pp 208–230. ISBN 0-85198-880-6

Carter DJ, Gilkes RJ, Walker E (1998) Claying of water repellent soils: effects on hydrophobicity, organic matter and nutrient uptake. In: 16th World Congress of Soil Science, Symposium 41, Reg. No. 2619, Montpellier, France. The International Union of Soil Science Inc, Austria

Cassman KG (1999) Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc Natl Acad Sci USA 96:5952–5959. doi:10.1073/pnas.96.11.5952

Cassman KG, Dobermann AD, Walters D, Yang H (2003) Meeting cereal demand while protecting natural resources and improving environmental quality. Ann Rev Environ Res 28:315–358. doi:10.1146/annurev.energy.28.040202.122858

Ceccarelli S, Guimarães EP, Weltzein E (eds) (2009) Plant breeding and farmer participation. Food and Agriculture Organization of the United Nations (FAO), Rome, p 671

Chambers R, Pacey A, Thrupp LA (eds) (1989) Farmer first. Farmer innovation and agricultural research. Intermediate Technology Publications, London, UK, p 213. ISBN 1-85339008-9

Chan KY, Heenan DP, So HB (2003) Sequestration of carbon and changes in soil quality under conservation tillage on light-textured soils in Australia: a review. Aust J ExpAgric 43:325–334. doi:10.1071/EA02077

Chauhan YS, Rao RCN (2014) Defining agro-ecological regions for field crops in variable target production environments: A case study on mungbean in the northern grains region of Australia. Agric Forest Meteorol 194:207–217. doi:10.1016/j.agrformet.2014.04.007

Christiansen S, Ryan J, Singh M, Ates S, Bahhady F, Mohamed K, Youssef O, Loss S (2015) Potential legume alternatives to fallow and wheat monoculture for Mediterranean environments. Crop Past Sci 66:113–121. doi:10.1071/CP14063

Cooper M, Woodruff DR, Phillips IG, Basford KE, Gilmour AR (2001) Genotype-by-management interactions for grain yield and grain protein concentration of wheat. Field Crops Res 69:47–67. doi:10.1016/S0378-4290(00)00131-3

de Wit CT, van Heemst HDJ (1976) Aspects of agricultural resources. In: Koertsler WT (ed) Chemical engineering in a changing world. Proceedings of the plenary sessions of the 1st World Congress on Chemical Engineering, Amsterdam. Elsevier Science Publishing Company, Amsterdam, pp 125–145. ISBN 0444415432

Dolling PJ, Porter WM, Robson AD (1991) Effect of soil acidity on barley production in the south-west of Western Australia. 1. The interaction between lime and nutrient application. Aust J Exp Agric 31:803–810. doi:10.1071/EA9910803

Donald CM (1981) Innovations in Australian agriculture. In: Williams DG (ed) Agriculture in the Australian economy. Sydney University Press, Sydney, NSW, Australia, pp 57–86

Dore T, Sebillotte M, Meynard JM (1997) A diagnostic method for assessing regional variations in crop yield. Agric Syst 54:169–188. doi:10.1016/S0308-521X(96)00084-4

Dore T, Clermont-Dauphin C, Crozat Y, David C, Jeuffroy M, Loyce C, Makowski D, Malezieux E, Meynard J, Valantin-Morison M (2008) Methodological progress in on-farm regional agronomic diagnosis. A review. Agron Sustain Dev 28:151–161. doi:10.1051/agro:2007031

Evans LT (1987) Opportunities for increasing the yield potential of wheat. In: The future development of maize and wheat in the third world. CIMMYT, Mexico, D.F, pp 79–93. ISBN 968-6127-16-X

Evans LT, Fischer RA (1999) Yield potential: its definition, measurement and significance. Crop Sci 34:1544–1551. doi:10.2135/cropsci1999.3961544x

FAO (2015) Food and Agriculture Organization of the United Nations. FAOSTAT homepage. Available at http://faostat3.fao.org/home. Accessed 23 Sep 2015

Farooq M, Flower KC, Jabran K, Wahid A, Siddique KHM (2011) Crop yield and weed management in rainfed conservation agriculture. Soil & Tillage Research 117:172–183. doi:10.1016/j.still.2011.10.001

Fettell NA, Gill HS (1995) Long-term effects of tillage, stubble, and nitrogen management on properties of a red-brown earth. Aust J Exp Agric 35:923–928. doi:10.1071/EA9950923

Fischer RA, Edmeades GO (2010) Breeding and cereal yield progress. Crop Sci 50:585–598. doi:10.2135/cropsci2009.10.0564

Fischer RA, Wall PC (1976) Wheat breeding in Mexico and yield increases. J Aust Inst Agric Sci 42:139–148

Fischer RA, Byerlee D, Edmeades GO (2014) Crop yields and global food security: will yield increase continue to feed the world? Australian Centre for International Agricultural Research, Canberra, http://aciar.gov.au/publication/mn158. ISBN 978- 1-925133-06-6

Fitzpatrick EA, Nix HA (1969) A model for simulating soil water regime in alternating fallow crop systems. Agric Meteorol 6:303–319. doi:10.1016/0002-1571(69)90023-5

Freebairn DM, Cornish PS, Anderson WK, Walker SR, Robinson JB, Beswick AR (2006) Management systems in climate regions of the world—Australia. In: Peterson GA, Unger PW, Payne WA (eds) Dryland agriculture, agronomy monograph no. 23, Secondth edn. American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc, Madison, Wisconsin, USA, pp 837–878

French RJ, Schultz JE (1984) Water use efficiency of wheat in a Mediterranean-type environment II. Some limitations to efficiency. Aust J Agric Res 35:765–775. doi:10.1071/AR9840743

French RJ, Malik RS, Seymour M (2015) Crop-sequence effects on productivity in a wheat-based cropping system at Wongan Hills, Western Australia. Crop Past Sci 66:580–593. doi:10.1071/CP14262

Gomez KA, Gomez AA (1984) Statistical procedures for agricultural research, 2nd edn. John Wiley and Sons, New York, USA, p 704. ISBN 978-0-471-87092-0

Grassini P, Eskridge KM, Cassman KG (2013) Distinguishing between yield advances and yield plateaus in historical crop production trends. Nature Communications 4:2918. doi:10.1038/ncomms3918

Hamza MA, Anderson WK (2002) Improving soil fertility and crop yield on a clay soil in Western Australia. Aust J Agric Res 53:615–620. doi:10.1071/AR01099

Hamza MA, Anderson WK (2005) Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil Till Res 82:121–145. doi:10.1016/j.still.2004.08.009

Hamza MA, Anderson WK (2010) Prospect and limitations of organic matter build-up in dry climates. Afr J Agric Res 5:2850–2861, **1991-637X**

Hochman Z, Holzworth D, Hunt JR (2009) Potential to improve on-farm wheat yield and WUE in Australia. Crop Pasture Sci 60:708–16. doi:10.1071/CP09064

Hochman Z, Gobbett D, Holzworth D, McClelland T, van Rees H, Marinoni O, Navarro Garcia J, Horan H (2012) Quantifying yield gaps in rainfed cropping systems: a case study of wheat in Australia. Field Crops Res 136:85–96. doi:10.1016/j.fcr.2012.07.008

Howard PJA, Howard DM (1990) Use of organic carbon and loss-on-ignition to estimate soil organic matter in different soil types and horizons. Biol Fert Soils 9:306–310. doi:10.1007/BF00634106

Hoyle FC, D'Antuono M, Murphy DV, Overheu T (2014) Capacity for increasing soil organic carbon stocks in dryland agricultural systems. Soil Res 51:657–667. doi:10.1071/SR12373

James J (2010) Mechanisms of access to the Internet in rural areas of developing countries. Telematics Informatics 27:370–376. doi:10.1016/j.tele.2010.02.002

Janzen HH, Larney FJ, Olson BM (1992) Soil quality factors of problem soils in Alberta. Proceedings of the Alberta Soil Science Workshop 17–28

Johansen C, Musa AM, Kumar Rao JVDK, Harris D, Ali MY, Shahidullah AKM, Lauren JG (2007) Correcting molybdenum deficiency of chickpea in the High Barind Tract of Bangladesh. J Plant Nutr Soil Sci 170:752–761. doi:10.1002/jpln.200700249

Johansen C, Bakr MA, Sirajul Islam M, Mondal NA, Afzal A, MacLeod WJ, Pande S, Siddique KHM (2008) Integrated crop management of chickpea in environments of Bangladesh prone to Botrytis grey mould. Field Crops Res 108:238–249. doi:10.1016/j.fcr.2008.05.008

Joshi A, Witcombe JR (1996) Participatory crop improvement. II. Participatory varietal selection. A case study in India. Exp Agric 32:461–477

Joshi KD, Devkota KP, Harris D, Khanal NP, Paudyal B, Sapkota A, Witcombe JR (2012) Participatory research approaches rapidly improve household food security in Nepal and identify policy changes required for institutionalisation. Field Crops Res 131:40–48. doi:10.1016/j.fcr.2012.03.001

eating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargreaves JNG, Meinke H, Hochman Z, McLean G, Verburg K, Snow V, Dimes JP, Silburn M, Wang E, Brown S, Bristow KL, Asseng S, Chapman S, McCown RL, Freebairn DM, Smith CJ (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288. doi:10.1016/S1161-0301(02)00108-9

Kelley TG, Ryan JG, Patel BK (1995) Applied participatory priority setting in international agricultural research: making trade-offs transparent and explicit. Agric Syst 49:177–216. doi:10.1016/0308-521X(94)00030-U

Khanna-Chopra R, Sinha SK (1987) Chickpea: physiological aspects of growth and yield. (In: Saxena MC, Singh KB (eds). The chickpea CAB International, Wallingford, UK pp163–189 ISBN:0-85198-571-8

Kingwell R, Fuchsbichler A (2011) The whole-farm benefits of controlled traffic farming: an Australian appraisal. Agric Syst 104: 513–521. doi:10.1016/j.agsy.2011.04.001

Kirkegaard JA, Conyers MK, Hunt JR, Kirkby CA, Watt M, Rebetzke GJ (2014) Sense and nonsense in conservation agriculture: principles, pragmatism and productivity in Australian mixed farming systems. Agric Ecosyst Environ 187:133–145. doi:10.1016/j.agee.2013.08.011

Krull ES, Skjemstad JO, Baldock JA (2012) Functions of soil organic matter and the effect on soil properties. Grains Research and Development Corporation, Project No CSO 00029. Residue Management, Soil Organic Carbon and Crop Performance. Available at http://www.grdc.com.au

Kumar Rao JVDK, Johansen C, Rego TJ (eds.) (1998) Residual effects of legumes in rice and wheat cropping systems of the Indo-Gangetic plain: proceedings of the Workshop, ICRISAT Patancheru, Andhra Pradesh, India, 26–28 August 1996. International Crops Research Institute for the Semi-Arid Tropics, Patancheru, Andhra Pradesh, India. ISBN:8120412974

Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Bijay S, Yavinder S, Singh Y, Singh P, Kundu AL, Sakal R, Ram N, Regmi AP, Gami SK, Bhandari AL, Amin R, Yadav CR, Bhattarai EM, Das S, Aggarwal HP, Gupta RK, Hobbs PR (2003) How extensive are yield declines in long-term rice-wheat experiments in Asia? Field Crops Res 81:159–80. doi:10.1016/S0378-4290(02)00219-8

Lemerle D, Gill D, Murphy CE, Walker SR, Cousens RD, Mokhtari S, Peltzer SJ, Coleman R, Luckett DJ (2001) Genetic improvement and agronomy for enhanced weed competition with weeds. Aust J Agric Res 52:527–548. doi:10.1071/AR00056

Lobell DB (2013) The use of satellite data for crop yield gap analysis. Field Crops Res 143:56–64. doi:10.1016/j.fcr.2012.08.008

Lobell DB, Ortiz-Monasterio JI (2006) Regional importance of crop yield constraints: Linking simulation models and geostatistics to interpret spatial patterns. Ecol Model 196:173–182. doi:10.1016/j.ecolmodel.2005.11.030

Loss SP, Siddique KHM (1994) Morphological and physiological traits associated with wheat yield increases in Mediterranean environments. Adv Agron 52:229–276. doi:10.1016/S0065-2113(08)60625-2

Loss S, Haddad A, Khalil Y, Alrijabo A, Feindel D, Piggin C (2015) Evolution and adaptation of conservation agriculture in the Middle East. In: Farooq M, Siddique KHM (eds) Conservation agriculture. Springer International Publishing, Switzerland, pp 197–224. doi:10.1007/978-3-319-11620-4

Loveland P, Webb J (2003) Is there a critical level of organic matter in the agricultural soils of temperate regions? A review. Soil Till Res 70:1–18. doi:10.1016/S0167-1987(02)00139-3

Malik AI, Ali MO, Zaman MS, Flower K, Rahman MM, Erskine W (2015) Relay sowing of lentil (*Lens culinaris* subsp. *culinaris*) to intensify rice-based cropping. J Agric Sci 153:656–665. doi:10.1017/S0021859614001324

Montgomery DR (2007) Dirt: the erosion of civilization. University of California Press, USA, p 296. ISBN 13:978-0-520-25806-8

Mrabet R, Moussadek R, Fadloui A, van Ranst E (2012) Conservation agriculture in dry areas of Morocco. Field Crops Res 132:84–94. doi:10.1016/j.fcr.2011.11.017

Neudumaran S, Abinaya P, Jyosthnaa P , Shraavya B, Rao P, Bantilan C (2015) Grain legume production, consumption and trade in developing countries. Working paper series No60. ICRISAT Research programs, markets, institutions and policies, Patancheru 502324, Telangana, India: International Crops Research Institute for the Semi-arid tropics. 64 pp

Neumann K, Verburg PH, Stehfest E, Müller C (2010) The yield gap of global grain production: a spatial analysis. Agric Syst 103:316–326. doi:10.1016/j.agsy.2010.02.004

Nguyen N, Green R, Lawson K, Goesch T (2015) Australia's wheat supply chains: infrastructure issues and implication, Australian Bureau of Agriculture and Resource Economics and Sciences Research report no. 15.1, Canberra. ISSN:1447-8358 ISBN:978-1-74323-222-4. Available at: daff.gov.au/abares/publications.

Oliver YM, Robertson MJ (2013) Quantifying the spatial pattern of the yield gap within a farm in a low rainfall Mediterranean climate. Field Crops Res 150:29–41. doi:10.1071/CP09122

Oliver YM, Robertson MJ, Stone PJ, Whitbread A, Oliver YM, Robertson MJ, Stone PJ, Whitbread A (2009) Improving estimates of water-limited yield of wheat by accounting for soil type and within-season rainfall. Crop Past Sci 60:1137–1146. doi:10.1071/CP09122

Palta JA, Peltzer S (2001) Annual ryegrass (*Lolium rigidum*) reduces the uptake and utilisation of fertilizer nitrogen by wheat. Aust J Agric Res 52:573–581. doi:10.1071/AR00085

Pannell DJ, Llewellyn RS, Corbeels M (2014) The farm-level economics of conservation agriculture for resource-poor farmers. Agric Ecosyst Environ 187:52–64. doi:10.1016/j.agee.2013.10.014

Passioura J (2006) Increasing crop productivity when water is scarce—from breeding to field management. Agric Water Manage 80:176–196. doi:10.1016/j.agwat.2005.07.012

Passioura JB, Angus JF (2010) Improving productivity of crops in water limited environments. Adv Agron 106:37–75. doi:10.1016/S0065-2113(10)06002-5

Perry MW, D'Antuono MF (1989) Yield improvement and associated characteristics of some Australian spring wheat cultivars introduced between 1860 and 1982. Aust J Agric Res 40:457–472. doi:10.1071/AR9890457

Qin X, Zhang F, Liu C, Yu H, Cao B, Tian S, Liao Y, Siddique KHM (2015) Wheat yield improvement in China: past trends and future directions. Field Crops Res 177:117–124. doi:10.1016/j.fcr.2015.03.013

Reynolds M, Foulkes J, Furbank R, Griffiths S, King J, Murchie E, Parry M, S lafer G (2012) Achieving yield gains in wheat. Pl Cell Envir 35:1799–1823. doi:10.1111/j.1365-3040.2012.02588.x

Richards RA (1991) Crop improvement for temperate Australia—future opportunities. Field Crops Res 26:141–169. doi:10.1016/0378-4290(91)90033-R

Richards RA, Hunt JR, Kirkegaard JA, Passioura JB (2014) Yield improvement and adaptation of wheat to water-limited environments in Australia—a case study. Crop Past Sci 65:676–689. doi:10.1071/CP13426

Robertson MJ, Llewellyn RS, Mandel R, Lawes R, Bramley RGV, Swift L, Callaghan C, Metz NO (2012) Adoption of variable rate fertiliser application in the Australian grains industry: status, issues and prospects. Precision Agric 13:181–189. doi:10.1007/s11119-011-9236-3

Sadras VO, Lawson C (2011) Genetic gain in yield and associated changes in phenotype, trait plasticity and competitive ability of South

Australian wheat varieties released between 1958 and 2007. Crop PastSci 62:533–549. doi:10.1071/CP11060

Schmidt CP, Belford RK (1993) A comparison of different tillage seeding systems: the interaction of tillage and time of sowing on sandplain soils in Western Australia. Aust J ExpAgric 33:895–900. doi:10.1071/EA9930895

Schwilch G, Laouina A, Chaker M, Machouri N, Sfa M, Stroosnijder L (2013) Challenging conservation agriculture on marginal slopes in Sehoul, Morocco. Renew Agric Food Syst 30:233–251. doi:10.1017/S1742170513000446

Scott BJ, Eberbach PL, Evans J, Wade LJ (eds.) (2010): Stubble retention in cropping systems in Southern Australia: benefits and challenges. EH Graham Centre Monograph No. 1. Graham Centre for Agricultural Innovation, Wagga Wagga, NSW, Australia Available at: http://www.csu.edu.au/research/grahamcentre/ ISBN:978-1-74256-020-5

Scott BJ, Podmore CM, Burns HM, Bowden PI, McMaster CL (2013). Developments in stubble retention in cropping systems in southern Australia. Report to GRDC on Project DAN 00170. In: C Nicholls and EC (Ted) Wolfe (eds.). Department of Primary Industries, Orange NSW pp 103. Available at: www.grahamcentre.net

Semenov MA, Stratonovitch P, Alghabari F, Gooding MJ (2014) Adapting wheat in Europe for climate change. J Cereal Sci 59: 245–256. doi:10.1016/j.jcs.2014.01.006

Serraj R, Siddique KHM (2012) Conservation agriculture in dry areas. Field Crops Res 132:1–6. doi:10.1016/j.fcr.2012.03.002

Sharma DL, Anderson WK (2014) Success of diagnostic approach to rainfed, wheat-based cropping systems in Western Australia. Agric Sys 123:22–33. doi:10.1016/j.agsy.2013.08.007

Sharma DL, D'Antuono MF, Anderson WK, Shackley BJ (2008) Variability of optimum sowing time for wheat yield in Western Australia. Aust J Agric Res 59:958–970. doi:10.1071/AR07406

Siddique KHM, Johansen C, Turner NC, Jeuffroy M, Hashem A, Sakar D, Gan Y, Alghamdi SS (2012) Innovations in agronomy for food legumes. A review. Agron Sustain Dev 32:45–64. doi:10.1007/s13593-011-0021-5

Simpson NL (n H), McTaggart RM, Anderson WK, Anderton L (2007) Can increased nutrition raise cereal yields to the rainfall-limited potential in the high rainfall cropping zone of south Western Australia? Aust J Exp Agric 47:39–47. doi:10.1071/EA04273

Slatyer RO (1956) Evapotranspiration in relation to soil moisture. Neth J Agric Sci 4:73–76

Solomon S (2010) Water: the epic struggle for wealth, power, and civilization. Harper Perennial, New York. ISBN 978-0-06-054831-5

Sperling L, Loevinsohn ME, Ntabomvura B (1993) Rethinking the farmer's role in plant breeding: local bean experts and on-station selection in Rwanda. Exp Agric 29:509–519. doi:10.1017/S0014479700021219

Srivastava SK, Sivaraman N, Mathur VC (2010) Diagnosis of pulses performance of India. Agric Econ Res Review 23:137–148, **0971-3441**

Stephens D, Western Australia Department of Agriculture and Food, Grains Research and Development Corporation (Australia) (2011) GRDC strategic planning for investment based on agro-ecological zones: second phase/David Stephens … [et al.]; project supervisor; David Stephens. Dept. of Agriculture and Food, South Perth, WA

Tokatlidis IS (2014) Addressing the yield by density interaction is a prerequisite to bridge the yield gap of rain-fed wheat. Ann App Biol 165:27–42. doi:10.1111/aab.121 21

United Nations (2015) World population prospects, the 2015 revision. United Nations Department of Economic and Social Affairs, Population Division. http://esa.un.org/unpd/wpp/ Accessed 27 September 2015

van Wart J, Kersebaum KC, Peng S, Milner M, Cassman KG (2013) Estimating crop yield potential at regional to national scales. Field Crops Res 143:34–43. doi:10.1016/j.fcr.2012.11.018

van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance—a review. Field Crops Res 143:4–17. doi:10.1016/j.fcr.2012.09.009

van Rees H, McClelland T, Hochman Z, Carberry P, Huth N, Hunt J, Holzworth D (2014) Leading farmers in South East Australia have closed the exploitable wheat yield gap: prospects for further improvement. Field Crops Res 164:1–11. doi:10.1016/j.fcr.2014.04.018

Verhulst N, Govaerts B, Verachtert E, Castellanos-Navarrete A, Mezzalama M, Wall P, Deckers J, Sayre KD (2010) Conservation agriculture, improving soil quality for sustainable production systems? In: Lal R, Stewart BA (eds) Advances in soil science: food security and soil quality. CRC Press, Boca Raton, FL, USA, pp 137–208. ISBN 13:978-1-4309-0058-4

Virgona JM, Gummer F, Angus JF (2006) Effects of grazing on wheat growth, yield, development, water use and nitrogen use. Aust J Agric Res 57:1307–1319. doi:10.1071/AR06085

vom Brocke K, Trouche G, Weltzien E, Barro-Kondomboc CP, Gozé E, Chantereau J (2010) Participatory variety development for sorghum in Burkina Faso: farmers' selection and farmers' criteria. Field Crops Res 119:183–194

Waddington SR, Li X, Dixon J, Hyman G, Carmen de Vicente M (2010) Getting the focus right: production constraints for six major food crops in Asian and African farming systems. Food Security 2:27–48. doi:10.1007/s12571-010-0053-8

Ward P, Siddique KHM (2014) Conservation agriculture in Australia and New Zealand. In: Farooq M, Siddique KHM (eds) Conservation agriculture. Springer International Publishing, Switzerland, pp 335–355. doi:10.1007/978-3-319-11620-4_14

Witcombe JR, Joshi KD, Gyawali S, Musa AM, Johansen C, VirkDS SBR (2005) Participatory plant breeding is better described as highly client-oriented plant breeding. I. Four indicators of client orientation in plant breeding. Exp Agric 41:299–319. doi:10.1017/S0014479705002656

Zika M, Erb KH (2009) The global loss of net primary production resulting from human-induced soil degradation in drylands. Ecol Econ 69:310–318. doi:10.1016/j.ecolecon.2009.06.014