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Review Article

Yield and soil improvement in rainfed crop production

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ABSTRACT

Resources of arable land and irrigation water available in the world are diminishing while the population continues to increase. This situation has contributed to chronic malnutrition and starvation in times of crisis. While the twin problems of overpopulation and unequal distribution of food between rich and poor people are political problems, increasing the supply of food from the existing resources of land and water is a problem that can be addressed by agronomists. It is widely recognised that average farm yields of rainfed crops, even in developed countries, seldom exceed half of the theoretical potential yield if all the rain is used efficiently. It is proposed that this 'gap' between actual and potential grain yield can be effectively addressed using existing technologies that do not destroy soil fertility, and may even improve it. This paper discusses the contributions that agronomists are making and can make in the future to increase the yields of rainfed crops. Agronomic practices that can improve yield and the management of soil resources that will sustain such improvements in the longer term are inter-linked. The increasing use and benefits of conservation agriculture, the benefits of rotating crops, especially with legumes, and the possibility of improving crop yields through diagnosing and treating the factors limiting production are discussed.

Key words : Conservation agriculture, Growing seasons rainfall, Potassium deficiency, Rainfed agriculture, Rainfall deficit, Salinity, Soil acidity

The world has an over-supply of mouths to feed (7 billion people) and an under-supply of arable land (eg. Ryan *et al*. 2006) and useable irrigation water (UNESCO, 2000, Vorosmarty *et al*. 2010). One of the obvious ways to alleviate this problem is to increase the yield of crops from the existing rainfed dry lands (150 to well over 500 mm rainfall). In addition, whether we believe in human-induced climate change that may lead to reduced rainfall or not, there is less controversial evidence of increasing seasonal volatility that threatens agricultural production (Kingwell and Johns 2004; Christensen *et al*. 2007; Ludwig *et al*. 2008). Increasing yield per unit area, especially in the better seasons, can provide some insurance against the inevitable poor seasons due to drought, flood, frost or other natural disasters.

Agronomists have a key role to play in this endeavour as one of the agents of change in agricultural practices. In fact it has been estimated that the greatest contribution to increased grain yield has come from improved management practices rather than from improved crop varieties (Anderson 2010). This is not to ignore the contribution that has come from plant breeding, especially since the greatest yield improvements may result when improvements to both management and varieties are implemented together (Evans 1987, Anderson *et al*. 2005).

In many countries agronomists have recognized that the average yield of rainfed crops on farms is less than the estimated potential yield or than the yields obtained on research stations managed according to 'best management practices' (BMP), (French and Schultz 1984, Evans 1987, Sadras and Angus 2006, Hochman *et al*. 2009). Finding methods that are technically capable of closing the yield gap is a suitable focus for crop researchers but in addition, assessment of the profitability of closing the gap is essential in improving crop productivity (Kingwell and Pannell 2008).

Vast areas of the world's dry lands are either naturally infertile or have been degraded through the use of exploitative farming practices over long periods (World Resources Institute 2000; Montgomery 2010). The pathway to long term crop yield improvement must surely include

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identifying and addressing the factors limiting soil productivity.

The gap between actual and potential grain yield

The size of the crop yield gap depends on the methods used to assess it as well as a reflection of the stage of development of the cropping system as a whole. There may be a gap between actual and theoretical potential yield, because it is not profitable in some circumstances to change management to close it. For example, in resource-poor cropping systems capital may be unavailable or available at too high interest rates that may not allow farmers to adopt the recommended BMP's, even if they do understand the benefits of these practices (e.g. Van den Bosch *et al*. 1998; Giller *et al*. 2009).

The size of the potential crop yield can be conveniently and simply estimated in rainfed environments using the seasonal rainfall, after making allowances for losses and using an estimate of transpiration use efficiency (French and Schultz 1984). An example for wheat (*Triticum aestivum*) in the rainfall zones of Western Australia (WA) is given in Table 1. In general the transpiration efficiency can be assumed to be greater in the higher rainfall zones, where the season is longer and the evaporative demand is less during the grain filling period. However, the losses of rainfall are likely to be greater in the higher rainfall areas due to run-off, deep drainage and surface evaporation. In WA, the northern regions are generally hotter and drier than the southern regions.

The most likely yield 'gaps' (based on these assumptions and indicated with asterisks in Table 1) range from less than half a tonne to more than 2 t/ha. Even if the assumptions are contestable, it will be possible biologically to increase the yield of wheat substantially. We suggest that it is the uncertain economic environment in terms of both input costs and grain prices, in combination with an uncertain climate (Turner *et al* 2011), that is largely responsible for the yield 'gap' in Western Australia. In varying degrees this perception of risk is characteristic of rainfed environments world-wide (eg. Marra *et al*. 2003).

It is our contention that the first step towards crop yield improvement is to estimate the potential yield. This can be followed by a careful analysis, based preferably on objective tests, farmer's observations, and field experimentation, of the factors that may be limiting yield.

Estimation of water-limited, potential grain yield

In most places information on growing seasonal rainfall (GSRF) and crop yield will be available at some level. These data can be plotted to estimate the rainfall-limited potential grain yield (Ypot), thus removing the need to rely on research station yields as the benchmark. The method is illustrated in Figure 1. Appropriate estimates of the losses of seasonal rainfall (X-intercept) and transpiration efficiencies can be used as in Table 1. The dotted lines in Fig. 1 illustrate the improvements that are theoretically possible.

It is clear from Figure 1 that the gap between farm yields and theoretical potential yield is greater in the wetter seasons. This is partly due to the assumption that transpiration use efficiency is the same at all levels of rainfall but we suggest that it is also due to the risk factors mentioned above. Part of the yield improvement that has occurred in Western Australia has been due to the reduction in losses of water from soil evaporation (Anderson 1992). This has been the result of the widespread adoption of reduced or zero tillage (D'Emden and L Lewllen 2006, Australian Bureau of Statistics 2008), the retention of crop residues on the soil surface (Leonard 1993, Australian Bureau of Statistics 2009), and advancing the sowing date

Table 1. The 'gap' (t/ha) between average yield and calculated potential yield in the wheat belt of Western Australia.

Transpiration use Efficiency (kg/ha.mm)	Losses of GSRF (%) 20	30	40	Losses of GSRF (%) 20	30	40
		HRF North			*HRF South*	
18	1.51	1.02	0.52	2.81	2.17	1.52
20	1.95	1.4	0.85*	3.38	2.67	1.85
22	2.39	1.78	1.18	3.95	3.17	2.38*
		MRF North			*MRF South*	
18	0.52	0.18	-0.15	1.51	1.09	0.66
20	0.82	0.44*	0.07	1.89	1.42	0.94
22	1.11	0.70	0.29	2.27	1.75*	1.23
		LRF North			*LRF South*	
18	0.62*	0.33	0.05	1.20	0.84	0.49
20	0.87	0.55	0.24	1.51*	1.12	0.72
22	1.12	0.78	0.43	1.82	1.39	0.96

*The most likely yield 'gaps' (see text); GSRF: Growing season rainfall; HRF: High ranfall; MRF: Medium rainfall; LRF: low rainfall

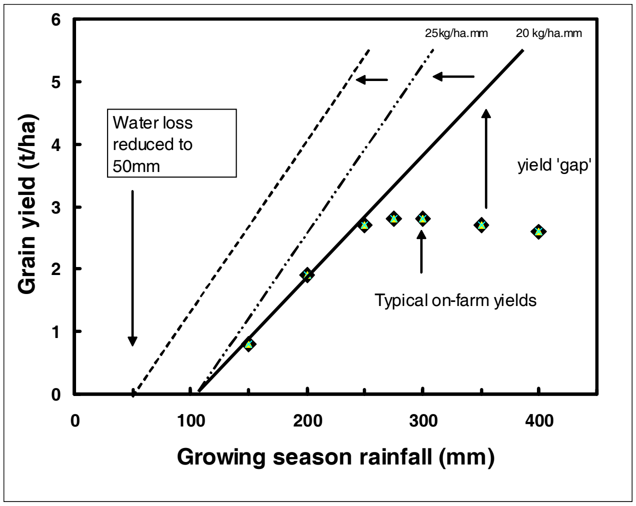

Fig. 1. Comparison of typical farm yield of wheat in Western Australia (data from Northam Shire 2000 to 2006) and theoretical estimates of the potential yield.

by about 20 days (Stephens and Lyons 1998).

Loss of water during the growing season is the sum of evaporation from the soil surface, drainage below the root zone, and surface run-off. In many rainfed situations the last two causes are too small to consider. In Western Australia the water loss during the season has been estimated at between approximately 50 mm in the low-medium rainfall zone (Anderson 1992) and 150mm in the high rainfall zone (Zhang *et al*. 2005), a range similar to that proposed by French and Schultz (1984).

The rainfall-limited potential yield can be estimated from equation.

Ypot = GSRF (mm) – [GSRF/3] × 20 (kg/ha/mm).

The estimates of losses (assuming one third of GSRF is lost) and transpiration use efficiency (20 kg/ha/mm) can be varied as in Table 1 to suit the field conditions. Some published estimates for wheat have included 13-16kg/ha.mm in field experiments (several authors, summarised in Anderson 1992), 20kg/ha/mm in a controlled environment (Passioura 1977) to 22kg/ha/mm for a range of rainfed environments world-wide (Sadras and Angus 2006). It seems that improvements in these figures are most likely to come from plant breeding through more and possibly larger kernel numbers per unit area (Fischer 1985) in ways similar to those that accompanied the introduction of dwarfing genes in wheat and rice.

Management efficiency

Comparing farm yields with the estimated rainfall-limited potential yields can provide a guide to the relative efficiency of current farming systems and can give some indication of progress when used over time (Stephens 2002). One example, based on average farm yields in some parts of Western Australia, is given in Table 2.

It can be observed from the second column in Table 2 that some improvements did occur over the period of record but more importantly that the range of changes shown in the third column indicates that the averages concealed a large amount of spatial variation. To further examine these trends it is necessary to focus at the farm or even to the paddock level (Figure 2).

In general the average efficiency of the whole shire, at about 40-50%, did reflect the pattern of performance on individual farms, being affected it is assumed, by the seasons. However, the range of performance between farms is striking with the best farm achieving almost 80% efficiency compared to the worst performer with barely 30% efficiency. This is perhaps the next great challenge for agronomists – to postulate the reasons for differences in management efficiency, test the reasoning through careful field experimentation, assess the results for likely profitability, and extend the messages learned to farmers.

How to close the yield gap?

Researchers have been commenting on the possibilities of improving crop yields for some time through modified physiology (Fischer 1979, Evans 1987), via modelling exercises (Hochman *et al*. 2009), through improved water use efficiency and improved agronomy (Calvino and Sadras 2002, Boling *et al*. 2004, Zhang *et al*. 2006, Anderson 2010). Not surprisingly, improvements in the various components of the hydrological cycle as it applies to rainfed field crops have been a major focus of these papers. Less discussion has taken place about the role of soil improvement that might allow crop plants to realise the

Table 2. Average yield of wheat is different shire groups in Western Australia as a percentage of calculated potential yield (management efficiency) comparing the yield in 1997-2001 with 2002 to 2007.[data from Alan Herbert, *Pers. Comm*., potential calculated as:[GSRF-(GSRF x 0.33)] x 20]

Shire group	Change in actual/potential yield (%)	Range of change (%)
North	Increase 54 to 64%	-8 (Wongan/Ballidu) to + 43 (Mullewa)
Centre	Steady at 59%	-25 (Nungarin) to + 13 (Cunderdin)
Great Southern	Increase 59 to 62 %	-11 (Kulin) to + 27 (Kent)
South Coast	Steady at 52%	-4 (Jerramungup) to + 11%(Ravensthorpe)

Note: A shire is an administrative district.

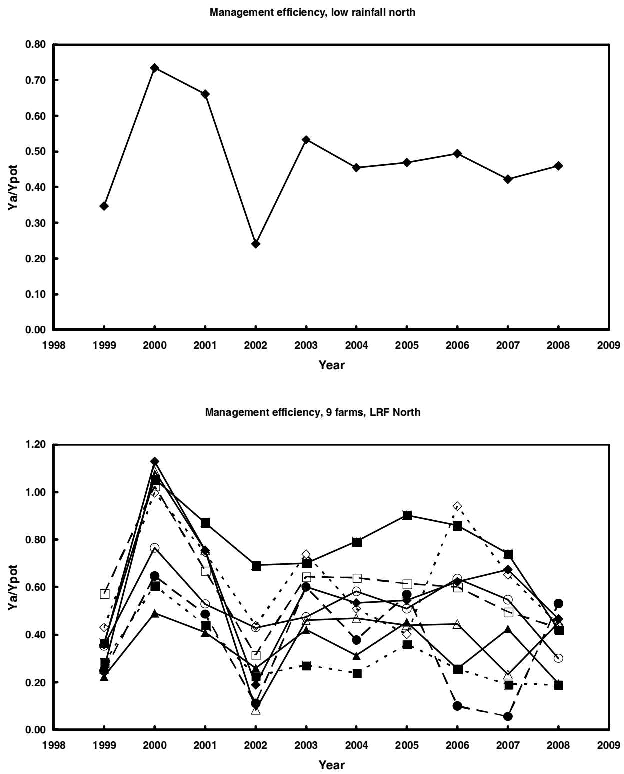

Fig. 2. Management efficiency (actual/potential yield of wheat), 1999 – 2008 (based on records supplied by Planfarm). The shire average (top) is compared with the data from nine individual farms (bottom) for the low rainfall shires in the north of Western Australia.

environmental potential although the positive role of conservation agriculture has been recognized (Farooq *et al*. 2011).

The role of conservation agriculture

Conservation agriculture (CA) has three key components; permanent crop residue retention, crop rotation, and minimal soil disturbance. Yield benefits from CA, especially with crop residue retention (Prasad and Power, 1991), are usually related to the positive environmental and soil effects compared with conventional tillage systems. Reduced erosion, less surface crusting, increased aggregate distribution and stability, increased water infiltration, soil organic carbon and water content of soil (Govaerts *et al*., 2009; Heenan *et al.*, 2004; Hobbs *et al*., 2008) are examples of these benefits.

CA generally has a positive effect on yields in relatively dry environments (< 560 mm of annual rainfall, (Farooq *et al*., 2011). Nonetheless, yields can decline with CA; for example, with impeded drainage on heavy soils or from lower temperatures due to crop residue and increased plant height variability in temperate environments (Wilhelm and Wortmann, 2004; DeFelice *et al*., 2006; Boomsma *et al*., 2010).

In addition to increased yields, tillage systems that reduce the number of cultivation steps save water, fuel, labour and machinery costs (Ribera *et al.*, 2004). Most analyses suggest that CA reduces machinery costs. Zero or minimum tillage means that farmers can use a smaller tractor and make fewer passes over the field. This also results in lower fuel and repair costs (Knowler and Bradshaw, 2001). Much attention has focused on the apparent reduction in labour requirements under CA. This reduction follows from the decreased demand for labour for land preparation at the beginning of the growing season. Some estimates put this reduction at 50-60 percent during this time period. However, against this is the potential increase in labour costs due to weeding, particularly with resource poor farmers, (Giller *et al*., 2009). Hand weeding is not feasible for large scale farming and in these situations increased herbicide costs can reduce or eliminate any cost advantages with CA (Lafond *et al*., 1993). Mueller *et al*. (1985) found that short-run average costs under CA exceeded long-run average costs by about 7 percent. The short-run average costs per hectare for CA were greater than for conventional tillage. However, after adjustments to capital, CA costs fell below those of conventional tillage in the long run. Similarly, the expectation is for fuel costs to be lower under CA, and this is generally the finding in most studies (Knowler and Bradshaw, 2001).

Clearly the economic benefits of CA will be site or region specific. Ribera *et al*., (2004) working in Burleson County, Texas, USA, found that no tillage (NT) would be more profitable compared to conventional tillage in three out of five rotation scenarios under risk-neutral rankings. However, assuming a risk-averse decision maker, CA would be preferred over conventional tillage in all five crop rotations. In east-central Saskatchewan, Lafond *et al*. (1993) found that CA (zero-till and minimum tillage) had higher production potential than conventional tillage because increased soil-moisture conservation generally provided higher net returns, although costs were the same. Higher yields and greater economic returns from CA in Western Australia have resulted from improved water conservation and timeliness of sowing (Flower *et al*., 2008). In contrast Giller *et al*. (2011) found that regular tillage with vegetation barriers gave the highest marginal rate of return in the Central Kenya highlands. This supports the idea that the benefits of the CA system are dependent on the whole system rather than any of its individual components.

Diverse crop rotations are important in CA systems to reduce pest, disease and weed build up. The inclusion of legumes can provide both a disease ‘break’ and add nitrogen through symbiotic fixation. Legumes in the rotation generally improve the yields of subsequent crops (Seymour *et al*. 2012) and this can have a positive effect on soil quality and organic carbon, particularly with a pasture legume (Donald 1981; Hamblin and Kyneur 1993; Hoyle *et al*., 2011) This may become much more important as the costs of fertiliser nitrogen increase.

CA is a technology that can improve both soil quality and yields. This and the wider use of legumes can help to close the yield gap. However, CA adoption is limited in a number or regions of the world and barriers to its adoption require further research. For example, crop residues are a key component of successful CA systems and the replacement of residues removed for fuel and livestock feeding needs investigation. Further work is required, that should be site and region specific to tackle technical, economic and social issues associated with CA adoption.

The role of legumes in the cropping system

Although there is increasing awareness of the importance of legumes in human, animal and soil health, adoption of improved production technologies for grain and pasture legumes is not proceeding at the same pace as for cereal crops (Siddique *et al.* 2008; 2012). In smallholder farming in developing countries, production trends have mostly been static or have declined over the past decade despite the existence of technology that should permit higher and more stable yields. Ability to reverse negative trends is jeopardized by climate change as legumes are mostly grown under rainfed conditions and are being exposed to increasingly variable and extreme weather.

Legumes are ideal crops for two components of CA, namely, soil cover and rotation; either as a growing crop or as residue (Siddique *et al*., 2012). In addition to fixation of atmosphere nitrogen and effectiveness is breaking disease and pest cycles, many legumes are deep rooted and contribute to nutrient cycling and water infiltration in the soil. Further, some legumes access nutrients otherwise unavailable to other crops, by mechanisms such as dissolution by root exudates, and render those nutrients available to subsequent crops (Siddique *et al.,* 2008).

The move toward more ecologically-based approaches in managing nutrition, weeds, diseases, and pests of crops under CA also offers prospects for greater inclusion of legumes in cropping systems. CA perhaps offers a more realistic framework for incorporating ecological approaches to management of the major abiotic and biotic constraints of legumes, with judicious reliance on synthetic chemical inputs. However, a major challenge remains in developing effective methods of weed management without reliance on either herbicides or tillage. Nevertheless, increased adoption of CA should encourage greater incorporation of legumes in various cropping systems (Siddique *et al*.2012).

A Diagnostic approach to yield improvement

Where it can be established that crop yields are less than the estimated potential it is logical to conduct some objective tests, in conjunction with consideration of the farmer's observations, to establish a list of likely limiting factors. A test of this idea was commenced in the high rainfall zone of Western Australia on two farmers' paddocks. At the first site (camp paddock) a soil pH (in $CaCl_2$) of 4.6 in the 10-20cm layer, an aluminium concentration of 6 mg/kg in the same layer and soil potassium concentration of 29 mg/kg appeared to be limiting crop production and the farmer reported that wind erosion and marginal non-wetting had been evident in the past. At the other site (one tree paddock), penetrometer readings exceeded 2,500KPa in the 10-20cm layer and the sodium concentration in the clover tissue was 0.87mg/kg. The farmer reported that the site had frequently been waterlogged for short periods in the past. Replicated experiments were conducted with factorial combinations of treatments designed to address the diagnosed problems. Treatments were applied once only in 2004 (except the tactical N treatment which was applied each season). The results of treating these potential limiting factors are shown in Table 3.

It seems that K and lime were implicated in the yield improvements in the Camp paddock in most years but tactical N was also implicated in the wetter years and on the oaten hay crop. Interestingly, tactical N resulted in a grain yield reduction in the dry year of 2006 as the late N caused 'haying off'. The best treatments yielded at or close to the calculated potential yield.

The key treatment for the One Tree paddock was gypsum, with raised beds and tactical N being effective in the wetter seasons. The achieved yields were somewhat above the calculated potential at this site, possibly due to an increased root zone after the soil sodium was leached (see later).

Improved soil fertility

Organic carbon (OC) values were measured in 2008 in these experiments and compared to the initial value in 2003 (Table 4). OC values increased at both sites by 2008 (Camp paddock and one tree paddock). Both farmers had adopted zero tillage methods just prior to commencement of our experiments and this is thought to have made a major contribution to the results. The OC values at both sites exceeded the level of 2% that is often used as the critical value for soils in temperate areas (Loveland and Webb 2003). This leads us to believe that the improvements in OC measured in these experiments were at least

Table 3. 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. [Yield of 'Best' treatments always significantly greater, P=0.05, than the control treatment].

Year and crop	Seasonal Rainfall (mm)	Best Treatment	Ya/Ypot (%)
Camp paddock			
2004 canola	245	Lime (2.5t/ha)	102 (1.64 cf 2.01)[2]
2005 barley	397	K (50kg/ha) + Tactical N[1]	98 (3.33 cf 4.47)
2006 oaten hay	177	Tactical N[1]	106 (7.70 cf 7.81)
2007 pasture	359	K (50kg/ha)	-
2008 canola	245	K + lime +clay (100t/ha) + tactical N	102 (1.42 cf 2.55)
One tree paddock			
2004 canola	225	Deep ripping to 20cm + Gypsum (2.5t/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	Gyp + tactical N[1]	122 (4.92 cf 5.42)

1. N applied one third at sowing then in two applications after heavy rain (>20mm in one fall).
2. Actual yields of control and highest treatment in t/ha in parentheses.

Table 4. Organic carbon (%) in the 0-10 cm layer for two sites in the high rainfall zone of Western Australia – 2003 and 2008. [all differences were significant at the 5% probability level].

Treatment	2003	2008
Camp paddock		
Control	1.63	2.05
K + Lime		1.84
One Tree paddock		
Control	1.98	2.62
Gypsum		2.76

partly responsible for the achievement of the potential yields in each season.

The tissue Na concentration in the barley plants in the One Tree paddock in 2008 was reduced by gypsum (-gypsum 1.12; + gypsum 0.86, Lsd 0.20 mg/kg). This reduction in Na uptake reflected a lower sodium concentration in the soil and an improvement in soil conditions that enabled the barley plants to explore deeper soil layers for water and other nutrients.

Even after a time as short as five years these experiments showed that soil improvements were possible, and associated with crop yield improvements. The added value of the best treatments compared to the control was assessed using costs applicable to 2011 and grain prices of $A246/t for barley and $A507/t for canola. The cumulative additional gross margin over the five years for the grain crops alone was over $A1,000/ha at both sites (L. Anderton, *Pers. Comm.,* Planfarm Bankwest Benchmarks, Annual series 1997 to 2008).

Suggested future research

It has been observed by advisers and agronomists that some farmers consistently achieve higher yields and returns than the average. One example is given in the lower part of Figure 2. If the reasons for this difference in management efficiency can be identified and extended to other farmers it should result in large increases in average farm yields. Two broad observations are often made about such exemplary performers:-

a. The timing and precision of all management operations. Sowing is made at the optimum time (Anderson and Smith 1990), fertilizer is applied according to soil and tissue tests (Simpson *et al*. 2007), machinery is adequately maintained, and marketing is well-researched.

b. Long term strategies to improve soil fertility have included additions of lime to acid soils sufficient to change pH (Gazey and O'Connell 2001), addition of gypsum, deep cultivation to break soil compaction (Hamza and Anderson 2003), increasing soil organic carbon through residue retention and/or additions of fresh organic materials, controlling salinity and preventing erosion (Carter *et al*. 1998) and transient water-logging (Bakker *et al.* 2001).

These propositions could be taken as hypotheses and examined thoroughly by research agronomists as one important means to increase crop yields to meet future demands for food.

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