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Crop sequences in Australia's northern grain zone are less agronomically efficient than implied by the sum of their parts

Zvi Hochman [a,*], Di Prestwidge [a], Peter S. Carberry [b]

[a] CSIRO Ecosystem Sciences/Sustainable Agriculture Flagship, PO Box 2583, Brisbane, QLD 4001, Australia
[b] CSIRO Sustainable Agriculture Flagship, 203 Tor Street, Toowoomba, QLD 4350, Australia

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ABSTRACT

The question addressed in this paper is whether the agronomic efficiency of cropping sequences can be improved in the northern grain zone of Australia. Analysis of whole systems over multiple seasons is particularly important in cropping regions such as Australia's northern grain zone, where farmers have the option of growing a variety of winter and summer crops and where fallowing is required to store water to safeguard yields of following crops. The study is based on a detailed longitudinal survey of the inputs and yields of 94 farmers' fields over 7 seasons. The Agricultural Production Systems Simulator (APSIM) was used to benchmark the 94 cropping sequences and to determine if the productivity of these cropping sequences can be improved through changed management, particularly of nitrogen nutrition and timely sowing of individual crops. Comparison of surveyed and simulated yields were then used to determine the yield gap that can be explained by factors unaccounted for in APSIM, i.e. biotic stresses such as weeds, pests and diseases or inadequate operational management. Using a generalised N response curve, data from the simulation analysis were plotted relative to a normalised input–output relationship to determine their position relative to an efficiency frontier representing the simulated production function. This analysis was conducted separately for both individual crops and for whole sequences in individual fields. The analysis of 193 individual crops showed that the average yield of 1.90 t/ha was 65% of the simulated water and nitrogen-limited yield potential of 2.92 t/ha. Investigation of nitrogen unlimited and early sowing management options revealed that there was relatively little yield advantage (0.15 t/ha) to be gained from these management improvements. The remaining gap between observed yields and what the simulations suggest may be attributed to factors such as weeds, pests and diseases, sub-optimal operations or extreme weather events. Three production criteria were used to compare cropping sequences: (1) dollar income, (2) metabolisable energy yield, and (3) crude protein yields. While the income from 36% of the individual crops in the study was found to be more than 80% of their production frontier values, only 29% of whole cropping sequences achieved this benchmark. Similar results were achieved when crops and crop sequences were evaluated in terms of their metabolisable energy and crude protein yields. It is concluded that in order to increase the agronomic efficiency of cropping in Australia's northern grain zone, attention should be focussed on the intensity and configuration of cropping sequences and on the management of fallows in addition to the management of individual crops.

1. Introduction

The world's population is projected to reach 9.2 billion people by 2050 (U.N., 2009; Nelson et al., 2010). This growth together with changing diets will increase anticipated world food demand by 60% relative to 2010 (Alexandratos and Bruinsma, 2012). Achieving the requisite growth rates globally cannot be taken for granted as land and water resources are scarcer than in the past and the potential for continued growth of yield is more limited (Bruinsma, 2009).

A number of partial solutions to filling the global food demand whilst sustaining the natural resource base and mitigating the drivers of global climate change are proposed. They include creating more value with fewer resources through ecological efficiency (WBCSD, 2000; Carberry et al., 2013); intensifying agriculture while maintaining the ecosystem (Matson et al., 1997; Cassman, 1999; Balmford et al., 2005; Hochman et al., 2013); and closing the gap between attainable and actual yields at local to global scales (Cassman et al., 2003; Fischer et al., 2009; Lobell et al.,

* Corresponding author. Tel.: +61 419799527; fax:+61 7 3833 5505.
E-mail address: zvi.hochman@csiro.au (Z. Hochman).

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2009; Grassini et al., 2011; van Ittersum et al., 2013). In Australia's cropping and mixed crop-livestock farms, productivity increases declined from 1.95% per annum in the period 1977 to 1999 to just 0.4% per annum over the period 1999 to 2007 (Hughes et al., 2011). In this paper we investigate the crop production efficiency in the northern grain cropping region of Australia in order to determine the scope for improving the productivity of this cropping system.

The northern grain cropping region of Australia includes central Queensland, southern Queensland, and northern New South Wales between 16° and 32°S, and 148° and 151°E. The region occupies 6 M ha of agricultural land, of which 75% is typically used for dryland agriculture. The climate of this region is sub-tropical with high potential evapotranspiration and low and variable summer-dominant rainfall (Webb et al., 1997). The most common cropping soils are grey, brown, and red cracking clays (Vertosols; Isbell, 1996), which are generally uniform in texture down to at least 1 m depth. Due to the summer-dominant rainfall, winter crops largely rely on water stored in the soil profile during the previous summer–autumn fallow (Freebairn et al., 2006). On average, grey Vertosols of this region have a plant-available soil water capacity (PAWC) of 182 mm (Hochman et al., 2001), but the presence of subsoil constraints (salinity and sodicity) limits the effective rooting depth and increases the crop lower limit, thereby reducing the amount of water and nutrients that plants can access from soils (Dang et al., 2006; Hochman et al., 2007).

The challenge for cropping systems in rainfed regions is to maximise production (profit) and minimise its volatility (risk). This requires agronomic efficiency in the growing of each individual crop but also a balance of capture and utilisation of precipitation through the sequence of crops and intervening fallow periods. In addition to optimising cropping intensity, crop sequences or rotations can be used to ameliorate weed, insect and disease pressures and to provide benefits such as N_2 fixation (Baumhardt and Anderson, 2006; Kirkegaard et al., 2008; Seymour et al., 2012). However, because break crops are usually less profitable and more risky, areas planted to break crops are declining throughout Australia (Seymour et al., 2012). Additionally, society demands that cropping systems and their management practices should minimise ecosystem disservices such as nutrient runoff, pesticide poisoning of non-target species, sedimentation of waterways and greenhouse gas emissions (Power, 2013). Little specific information is available on the current intensity of cropping and the cropping sequences practiced in the northern gain zone. In 2005–06, 4.28 M ha were under rainfed cultivation in Queensland. Of this, 59% was cropped while 41% was in fallow (ABS, 2006). In the period of this study (2005–2008) the production areas in Queensland were allocated to wheat (average 46%), sorghum (29%), grain legumes (11%), barley (5%), oil seeds (2%) and oats (1%), with other crops such as cotton and maize contributing less than 1% each. The amount of crop produced (area sown × yield per ha) varies widely from year to year; for example while 947 t of wheat were produced per farm in 2008, only 315 t per farm were produced in 2006 (AgSurf 2012, http://abare.gov.au/ame/agsurf/agsurf.asp; last accessed 21 March 2014). An earlier survey of farmers in the northern wheat belt of New South Wales, taken between 1983 and 1985, showed 64% of fields surveyed grew wheat, 14% were in bare fallow, 9% were in grazed fallow and 5% were in sorghum (Martin et al., 1988).

The efficiency of production of rainfed crops grown under the highly variable Australian rainfall environment can be evaluated in terms of the water use efficiency (WUE) of individual crops (French and Schultz, 1984; Sadras and Angus, 2006). WUE is a very effective instrument for comparing the performance of crops across seasons and districts in Australia's southern and western grain zones where winter crops are grown largely on in-season rainfall. However, in the northern grain zone where both winter and summer crops are grown, it is more difficult to evaluate cropping sequences using the WUE of individual crops because the influence of the variable length of fallowing can be significant. The cumulative beneficial effect of long fallows on crop yields needs to compensate for a lower cropping intensity when compared to alternative cropping systems with higher cropping intensity and often lower yields per crop.

Another approach to evaluating the agronomic efficiency of crops is based on the yield response to increasing levels of external inputs such as energy, nutrients, water, seed and pest control measures (Cassman, 1999; Lawlor, 2002). A number of studies have investigated cropping intensity and crop sequences in Australia's northern grain zone using a normative simulation approach. Berndt and White (1976) used simulation to compare three cropping systems at three locations in southern Queensland. The three systems were continuous wheat-fallow, continuous sorghum-fallow, and an opportunity cropping system in which either wheat or sorghum would be sown in their respective seasons subject to water storage conditions being met. They found that continuous wheat was more profitable than continuous sorghum and that opportunity cropping reduced soil loss but had an economic advantage only in the less arid site. They also found that long fallow durations were not warranted as the higher yields did not compensate for the fewer crops. de Voil et al. (2006) combined simulation, with optimisation using evolutionary algorithms and Pareto-optimality to discover profit-sustainability tradeoffs for crop rotations at a single site, also in southern Queensland. They looked at three criteria: average yearly gross margin, risk of economic loss, and soil loss. The crops studied were cotton, wheat, sorghum and chickpea sown on soil water thresholds. Their optimised system favoured winter crops over summer crops: wheat over chickpea and sorghum over cotton. Among their pareto-optimal set of rotations, the sorghum–wheat–sorghum–chickpea rotation (up to 2 crops per year depending on soil moisture conditions) had the highest gross margin but also the highest financial risk and soil erosion, while a sorghum–wheat–fallow–wheat rotation with a higher soil water threshold for sorghum had a much lower gross margin but lower financial risk and erosion outcomes. Moore et al. (2011) investigated the soil water utilisation efficiency of a wheat–sorghum–chickpea rotation with three levels of cropping frequency on three soil types at a site at the northern end of this cropping region. In agreement with the earlier studies they showed that the productivity of the rotation was primarily determined by cropping frequency. However, they found that crop choice or cropping season (winter or summer crops) had little influence on the productivity of the rotations.

In contrast, this study is based on a detailed longitudinal survey of the actual management, crop sequences and yields of 94 farmers' fields over seven seasons. The Agricultural Production Systems Simulator (APSIM) (Keating et al., 2003) used to analyse the performance of these real cropping sequences in northern Australia has previously been validated in commercial crops, including many in the study region (Hochman et al., 2007; Carberry et al., 2009) and has also been applied successfully to analysis of experimental crop rotations involving cereal and legume crops over a number of seasons in the northern grain zone (Turpin et al., 1996; Probert et al., 1998a,b).

2. Methods

A longitudinal study of 94 farmers' fields from 47 farms in the northern cropping zone of Australia (Fig. 1) was conducted via a repeated 6 monthly survey over 7 seasons (3.5 years). Grain growers were widely canvassed by open mail-outs to members of a conservation farming association in this northern grain region and