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Magnitude and mechanisms of persistent crop sequence effects on wheat

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ABSTRACT

The impacts of broadleaf crop, pasture or fallow breaks within cereal-based cropping systems are widely acknowledged, but most studies have focussed on the first cereal crop after the break. We report a series of four field experiments in a semi-arid cropping zone of Southern Australia in which the impacts of a range of Year 1 sequence options (crops, pasture and fallow) on Year 3 and 4 wheat crops were investigated. In three of the experiments, two phases of the same experiment were commenced in successive years, providing seven sequence phases. In three of the seven phases (at three of the four sites), the Year 1 treatments influenced the yield of Year 3 or Year 4 wheat crops by 0.6, 0.9 and 0.9 $\mathrm{t\,ha^{-1}}$, although different responses between phases of the same experiments at two sites provided clear evidence of significant seasonal interactions. Interactions of Year 1 sequence treatments with tillage, crop species/varieties and/or added P-fertiliser treatments in intervening years also occurred at some sites. The largest persistent yield impacts related to the preservation of differences in residual nitrogen (N), and in some cases water following Year 1 crops through subsequent dry seasons, which were frequent in most experimental phases. Higher residual N levels after legumes and canola could persist for 2–3 years and induce yield penalties due to "haying-off" when Year 3 or 4 wheat crops experienced dry spring conditions. Such effects were offset following Year 1 fallow due to increased residual water at depth. Increases in the cereal root diseases take-all (*Gaeumannomyces tritici*) and rhizoctonia (*Rhizoctonia solani* AG8) due to Year 1 wheat also persisted through dry seasons and reduced Year 3 wheat yield in some experiments. We found no evidence for a significant role for arbuscular mycorrhizal fungi in yield of Year 3 and 4 wheat crops. We demonstrate that large and significant yield impacts (>0.5 $\mathrm{t\,ha^{-1}}$), both positive and negative, can persist for 3–4 years in semi-arid environments as a result of water, N and disease inoculum legacies of Year 1 crop sequence choices. Prolonged dry periods help to preserve these legacies, so that persistent and unpredictable crop sequence effects will be a feature of cropping systems in semi-arid areas with variable climates.

1. Introduction

Break crops such as grain legumes and oilseeds, or annual pasture phases, are important components of profitable and sustainable cereal cropping systems worldwide as they provide diversity of income and a significant grain yield boost to subsequent cereal crops through the 'break-crop effect' (Kirkegaard et al., 2008). The magnitude and mechanisms of these benefits have been extensively reviewed (Kirkegaard et al., 2008; Angus et al., 2008, 2011; Peoples et al., 2009; Anderson, 2011) and can arise from control of intractable weeds and diseases, enhanced nitrogen (N) supply, improved water availability and improved soil physical or biological fertility. The break-crop benefits interact strongly with seasonal conditions and vary significantly depending on a range of site, crop, season and system characteristics. Overall mean yield improvements reported for the first subsequent wheat (*Triticum aestivum* L.) crop after a break crop are typically 20% or 0.8–1.0 $\mathrm{t\,ha^{-1}}$ of additional grain yield (Kirkegaard et al., 2008; Angus et al., 2008, 2011; Peoples et al., 2009; Seymour et al., 2012) compared to wheat grown after wheat, although the variability in the response is largely due to soil and seasonal interactions with crop response (Kirkegaard et al., 2008).

Most of the reported literature has focussed on the magnitude and mechanism of responses in the first wheat crop (Year 2) after the break crop, pasture or fallow treatments (Year 1). However, some studies have also demonstrated break-crop benefits

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Table 1
Summary of the timing and crop and pasture treatments in four crop sequence experiments, three of which were sown in successive years (Phase 1 and Phase 2).

Year	GSR (mm)	% long-term mean GSR	Experiment 1 (Bethungra)		Experiment 2 (Gundibindyal)		Experiment 3 (Gundibindyal)		Experiment 4 (Temora)
			Phase 1	Phase 2	Phase 1	Phase 2	Phase 1	Phase 2	Phase 1
1993	363	119	W, O, C, L, Pa						
1994	166	55	W, T, B, O, C, Pe	W, O, C, L, Pa					
1995	379	125	**Wheat**	W, T, B, O, C, Pe					
1996	331	109		**Wheat**					
1999	374	115							C, Li, Pa, CFa, TFa
2000	461; 355	128; 109			W, C(4), M, L, CFa				W, C, P (±P)
2001	307; 267	86; 82			W	W, C(4), M, L, CFa	W, C		**Wheat**
2002	217	60			L, Pe	W	W (8 ± Till)	W, C	
2003	281	78			**Wheat**	L, Pe	**Wheat**	W (8 ± Till)	
2004	295	82				**Wheat**		**Wheat**	

B = Barley; C = canola; TFa = tilled fallow; CFa = chemical fallow; Li = linseed; L = lupin; O = oats; Pa = grass/sub-clover pasture; Pe = pea; T = triticale; W = wheat.
Additional agronomic treatments; Till = tillage; P = phosphorus.
Numbers in brackets indicate when more than one variety was included.
GSR = Growing season rainfall (April–October) at the sites (*Note*: in 2000, 2001 numbers are for Gundibindyal and Temora, respectively).
The wheat crops shown in bold in Year 3 or Year 4 (and effects of previous treatments on them) are the focus of this paper.

persisting to second (Year 3) and third (Year 4) subsequent wheat crops in a continuous cropping sequence. These effects have important practical and theoretical implications to develop more accurate assessments of the overall system impacts of crop sequence choices. Kirkegaard et al. (1997) demonstrated a 15% yield increase in a second successive wheat crop (Year 3) following *Brassica* break crops in Year 1 compared to a continuous monoculture of wheat in South-Eastern Australia, while Seymour et al. (2012) showed a relatively consistent increase in the second wheat crop after narrow leaf lupin (*Lupinus angustifolius* L.) of $0.4 \pm 0.08\,\mathrm{t\,ha^{-1}}$ in 29 experiments in Western Australia. In the semi-arid areas of the Great Plains of North America, impacts of a range of Year 1–Year 2 sequence treatments on Year 3 wheat have also been reported in 'dynamic crop sequence' studies designed to develop predictive tools to assist growers with crop sequence decisions (Krupinsky et al., 2006).

Fewer studies have investigated responses persisting into a fourth cereal crop. In two experiments in Western Australia, the yield response for a third wheat crop (Year 4) after lupins (Year 1), varied from no response to a $1.8\,\mathrm{t\,ha^{-1}}$ yield increase compared to a fourth successive wheat crop (Seymour et al., 2012). Interestingly, Harris et al. (2002) showed a significant effect (19%, $0.5\,\mathrm{t\,ha^{-1}}$) of Year 1 canola (*Brassica napus* L.) break crops on a Year 4 wheat crop compared to Year 4 wheat after Year 1 wheat, despite intervening wheat (Year 2) and lupin (Year 3) crops in both treatments (i.e. W–W–L–W vs C–W–L–W). The authors ruled out nitrogen, disease or soil structural effects as factors leading to this benefit (mostly by inference rather than measurement), but suggested that reduced root colonisation by arbuscular mycorrhizal fungi (AMF) in the fourth wheat crop due to two non-host crops in the sequence (canola and lupin) may have reduced the drain by the fungi of wheat assimilates and thereby improved yield. Lower colonisation by AMF following non-mycorrhizal break crops has been repeatedly demonstrated in Australia (Ryan et al., 2002; Ryan and Angus, 2003; Owen et al., 2010) and evidence that assimilate use by AMF can decrease the vegetative growth of wheat in the southern cropping zone was provided by Ryan et al. (2005). As a result, Angus et al. (2011), following Harris et al. (2002), proposed such impacts of AMF might constitute a small part ($\sim 0.1\,\mathrm{t\,ha^{-1}}$) of the positive persistent impacts of non-mycorrhizal break crops (lupins and canola), but this remains to be demonstrated. A recent review of all Australian literature on the role of AMF in extensive cropping concluded that there is no evidence for the fungi playing a positive role in nutrition or yield of crops in the southern temperate cropping zone and that a positive relationship between colonisation and yield intermittently occurs in the northern subtropical cropping zone (Ryan and Kirkegaard, 2012).

In semi-arid dryland farming systems, such as found in Australia and in the Great Plains of North America, the magnitude and persistence of crop sequence choices is a key factor in adoption, as the break crops themselves can be less profitable and more risky than cereals due to sensitivity to drought and disease, and the often low and variable prices (Robertson et al., 2010; Lawes and Renton, 2010). The magnitude and mechanisms of break-crop benefits to the first subsequent wheat crop have been extensively reviewed, but our aims in this paper were to (i) provide insights into the magnitude and persistence of break-crop effects on cereal crops further down the crop sequence and (ii) investigate the mechanisms by which these break-crop effects persist. Accurate estimates of the magnitude and persistence of break-crop benefits and improved understanding of the mechanisms are important to fully assess the value of break crops, and to assist managers to make decisions about when and how to include break crops for maximum system benefits. Quantitative estimates linked to mechanisms may also assist in the development of parameters for farming systems biophysical or economic optimisation models which are both used as tools to evaluate break-crop benefits within farming systems.

2. Material and methods

2.1. Sites and experimental design

Four break-crop experiments of 3 or 4 years' duration were conducted at three sites in Southern New South Wales (NSW) Australia over a 12-year period from 1993 to 2005 (Table 1). Three of the four experiments included two phases so that the effects of seasonal interactions could be investigated. The experiments were designed to investigate the effect of a range of crop sequence options (break crops, pasture or fallow) (Year 1) on the productivity of a subsequent wheat crop (Year 2) and, in most cases, these 2-year sequence effects and experimental details have been reported previously (Bethungra: Kirkegaard et al., 2001; Gundibindyal 1: Smith et al., 2004; Temora: Ryan and Angus, 2003). However, all of the experiments were designed and