



Review

Break crop benefits in temperate wheat production

John Kirkegaard^{a,*}, Olaf Christen^b, Joseph Krupinsky^c, David Layzell^d^a CSIRO Plant Industry, GPO Box 1600, Canberra 2601, Australia^b Institute of Agronomy and Crop Science, Martin-Luther-University, Halle-Wittenberg, D-06099 Halle/S, Germany^c USDA-ARS, Box 459, Mandan, ND 58554-0459, USA^d Queens University, Kingston, Ontario, Canada K7L3N6

ARTICLE INFO

Article history:

Received 24 December 2007

Received in revised form 17 February 2008

Accepted 18 February 2008

Keywords:

Disease

Structure

Soil biology

Sequence

Rotation

Preceding crop

ABSTRACT

Changes in the sequence of crops grown on agricultural land are well known to enhance the yield of grain crops such as wheat. A survey of the literature gathered from around the world show mean yield benefits of up to 20% or more. Much is known about the principal mechanisms responsible for these benefits, including effects on disease control, improved nitrogen nutrition and water supply, although researchers continue to be challenged by inexplicable “rotation effects” that have yet to be documented or fully understood. This review summarizes our current understanding of the ‘better-known’ mechanisms of crop rotation, and discusses other mechanisms (e.g. changes in rhizosphere biology, allelopathy or soil structure) that may help to account fully for the rotation benefits that have been observed by agricultural producers for more than 2000 years. Where possible we emphasise new techniques employed to investigate these less well-understood aspects of the “rotation effect”. At the farm level, the inability to capitalize on the benefits of break crops may owe more to economics, the availability of suitable break crops and the complexity of the crop response. Computer-based decision support tools have been developed to assist growers to apply the information gathered from scientific studies, although efforts to integrate this information at whole-farm scales are embryonic.

© 2008 Elsevier B.V. All rights reserved.

Contents

1. Introduction	186
2. Magnitude of break crop benefits	186
3. Disease control	187
3.1. Non-hosting of cereal pathogens	187
3.2. Mechanisms other than non-hosting	188
4. Residual water and nutrients	188
4.1. Residual nitrogen	188
4.2. Residual phosphorus and other nutrients	189
4.3. Residual water	189
5. Soil biology impacts unrelated to disease	190
5.1. Arbuscular mycorrhizal fungi (AMF)—friend or foe?	190
5.2. Hydrogen release by legumes	190
6. Soil structure effects	190
7. Allelopathy, weeds and herbicide residues	191
8. The “rotation” effect	192
9. Environmental benefits of break crops	192
10. Scaling issues and adoption	192
References	193

* Corresponding author. Tel.: +61 2 62465080; fax: +61 2 62465399.

E-mail addresses: john.kirkegaard@csiro.au (J. Kirkegaard), Christen@landw.uni-halle.de (O. Christen), Krupinsj@mandan.ars.usda.gov (J. Krupinsky), layzell@biocap.ca (D. Layzell).

1. Introduction

Adopting an appropriate crop sequence underpins sustainable production systems in many areas of the world. In this review we consider the magnitude and mechanisms of break crop benefits using the temperate dryland wheat production system as a focus, and using examples drawn from the contrasting farming systems of northern Europe, southern Australia and North America. We acknowledge, but deliberately avoid detailed consideration of the longer term effects of crop rotations, which can become evident over time in both set and diversified rotations (e.g. Karlen et al., 1994), but focus on the more immediate impacts of preceding crops on subsequent wheat growth and yield. In modern broad-acre farming, the choice of crop sequence has become more flexible and often diversified, reflecting a range of factors related to

commodity and input prices and the biophysical conditions of individual paddocks. We attempt to provide some clarity in explaining the enormous variability reported in the response of wheat to preceding crops and consider the new techniques being used to understand these mechanisms and to extend these insights at the farm level.

2. Magnitude of break crop benefits

The magnitude of the average yield response in wheat to preceding broad-leaf break crops compared to wheat following wheat is surprisingly consistent across broad regions and time scales, although there is significant variation in the response of individual crops depending on site, weather conditions and other aspects of crop management (Table 1). In different areas of North

Table 1
A summary of the magnitude and range of yield response of temperate dryland wheat to previous break crops compared to previous wheat crops in three regions throughout the world

Location	Years	Cereal ^a	Break crops ^a	W-W yield (t/ha)	Yield response to break crops (%)	Other treatments ^b	References
<i>North America (mean overall response = 14)</i>							
Saskatchewan, CAN	1993–1994	SW	Pe	1.6	62		Stevenson and van Kessel (1996)
Oregon, USA	1988–1992	WW	Pe, C, B	4.4	52 (40–60)		Smiley et al. (1994)
Saskatchewan, CAN	1996–1999	SW	Pe, C, Le, M, Ch	2.1	23 (14–35)		Miller et al. (2003)
Alberta, CAN	1993–2000	WW	Pe, C, F	1.9	20 (13–24)	T	Soon and Clayton (2002)
Nth Dakota, USA	1998–1999	SW	Various	3.0	15 (0–30)		Krupinsky et al. (2002)
Saskatchewan, CAN	1993–1997	SW	Various	2.0	15 (0–21)		Miller et al. (2002)
Saskatchewan, CAN	1983–1987	B, SW	Pe, Be	2.6	21 (–12 to 49)	T, N	Wright (1990) ^c
Manitoba, CAN	1982–1993	SW	Pe, C, Fl	2.2	12 (8–16)		Bourgeois and Entz (1996)
Alberta, CAN	1997–1999	SW	Pe, C	2.9	8 (0–11)		Arshad et al. (2002)
Saskatchewan, CAN	1996–2000	DW	Various	2.2	6 (5–7)		Gan et al. (2003)
Nth Dakota, USA	1999–2000	SW	C, Pe, Be, Sa, Su, So, Li, Cr	3.1	0 (0–11)		Krupinsky et al. (2004, 2006)
Saskatchewan, CAN	1979–1997	SW	Le	1.6	0		Zentner et al. (2001)
Montana, USA	1999–2001	SW, DW	Pe, L, Ch, Su, Mi, F	1.8	0 (–51 to 18)		Miller and Holmes (2005)
Washington State, USA	1992–2000	SW	Sa, M	2.9	–10		Cook et al. (2002)
Nth Dakota, USA	1989–1993	SW	Pe	2.1	–13		Tanaka et al. (1997)
<i>Southern Australia (mean overall response = 33)</i>							
NSW	1992–1993	SW	C, M	2.6	99 (94–103)		Gardner et al. (1998)
NSW	1989–1993	SW	C, Li, Lu, Pe, Le, Ch	2.8	93 (–6 to 187)	SD	Heenan (1995) ^c
WA	1992–1994	SW	C, M, L, Pe, Lu, Le, Fa, Ch	2.4	74 (3–53)		Gregory (1998)
SA	1978–1993	SW	Pe, Lu	1.6	49 (45–85)	N, S, T	Schultz (1995)
NSW	1991–1993	SW	Pe, Lu	2.1	38 (–6 to 544)		Evans et al. (1991)
ACT, NSW	1999–2002	SW	C, M, L, Lu, F	3.2	36 (0–112)		Smith et al. (2004)
VIC, NSW	1997–2000	SW	Various	2.5	36 (–6 to 108)		Ryan et al. (2002)
NSW	1991–1993	SW	C, M, L	3.1	21 (–25 to 59)	N	Kirkegaard et al. (1997)
NSW	1997–2002	SW, DW	C, M, Ch	2.6	21 (–17 to 59)	V	Kirkegaard et al. (2004)
WA	1982–1983	SW	Lu	2.1	20 (–2 to 133)	N, T	Delroy and Bowden (1986)
NSW	1988–1989	SW	C, M, L	3.0	19 (12–26)	N	Angus et al. (1991)
ACT, NSW	1995–1998	SW, WW	C, M, L	4.9	18 (–14 to 69)	V	Kirkegaard et al. (2000)
WA	1979–1984	SW	Lu	0.9	15 (–10 to 113)	N	Rowland et al. (1988)
VIC	1991–1998	SW	C	2.7	12	P	Harris et al. (2002)
NSW	1989–1991	SW	C, M, L, Pe	3.6	8 (–12 to 32)	Fum	Kirkegaard et al. (1994)
WA	1985–1986	SW	Lu	1.0	3 (–24 to 67)	N, Fum	Wilson and Hamblin (1990)
NSW	1993–1995	SW	C, Lu, O	1.7	0 (–21 to 18)		Kirkegaard et al. (2001)
<i>North Europe (mean overall response = 24)</i>							
Sweden	1984–1988	WW	Ra, Pe, O, B	3.3	59 (12–145)	T	Olofsson (1993)
England	1982–1984	WW	O	7.1	38 (19–75)	SD, N, F, I, GR	Prew et al. (1986) ^c
South Germany	1970–1984	WW	Ra	4.0	25 (–8 to 52)		Schönhammer and Fischbeck (1987a)
England	1986–1989	WW	Ra, Pe, Lu, Su, O, F	2.0	21 (–12 to 224)	N	McEwen et al. (1989)
England	1980–1983	WW	Be	4.6	21 (0–71)	N, F, I, V	Widdowson et al. (1985)
South Germany	1979–1992	WW	Ra, Pe, Be, O, Po, M	6.1	14 (–12 to 36)	N, F	Panse et al. (1994)
North Germany	1993–1999	WW	Ra	7.6	10 (0–39)	SD, SR, N	Sieling et al. (2005)
North Germany	1987–1989	WW	Ra, Pe	7.3	7 (–27 to 28)	N, F	Christen et al. (1992)

Data are sourced from selected published studies since 1985 and the mean overall response to break crops and other treatments (bold) as well as the range in response to individual treatment combinations (brackets) are shown.

^a C, canola; Ra, rapeseed; Pe, field pea; M, mustard; Cr, crambe; L, linseed/flax; Lu, lupin; Ch, chickpea; Le, lentil; Be, dry bean; F, fababean; Su, sunflower; Po, potato; O, oats; F, fallow; Mi, millet.

^b N, nitrogen; T, tillage; S, stubble; Fum, fumigation; SD, sowing date; SR, seeding rate; V, variety; F, fungicide; I, insecticide; GR, growth regulators; P, phosphorus.

^c Response compared using barley rather than wheat.

America the average overall yield response of wheat to a previous break crop in the experiments reviewed is around 14%, although responses can range from –51% (Miller and Holmes, 2005) to 62% (Stevenson and van Kessel, 1996) (Table 1). In southern Australia the average yield benefit is somewhat higher at 33% (Table 1) but the magnitude of the variation –25% to 544% for individual treatments in specific experiments is even greater. In northern Europe, the average yield response is around 24% but ranges from –27% to 224% in individual studies. Positive yield responses are notably less reliable and generally smaller in semi-arid areas (Gan et al., 2003; Zentner et al., 2001) or in drier seasons (Kirkegaard et al., 2001) and may be negative where break crops replace fallow (Miller and Holmes, 2005). The benefits in yield may be accompanied by increased grain protein (Kirkegaard et al., 1994; Gan et al., 2003) and can also persist into a second cereal crop (Kirkegaard et al., 1997; Evans et al., 2003) or even further down the sequence (Harris et al., 2002). Successive break crops prior to a cereal in a sequence may also provide a greater yield benefit than a single break crop (Sieling et al., 2005). The inclusion of many interacting treatments such as nitrogen, variety, sowing date, fumigation, and fungicides in many of the experiments summarised in Table 1 provide an opportunity for greater insight into the underlying mechanisms of crop response. In some studies the mechanisms behind these yield responses, and their interactions with other crop management practices are clear, while in others a significant portion of the crop response could not be explained by commonly measured variables (e.g. disease, nitrogen and water), leading to speculation regarding the nature of the “rotation effect”. In the following sections we will consider the better known and less well understood mechanisms which underpin these responses to break crops and attempt to clarify the enormous variation exemplified in Table 1.

3. Disease control

Disease control is implicit in the term “break crop” as it refers to breaking the life cycle of crop-specific pathogens by growing a non-host crop in sequence. Wheat crops grown repeatedly in sequence can suffer from various soil and stubble-borne disease, although the range and severity of the particular pathogens vary widely both regionally and seasonally. For some diseases, crop tolerance (e.g. for crown rot caused by *Fusarium pseudograminearum*), resistance (e.g. for cereal cyst nematode, *Heterodera avenae*) or seed dressings and fungicides (e.g. for eyespot caused by *Tapesia yallundae* and tan spot by *Pyrenophora tritici-repentis* in Europe) form part of the control strategy. Some important soil-

borne diseases have a wide host range and may not be adequately controlled by broad-leaf break crops (e.g. *Rhizoctonia solani*, Cook et al., 2002) while others require more than one season without a host to reduce the inoculum to safe levels (e.g. *Bipolaris sorokiniana*). The host ranges of some wheat pathogens are also quite specific—for example the root lesion nematode *Pratylenchus neglectus* hosts on canola and chickpeas but not on lupins, while the closely related *Pratylenchus thornei* hosts only on chickpea.

3.1. Non-hosting of cereal pathogens

Clearly the value of break crops will depend on the diseases present in particular cropping systems, the host status of the proposed break crop, and the availability of other strategies such as tolerance, resistance or chemical control. However break crops remain the control strategy for several wheat diseases including take-all, caused by the pathogen *Gaeumannomyces graminis* var *tritici* (Ggt), an important wheat disease worldwide. In southern Australia, much of the break crop benefit under well-fertilised dryland wheat crops has been attributed to the control of take-all (Kollmorgan et al., 1983; Kirkegaard et al., 1994; Gardner et al., 1998), and a previous compilation of studies revealed an average response of around 19% (Angus et al., 2001). In the Inland Pacific Northwest of the US, the average response of winter wheat to soil fumigation was 7% in fields cropped no more than every third year to wheat, 22% in fields cropped every second year to wheat, and an astounding 70% in fields cropped every year to wheat (Cook, 1990). The yield responses to these treatments were primarily due to control of root diseases including take-all, *Rhizoctonia* and *Pythium*. In the high input systems of northern Europe, the incidence and severity of take-all is also one of the most important factors influencing yield of winter wheat after different preceding crops (Christen et al., 1992). A typical response of wheat to preceding crops where disease is a key limiting factor is shown in Fig. 1A. The magnitude of the disease effect may differ widely depending on the number and severity of wheat diseases present, but an average yield reduction of 20–30% is common, and cannot be substituted with higher inputs (Kirkegaard et al., 1997; Sieling et al., 2005). The use of fumigation, sowing date or tolerant varieties as interacting treatments in several experiments (Table 1) has assisted to separate and quantify the role of disease. In some cases the disease reduction can extend beyond the first year and result in yield benefits in a second successive wheat crop (e.g. 13% reported by Kirkegaard et al., 1997). For many diseases including take-all, seasonal conditions dictate the extent to which disease influences

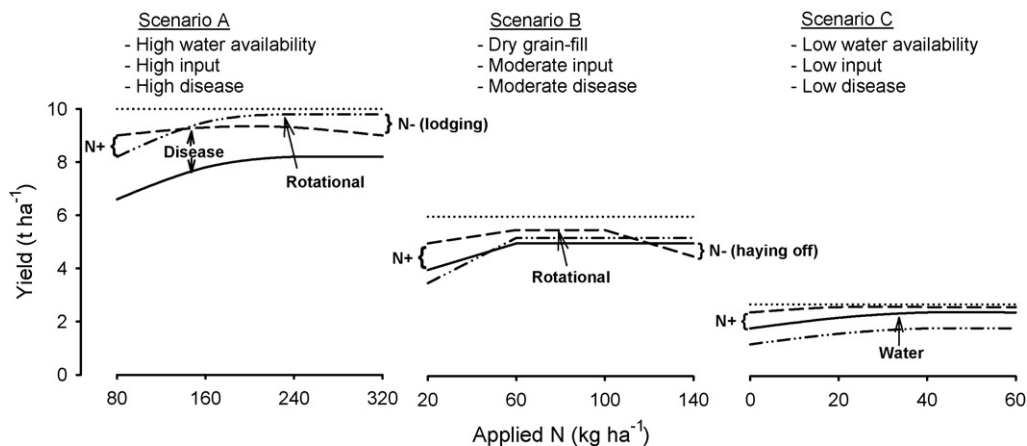


Fig. 1. Typical response of wheat to previous wheat (solid), legume (dashed) and oilseed (dot-dash) break crops under different potential yield scenarios and different N application rates. The dotted line shows the potential yield. The mechanisms causing responses to differ between previous crops are shown (N = nitrogen, ± denotes yield increase or decrease associated with N).

crop growth, as inoculum survival, pathogen infection and disease expression are all influenced by rainfall patterns and temperature (Smiley et al., 1996).

As a result, the non-host benefit of break crops (as estimated by the level of inoculum present immediately prior to sowing wheat) may not be reliably reflected in a break crop benefit. In south eastern Australia, Kirkegaard et al. (1997) found that when conditions for the development of take-all were poor, wheat following wheat could achieve similar yields to that after break crops with sufficient attention to nutrition, as represented here in Fig. 1B. Recent studies in the semi-arid areas of the northern Great Plains of Canada using multivariate analysis showed that the annual environment explained between 59% and 75% of the variation in wheat disease severity while crop sequence played a minor role in determining the incidence and severity of disease (Bailey et al., 2000, 2002), despite the overall reductions in populations of pathogens such as *B. sorokiniana*, *Septoria tritici* and *Stagnospora nodorum* and higher yields in more diverse rotations. The recent advent of pre-sowing DNA-based soil testing such as the Predicta-B® tests used in Australia for a range of cereal diseases can reduce the risk of severe losses (Herdina et al., 1997). However similar inoculum levels at the start of the season can result in either of the scenarios depicted in Fig. 1A and B, depending on seasonal conditions and disease development.

3.2. Mechanisms other than non-hosting

Break crops may differ in the extent to which they influence the populations of specific rhizosphere organisms which may compete, antagonise or suppress pathogens. For example Cotterill and Sivasithamparam (1988) showed that the reduction in take-all with different crop rotations is not simply due to denying a host to the pathogen and that the mechanism may vary between crops. Take-all hyphal growth in soil was suppressed and disease severity was reduced under lupins, oats or field pea, but only lupins and oats reduced the inoculum of the pathogen. Observations of superior wheat growth following *Brassica* break crops compared with other broadleaf break crops in southern Australia during the early 1990s (Angus et al., 1991; Kirkegaard et al., 1994) prompted speculation that allelochemicals unique to brassicas, principally isothiocyanates (ITCs), may actively suppress disease organisms in a process termed “biofumigation” (Angus et al., 1994). Subsequent laboratory and pot studies demonstrated that key cereal pathogens such as *Ggt* were highly sensitive to the ITCs released by canola roots (Sarwar et al., 1998). However while subsequent field studies revealed some evidence for suppression of *Ggt* inoculum during the period of canola root decomposition in soil, the benefits to following wheat crops via enhanced *Ggt* suppression were limited (Kirkegaard et al., 2000). Recent field studies by Smith et al. (2004) failed to detect any evidence that ITCs released by brassicas influence the levels of *Ggt* or other rhizosphere organisms on subsequent wheat crops. Thus, despite reports of ITC-induced changes in the rhizosphere of canola (Rumberger and Marschner, 2003, 2004) it appears these effects do not generally persist to influence the levels of disease on wheat in a subsequent season (Watt et al., 2006a).

In similar studies investigating the impacts of different preceding crops on crown rot in durum wheat, Kirkegaard et al. (2004) showed that *Brassica* break crops led to lower levels of crown rot and higher yield in durum wheat compared with wheat following chickpea. There was no evidence that the effect was related to biofumigation, but several plausible explanations were suggested including (1) more rapid breakdown of residual wheat stubble under dense canola canopies reducing carry-over of crown rot inoculum; (2) higher soil N status following chickpea increasing crown rot severity; and (3) altered soil/residue biology that was

less conducive to crown rot inoculum survival. The latter possibility was supported by the higher levels of *Trichoderma* spp., known antagonists of crown rot, which were isolated from wheat following brassicas. This study serves to illustrate the complexity of mechanisms by which the levels of disease can be influenced by previous crops, and the difficulty identifying the basis for break crop effects, even when reduction in severity of one disease is considered to be the major cause of the yield response.

Clearly while reduced disease levels may serve to define “break” crops, and in some cases may alone explain the response in following crops (Cook, 1990), there are many reports of significant break crop effects which cannot be accounted for by disease alone. Both Schönhammer and Fischbeck (1987a,b) and Sieling et al. (2005) concluded that only minor parts of the 10–25% wheat response to previous rapeseed crops (similar to those shown in Fig. 1A) could be explained by the levels of disease measured in the experiments. Thus while monitoring key pathogens within the crop sequence is a logical first step in accounting for break crop benefits, other factors are clearly also involved.

4. Residual water and nutrients

4.1. Residual nitrogen

Not surprisingly, due to the inclusion of legume break-crops in many experiments, nitrogen (N) is the most commonly utilised interacting treatment in many crop sequence experiments (Table 1). Many studies have shown that cereals derive both yield and N benefits from rotations with grain legumes compared with cereal monoculture. The yield advantage may be entirely due to N or to other factors, but more commonly a combination of both (Chalk, 1998). In a compilation of field studies in Australia during the 1970s and 1980s the yield of wheat following legumes exceeded that following wheat by an average of 49% (Evans and Herridge, 1987), similar to the value of 37% reported in tropical systems (Peoples and Craswell, 1992). In a later review of 135 site-years (Angus et al., 2001) found a similar magnitude of yield response (40–50%) following grain legumes when low levels of N were applied to following wheat. However this yield benefit dropped to 10–17% when economically optimum N fertiliser rates were applied, which was similar to the benefit for oilseed break crops. Clearly the disease-break benefits of legume crops can be as important as the N benefits, as represented in Fig. 1A, at low rates of applied N. Indeed Stevenson and van Kessel (1996) found that 91% of the wheat yield benefit from a preceding pea crop came from reduced leaf disease and weed infestation, while only 9% was estimated to have derived directly from N. In contrast, Beckie and Brandt (1997) working in the same soil zone concluded that the benefit of pea crops to following wheat crops was overwhelmingly due to N contribution of the legume. The relative importance of N- and non-N benefits of legumes will clearly vary in specific experiments according to many soil and climatic factors. Benefits in N nutrition to wheat may also arise from break crops simply because the healthier root system is able to utilise existing soil N or applied N more efficiently (Cook, 1990).

Previous assessments of the N benefit of legumes using “fertiliser equivalents” and cereal monocultures as a reference are generally thought to overestimate the N benefits of legumes (Chalk, 1998; Peoples and Craswell, 1992; Beckie and Brandt, 1997), while shoot-based isotopic approaches applied to N budgets may underestimate the 25–70% of legume N which can be contributed by the nodulated roots (Khan et al., 2003; Walley et al., 2007). Although the assumption is often made that additional N contributed by legumes is primarily from biological fixation, the cereal in a legume–cereal rotation may also benefit from reduced use of mineral N by the legume (sparing N), subsequent decomposition of legume residues,

or from reduced immobilisation of existing soil mineral N due to lower C:N ratio of legume residues. The relative importance of these mechanisms may vary, but all can make significant contributions to the N benefit. Direct measurements of the additional nitrate N available to wheat crops following legumes compared with cereals in temperate Australia average around 37 kg N/ha (range 14–46 kg/ha) (Peoples et al., 1995; Chalk, 1998), and is similar in comparable environments elsewhere (Soon et al., 2001). Many factors influence the magnitude of the N benefit from preceding legumes, and Evans et al. (2001) have estimated that average net N input from grain legumes to be 47 kg/ha N in south eastern Australia and 90 kg N/ha in south western Australia. Beckie et al. (1997) estimated a value of 25 kg N/ha for pea crops in the moist Dark Brown soil climatic zone of Saskatchewan, and similar annual N benefits have been estimated in drier locations in Canada (Van Kessel and Hartley, 2000). A recent comprehensive review of similar estimates for the Northern Great Plains by Walley et al. (2007) highlighted the enormous variability (from –100 to +100 kg N/ha) in reported values from individual experiments. Their review concluded that most of the variation in N contribution both among different legume species and in different environments arose from differences in the amount of N₂ fixation which was extremely variable. In general, positive N contributions were apparent when more than 48% of the legume N derived from N₂ fixation, somewhat higher than the value of 42–44% estimated in Australia (Evans et al., 2001). Generally the N benefits of the legume break crops to following cereals are evident at lower rates of applied fertiliser N (shown as N+ in Fig. 1A and B) where yield following the legume break crops are often superior to that following non-legumes, an effect which diminishes as higher rates of fertiliser N are applied.

Non-legume break crops may also differ significantly in the amounts of mineral N left in the profile. Kirkegaard et al. (1997) found that residual N remaining after a range of winter oilseeds was a key factor in determining subsequent wheat yields in the absence of disease. Linseed had a shallower rooting system, produced less biomass and left 30–50 kg/ha more N in the profile at harvest than canola or mustard. Accumulation of mineral N from break crop residues may also differ during the fallow period prior to cropping and this may not be simply related to the C:N ratio of the residues (Kirkegaard et al., 1999; Ryan et al., 2006). Too much residual N can also reduce the yield of subsequent cereals, but for different reasons in different environments. In high-yielding environments such as northern Europe, higher levels of residual N following break crops can cause lodging if fertiliser additions are not modified (Christen et al., 1992), as represented as (N–) in Fig. 1A. In drier environments, high levels of applied or residual soil N can stimulate excessive vegetative growth and reduce the levels of stored soluble carbohydrates in wheat leading to a reduction in yield through “hay off” when water availability is limited during grain filling (Van Herwaarden et al., 1998; Kirkegaard et al., 1994, 1997). Such a scenario is depicted as (N–) in Fig. 1B following legumes at higher rates of applied N. The distribution of residual N within the soil profile following break crops may also influence both the yield and protein content of subsequent wheat crops (Evans et al., 2003).

4.2. Residual phosphorus and other nutrients

Evidence regarding the effect of crop sequence on the availability of nutrients other than N is limited, although there are some examples, particularly with respect to phosphorus (P). Some break crops, including chickpea, pigeon pea and white lupin can mobilise fixed forms of soil P by the secretion of organic acids such as citrate and malate and other compounds from their roots (Hocking, 2001). Glasshouse experiments using a highly P-fixing soil showed better wheat growth following white lupin than

soybean (Hocking and Randall, 2001) and suggested that the cereal was able to access P made available by the previous white lupin break crop. Zhu et al. (2002) also demonstrated that buckwheat (*Fagopyrum esculentum*) was able to access P from Ca-bound forms in soils to a much greater extent than wheat, an ability thought to relate to a capacity to acidify the rhizosphere. The persistence of these effects and the magnitude of yield benefits to cereals in rotation or inter-cropped with these species in the field are uncertain. On soils with marginal levels of soil nutrients, differences in uptake and redistribution of nutrients by different break crops can also influence the growth of following cereals. For example on acid sandy soils of south-western Australia, K deficiency combined with Mo deficiency and Al toxicity in wheat, were identified when canola residues were concentrated into windrows and burnt, creating waves of better growth throughout a following wheat crop (Brennan et al., 2004).

4.3. Residual water

Most of the negative impacts of broadleaf break crops on following cereals relate to impacts on residual water in semi-arid environments, where complete recharge of the soil water profile may not occur prior to, or during the growth of the subsequent wheat crop (Table 1). In the drier regions of the Australian wheat-belt, the Great Plains of US and Canadian prairies, a traditional fallow-wheat system has been practiced to store water for the following crop. In recent years, the adoption of conservation farming techniques to conserve water has resulted in moves to replace the wheat-fallow system with either a wheat-summer crop-fallow sequence, or introduction of various break crops to replace the fallow completely. Halvorson et al. (2002) found that winter wheat yield was unaffected by such changes in either tillage or crop sequence in the Central Great Plains, however the yield of the corn summer crop was reduced under continuous cropping. Norwood (2000) found that the species of summer crop grown in such systems also influenced residual soil water and yield of wheat. Sunflower and soybean reduced soil water by 20% and 10%, respectively, compared with corn or sorghum. Nielsen et al. (2002) showed that increasing cropping intensity to two crops in 3 years had little impact on soil water content at wheat planting or grain yield, however elimination of fallow completely reduced soil water at planting by 118 mm and yields by 0.45–1.65 t/ha. In a 10-year study on the Canadian Prairies, Larney and Lindwell (1995) found that the starting available soil water content at the establishment of winter wheat was least after canola (45 mm), followed by continuous wheat (59 mm), lentils/linseed (74 mm) and fallow (137 mm). The impact of these differences in residual water on subsequent wheat crops in semi-arid environments is depicted in Fig. 1C. Under conditions of low water availability, low disease pressure and low yield potential, the amount of pre-sowing soil water, which is generally higher following legumes than oilseeds, dictates the yield of following wheat which may be relatively unresponsive to other inputs. However, other responses have been reported in these drier environments. Miller et al. (2002) found that wheat yields were 21% higher following a range of legume break crops compared to wheat, but did not differ after oilseed crops. The effects were related to both increased soil water and N following the legumes. Gan et al. (2003) found increases in yield and protein of durum wheat following break crops with generally higher yield (7%) and protein (11%) after legumes compared with oilseeds (5% and 6%). Interestingly in that study, the amount of residual water and nitrate in the profile could only account for 3–28% of the impacts on yield and 12–24% of the impacts on protein suggesting that other unidentified factors also contributed to these effects. Kirkegaard et al. (2001) found better than expected yield of wheat following canola based on the amount of pre-sowing water

available, an effect apparently related to deeper infiltration and more efficient use of limited rainfall during the grain-filling period. These “in crop” impacts of previous crops on water use by wheat can also result from the more effective water use by healthy roots, even in high rainfall environments such as northern Germany (Sieling et al., 2005), and may contribute in part to a portion of the inexplicable rotation effects as they are transient and difficult to measure.

5. Soil biology impacts unrelated to disease

Aside from their impacts on disease severity, break crops may also influence the populations of other rhizosphere organisms which stimulate or suppress plant growth, or influence the availability of soil nutrients (reviewed by Bowen and Rovira, 1999). Despite significant investigations of plant-growth-promoting rhizobacteria (PGPR) such as *Bacillus* spp., or deleterious rhizobacteria (DRB) such as *Pseudomonas* spp., there are few examples demonstrating a clear role for these organisms in the response of wheat to crop sequence in the field, although their negative impact in no-till systems has been demonstrated (Simpfendorfer et al., 2002; Watt et al., 2003). A study by Rovira et al. (1990) in the Pacific Northwest, USA indicated that as the frequency of wheat in the rotation increased, the populations of DRB increased in the wheat rhizosphere. Recently a study by Gupta et al. (2004) demonstrated that different wheat varieties in a successive wheat sequence generated different responses in following wheat crops which were related to changes in specific components of the rhizosphere bacterial populations. Such studies indicate that bacterial populations can be influenced by previous crops, or even crop varieties in ways that significantly influence the growth of subsequent crops, which may explain some of the apparent benefits of break crops in the absence of known major disease organisms. Lupwayi and Kennedy (2007) recently reviewed the impacts of grain legumes on selected soil biological processes in the Northern Great Plains and nominate changes in both symbiotic and non-symbiotic bacteria, mycorrhizae and soil fauna among the components of the soil biology influenced by legume break crops. Endophytic rhizobia and other bacteria were reported in higher numbers in the roots of barley, wheat and canola following pea crops compared to those following wheat and evidence for various benefits including growth stimulation, disease protection, changes in root architecture and nutrient acquisition were proposed, but the benefits under field conditions remain uncertain. Recent field studies in Australia by Smith et al. (2004) failed to find significant soil biological changes in the rhizosphere of wheat following different legume and *Brassica* break crops. Despite the difficulty in isolating and quantifying the impacts of specific changes in rhizosphere microbiology on crops within a sequence at the field scale, there remains optimism that the application of new molecular tools and microscopy techniques in this area will create opportunities to manipulate management and genotypes to improve crop productivity (Watt et al., 2006a). Two examples of soil biological changes associated with break crops are considered below.

5.1. Arbuscular mycorrhizal fungi (AMF)—friend or foe?

Wheat is not highly dependant on AMF for nutrient acquisition and although there are some reports of poor growth associated with lower colonisation of wheat following fallow or non-host crops such as canola on low P soils (Thompson et al., 2001), large growth benefits from AMF colonisation in agricultural crops are rare under field conditions (Ryan and Graham, 2002). Indeed if AMF do not provide benefits in nutrient acquisition then host growth can be decreased as a result of the carbon loss to support

fungal structures in the roots. Recent studies on wheat in southern Australia showed that lower AMF colonisation in wheat following brassicas and fallow did not reduce growth or yield in autumn-sown wheat despite strong P limitations on crop growth and yield (Ryan and Angus, 2003). The authors hypothesised that for these crops AMF must have been parasitic at least prior to spring. This suggestion was supported by subsequent measurements of lower soluble carbohydrates as AMF colonisation increased (Ryan et al., 2005). Thus reduced parasitism by AMF may partly explain the superior growth of wheat following brassicas in south eastern Australia, and form part of the unexplained “rotation effect” particularly cases in which *Brassica* break crops are superior to legumes for inexplicable reasons, as depicted in Fig. 1A at optimum N rates.

5.2. Hydrogen release by legumes

Hydrogen (H₂) gas is an obligate by-product of the N₂-fixing enzyme nitrogenase in legume nodules. In some legume systems, an additional hydrogenase uptake enzyme system (HUP) oxidises and recovers some of the energy used in H₂ production. However many legumes evolve H₂ in substantial amounts, up to 5000 L H₂/ha/day, due to an absence or low activity of HUP (HUP-) (Arp, 1992). H₂ production by legume nodules induces rapid multiplication of soil micro-organisms, as yet unidentified, that are capable of utilising the H₂ as an energy source. Exposure to H₂ at levels similar to that which occurs next to nodules greatly increased the growth of both legumes (14%) and non-legumes (18–32%) (Dong et al., 2003). Moreover the activity is extractable and is present even when the H₂-treated soil is diluted to 5%, or when a water extract of the soil is applied to seed. The mechanisms are as yet unknown, but the organisms may enhance plant disease resistance, induce disease suppression, or impact directly through plant growth regulators to contribute to the non-N benefits of legumes.

Other examples of significant impacts of break crops on subsequent wheat yield via specific changes in soil microbial populations are rare. Thus while an array of DNA-based and other analytical techniques (e.g. BIOLOG, FAME, PFLA, DGGE, RISA, T-RFLP) make it possible to detect ever more subtle changes in rhizosphere microbial populations, the challenge will be to identify changes which are consistent and agronomically significant in order to use them to improve crop sequence.

6. Soil structure effects

The roots and residues of break crops may influence several aspects of soil structure through exudation or release of stabilising or destabilising substances in the rhizosphere, root and associated hyphal enmeshment or fragmentation, and the production of stable biopores. Improved soil structure arising from longer term increases in soil organic matter through appropriate rotations is generally accepted (Kay, 1990), but demonstrating shorter term break crop benefits has been more problematic. In southern Australia, Reeves et al. (1984) reported that differences in soil water-stable aggregates and bulk densities following wheat and lupin crops were small and inconsistent. Chan and Heenan (1996) reported soil following canola and lupin was more porous, had lower soil strength and had stronger, more stable aggregates than soil after peas or barley, and the improvements related to the impacts of roots on soil aggregate formation and macro-pore creation. Interestingly, both lupin and canola are non-AMF hosts so that the improvements in aggregate stability following those species could not be explained by glomalin production by the associated AMF as has been recently demonstrated for other crops by Wright and Anderson (2000). These impacts on soil character-

istics were transient under conventional cultivation regimes and no data on the growth of following wheat crops was reported. Cresswell and Kirkegaard (1995) reviewed the evidence for improvements in subsoil structure by break crops and concluded that the effects were either small, not evident, or could not be adequately distinguished from additional influences of break crops such as reduction in soil-borne diseases. A later study at the same site confirmed that perennial pastures such as lucerne (*Medicago sativa*) and Phalaris (*Phalaris aquatica*) were able to improve the macroporosity of the subsoil layers (McCallum et al., 2004). In longer term studies in southern Germany higher yield in wheat has been linked to improved root density and penetration associated with favourable effects of spring rape on components of soil structure including aggregate stability and porosity, both of which were reduced by wheat and barley in the rotation (Schönhammer and Fischbeck, 1987b).

Linking soil structural changes to crop response may be limited by traditional indirect structural measurements which may not capture the changes in soil structure to which roots are sensitive (Passioura, 2002). The vastly different chemical, physical and biological characteristics in and around macro-pores where roots often concentrate (Pierret et al., 1999) suggest that bulk soil structural properties are unlikely to account for important features influencing following crops. The increasing shift to no-till farming with controlled traffic systems using satellite guidance systems is likely to preserve structural and biological changes induced by preceding crops. Novel approaches such as the use of cryo-scanning electron microscopy in which the soil and roots within it are frozen to facilitate detailed examination of root–soil interactions in an undisturbed state (McCully et al., 2000) are revealing details of root–soil interactions not previously seen (Fig. 2). Preliminary investigations of biopores in soils under no-till canola-wheat systems reveal the longevity and close association of previous root systems and their associated organisms with roots of current crops. Closer examination of roots in intact field soils are revealing important interactions between roots, soil structure and rhizosphere biology which can influence plant growth. For example Watt et al. (2003) have

recently shown that DRB can build up on the roots tips of wheat growing slowly in high strength, no-till soil, a limitation which can be removed by cultivation or fumigation. More than 50% of the root system of wheat crops has been shown to be in direct contact with the roots of previous crops (Watt et al., 2005) and new DNA and microscopy techniques have shown that this contact has a significant influence on the types of rhizosphere organisms which are present along the roots of the current crop (Watt et al., 2006b). Thus although current evidence for impacts of break crops via soil structural or biological changes is limited, new approaches to study crop roots in intact field soil may reveal some of the mechanisms responsible for inexplicable “rotation effects” particularly in modern, no-till, controlled traffic farming systems, where the intimate contact between the roots of successive crops in a sequence (as depicted in Fig. 2) is increased.

7. Allelopathy, weeds and herbicide residues

Here we confine our definition of allelopathy to the impacts of phytotoxic substances released either directly from, or during the decomposition of prior crop residues. Several studies in different countries have shown that retained stubbles from a range of crops can reduce yield of following wheat crops (e.g. Purvis, 1990), although doubt remains regarding the role of allelopathy in these observations. Much of the supporting research utilises laboratory-based assays of germination or seedling growth upon exposure to stubble leachates extracted under conditions with little or no relation to field conditions (Leather and Einhellig, 1986) and while these studies confirm that phytotoxic phenolic and short chain aliphatic acids can be extracted from decomposing residues (Tang and Waiss, 1978), few studies clearly link these compounds with crop response in the field. Gubbels and Kenaschuk (1989) clearly demonstrated the temporary nature of phytotoxic water-soluble compounds associated with killed volunteer canola and barley seedlings in Canada and their potential impacts on subsequent crops. The potential impact of short-term application of p-hydroxybenzoic acid to spring barley was demonstrated by Christen and Lovett (1993) causing yield reductions up to 20%. Sieling et al. (2005) used a *Lemna* bioassay on soil extracts from different crop sequences to suggest a possible role for allelochemicals in reduced growth of wheat in a wheat–wheat sequence, however other causes could not be ruled out. Allelopathy remains a plausible mechanism by which previous crops may influence wheat growth, but the challenge remains to definitively separate and quantify allelopathic effects from other impacts of retained residues in the field including increases in soil-borne pathogens (Cook and Hagland, 1991), or the changes in the microclimate of emerging seedlings (Bruce et al., 2006).

Weed control considerations strongly determine crop sequence choices for primary producers in many farming systems; particularly where resistance to herbicides has developed. There is no doubt that weeds within or following preceding crops can affect following cereal crops via hosting of common diseases, or utilisation of water and nutrients (Stevenson and van Kessel, 1996). In most small-plot experiments weeds are carefully controlled to avoid their confounding effects on crop response, however at a paddock scale where such complete weed control is rarely economic, they are likely to play a significant role. Recently it has also become apparent that the residual herbicides applied to control weeds in different break crops may influence subsequent cereal crops, a phenomenon which is primarily influenced by the seasonal effects on herbicide break-down rates and on soil pH. For example triazine herbicides applied to lupin or canola crops can persist on alkaline soils, especially if there is a late start to the season reducing opportunities for break down. Imidazolinone tolerant (IT) canola varieties also present residue issues on acid

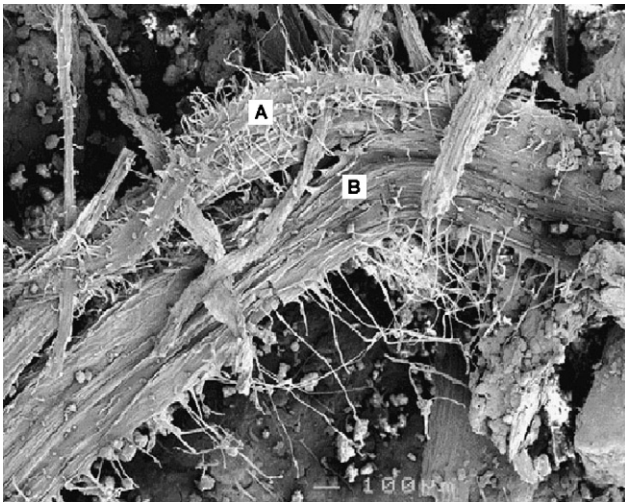


Fig. 2. Cryo-SEM image of (A) a wheat root 1 month after harvest, in close association with a root of a previous canola crop (B) within a structural biopore at a depth of 60 cm. Cryo-SEM allows visualisation of such intact associations of soil structure, biology and roots in field-grown samples providing insights which are lost in disturbed samples. Note residual root hairs extending from the old canola root to the biopore wall (at least 12 months since crop harvest), and the new wheat root emerging from, and in close association with the remnants of the old canola root. Recent estimates suggest 40–80% of subsoil roots are confined to these biopores (Image M McCully CSIRO Plant Industry, Canberra Australia).

soils in seasons with less than 250 mm rainfall as the herbicide requires soil moisture to facilitate microbial breakdown.

8. The “rotation” effect

Although in some studies the impacts of the key issues such as disease, water and N nutrition adequately account for break crop benefits (Cook, 1990; Kirkegaard et al., 2001), many other studies failed to identify the source of significant benefits, referring to a “rotation effect” as depicted in Fig. 1 as “R”. The previous sections of this review highlight the fact that in many cases, these inexplicable effects may simply be a result of straightforward but unmeasured parameters, as few studies are able to monitor all diseases, all nutrients, the water balance or their interactions. Often the impacts on the following wheat crop occur in transient but additive ways which defy measurement in many agronomic field studies. In other cases, measured parameters such as soil structure or allelopathy provide plausible explanations for some crop responses, but may involve indirect measurements which are poorly correlated with plant response in the field. In this regard, farming systems research embracing multidisciplinary approaches in the investigation of crop sequence is likely to provide useful information on interactions of well understood biological process, while new techniques which focus on field-based assessments of less well defined changes in soil biology, structure and allelochemicals will continue to shed light on these mechanisms.

9. Environmental benefits of break crops

There are several potential environmental benefits arising from integrating appropriate break crops into the farming system, and in many cases these occur together with the grain yield and quality benefits already discussed. In semi-arid systems, in which the break crop is introduced to replace fallow, the major benefits arise in the more efficient use of water, reduced risk of deep drainage, maintenance of soil cover and reduced erosion risk (Tanaka et al., 1997; Johnston et al., 2002). Foremost among the benefits in wetter areas are the improved nutrient (existing and applied) and water use efficiency arising from the lower levels of crop disease (Cook, 1986). Deeper and healthier root systems of more vigorous wheat crops following break crops use around 20–30 mm more water and 30–40 kg/ha N from the subsoil below 1 m, reducing the risk of deep drainage and N leaching and the resultant salinisation and acidification risk as well as improving efficiency of fertiliser nitrogen use (Kirkegaard et al., 1994; Angus et al., 2001). Break crops also facilitate the adoption of conservation farming systems as they do not carry-over stubble-borne diseases, and the residual stubble loads are generally lower than cereals which presents fewer problems for the sowing operations of following crops. Some break crops may leave very low residue levels (e.g. field pea) which can increase the risk of wind or water erosion particularly if grazed by sheep. The N benefits of legume break crops are often considered to constitute an environmental benefit in that they replace an N input (fertiliser) which must otherwise be sourced from non-renewable resources (Evans et al., 2001). Conversely, rapid mineralisation of legume N can pose a risk of groundwater pollution if not synchronised with crop demand, an outcome potentially under more control for fertiliser N sources. Several recent comprehensive reviews have considered the relative environmental benefits of N derived from legumes with that derived from N fertiliser with respect to a range of issues including energy demand, global warming, and various N-loss processes (Crews and Peoples, 2004; Lemke et al., 2007; Peoples et al., 2008). In general it appears the major environmental benefit of legume-derived N compared with fertiliser N in rain-fed farming systems derives from a more favourable energy balance, as loss processes

and greenhouse gas emissions are similar or only marginally different between the two N sources. Of more obvious importance is the considerable scope to improve the efficiency of use from both N-sources at the farm scale from the 40% to 50% currently achieved to the 80% often reported in small-scale research plots (Peoples et al., 2008). In some farming systems, break crops can also have unforeseen environmental benefits. For example the introduction of canola into the mixed farming systems on acidic soils of south eastern Australia also brought with it an unexpected benefit in the fight against soil acidity, the most serious threat to sustainable production in that area. Liming was essential for the successful growth of canola, and the crop response paid for the lime in the same year providing a longer term benefit to the farming system as a whole. Increasing soil pH also facilitated better growth and establishment of lucerne into the farming system which provides more effective whole-of-rotation water use. Although in general, most broadleaf break crops require greater application of a range of pesticides than wheat, the potential environmental threats posed by these chemicals seem to be minor when compared with the combined immediate threats of acidity, salinity, inefficient N use and soil erosion, which typify poorly managed cereal monocultures in some areas.

10. Scaling issues and adoption

Much of the knowledge regarding break crop benefits has come from replicated field experiments using small plots. Some studies have investigated how well this translates to responses at a paddock scale. In a Canadian study, Bourgeois and Entz (1996) investigated the effect of previous crops on wheat yield using appropriate analysis of a crop database for the years 1982–1993. Wheat yield was increased by preceding flax (16%), pea (11%) and canola crops (8%) compared to wheat after wheat or barley and the overall responses suggested that rotational benefits recorded in small-plot rotation trials are also observed in commercial paddocks. Similar paddock-scale database analysis in Australia by Mead (1992) also reflected the trends in responses observed in smaller experimental plots. Exceptions to this observation may arise where wind-borne fungal diseases, which may spread easily within small plots, are a key driver of the yield response. For example Stevenson and van Kessel (1996) showed that there was a 17% greater response of wheat to a preceding pea crop at a landscape scale than at the small-plot scale, partly due to the involvement of a *Septoria* leaf disease complex which spread more readily between different treatments in the small-plot experiment.

The list of potential impacts of crop sequence on crop performance and sustainability make the task of planning optimum crop sequences formidable, and suggest a role for computer-based decision support systems. Although the use of information technology by producers to date has been modest, changing circumstances will increase the producers demand for products supporting their management practices, particularly if it is economically beneficial (Thyssen, 2000). Programs have been developed to generate possible crop rotations to support sustainable small-holder farming systems in southern Uruguay (Dogliotti et al., 2003), and a system was also designed to help producers select the best combination of crops for dryland farming in Australia (Tennakoon and Bell, 1998). Recently, researchers produced a crop sequence calculator (CSC) for producers in the northern Great Plains of the USA (Fehmi et al., 2001; Krupinsky et al., 2003, available at <http://www.mandan.ars.usda.gov>). The CSC requires only basic computer knowledge and can present the short-term experimental crop production effects of the 10 crops grown in any 2-year combination. Once the previous crop (residue producing crop) and the expected crop are entered, summary

statements appear for crop production, economics, plant diseases, soil water, weeds, soil surface properties, and insects. Supplemental information, including photographs of weeds, plant diseases, and insects is easily accessed. The distribution of over 9000 copies indicates that this technology fulfills a substantial need for integrated information within the agricultural community. However the transferability of these decision aids, and the inevitable variation in crop responses discussed throughout this review (and exemplified in Table 1 and Fig. 1), highlight the challenge in developing reliable and robust decision aids for cropping sequence advice which can be applied in a paddock-specific way. At a broader scale, assessing the impact of crop sequence and other management decisions on aspects of whole-farm operations and off-site effects is an emerging field in agronomy (Christen, 1999). Some approaches are more focused on the effect of farming systems on pesticide use and biodiversity (Reus et al., 2002) or soil conditions (Sands and Podmore, 2000) while other systems try to incorporate diverse aspects such as energy and material flows as well as nutrient balances and effects on fauna, flora and soil conditions (Kalk et al., 1998; Hülsbergen et al., 2001; Christen and Hülsbergen, 2003). The consideration of interactions among various indicators used for optimisation at the farm level is crucial in these systems as in the REPRO approach developed at the university of Halle-Wittenberg (Hülsbergen et al., 2001). For example, if the indicator “nitrogen balance” gives a high positive result, the solution to apply less nitrogen may be inappropriate if the high nitrogen balance is the result of low yield caused by suboptimal application of pesticides. The correct action would be to improve pesticide management rather than reduce N use. If the optimisation of husbandry, fertilizer or pesticide management at the farm level is the target, such interactions must be considered. Thus, at paddock, whole-farm and regional scales computer-assisted technologies can provide insights to assist decision making, but cannot replace the need for considerable interpretation of specific circumstances by experienced locals.

Recent economic analysis in both Australia and North America suggest that adoption of more diverse and dynamic crop sequences including cereal and pulse crops can contribute to higher and more stable net farm income despite a requirement for increased expenditures on purchased inputs (Zentner et al., 2002). The good economic performance results from production of higher-valued crop types (which can more than offset the higher production costs) and the break crop benefits that often accompany the mixed cropping systems. Diversified crop sequences showed good economic and risk performance under most price scenarios and where relevant, are compliant with Government farm policies. Further adoption may be limited by markets and/or low or variable prices for oilseeds and pulses, or a lack of suitable adapted break crop species for some of the areas where cereal monoculture remains the most viable production system.

References

- Angus, J.F., van Herwaarden, A.F., Howe, G.N., 1991. Productivity and break-crop effect of winter-growing oilseeds. *Aust. J. Exp. Agric.* 31, 669–677.
- Angus, J.F., Gardner, P.A., Kirkegaard, J.A., Desmarchelier, J.M., 1994. Biofumigation: isothiocyanates released from *Brassica* roots inhibit the growth of the take-all fungus. *Plant Soil* 162, 107–112.
- Angus, J.F., Kirkegaard, J.A., Peoples, M.B., 2001. Rotation, sequence and phase: research on crop and pasture systems. Proceedings of the 10th Australian Agronomy Conference, www.regional.org.au/au/asa/2001/plenery/4/angus.htm.
- Arp, D.J., 1992. In: Stacey, R.H., et al. (Eds.), *Biological Nitrogen Fixation*. Chapman & Hall, New York, pp. 432–460.
- Arshad, M.A., Soon, Y.K., Azooz, R.H., 2002. Modified no-till and crop sequence effects of spring wheat production in northern Alberta Canada. *Soil Till. Res.* 65, 29–36.
- Bailey, K.L., Gossen, B.D., Derksen, D.A., Watson, P.R., 2000. Impact of agronomic practices and environment on disease of wheat and lentil in southeastern Saskatchewan. *Can. J. Plant Sci.* 80, 917–927.
- Bailey, K.L., Gossen, B.D., Lafond, G.P., Watson, P.R., Derksen, D.A., 2002. Effect of tillage and crop rotation on root and foliar diseases of wheat and pea in Saskatchewan from 1991 to 1998: univariate and multivariate analyses. *Can. J. Plant Sci.* 81, 789–803.
- Beckie, H.J., Brandt, S.A., 1997. Nitrogen contribution of field pea in annual cropping systems. 1. Nitrogen residual effect. *Can. J. Plant Sci.* 77, 311–322.
- Beckie, H.J., Brandt, S.A., Schoenau, J.J., Campbell, C.A., Henry, J.L., Janzen, H.H., 1997. Nitrogen contribution of field pea in annual cropping systems. 2. Total nitrogen benefit. *Can. J. Plant Sci.* 77, 323–331.
- Bourgeois, L., Entz, M.H., 1996. Influence of previous crop type on yield of spring wheat: analysis of commercial field data. *Can. J. Plant Sci.* 76, 457–459.
- Bowen, G.D., Rovira, A.D., 1999. The rhizosphere and its management to improve plant growth. *Adv. Agron.* 66, 1–102.
- Brennan, R.F., Bolland, M.D.A., Bowden, J.W., 2004. Potassium deficiency, and molybdenum deficiency and aluminium toxicity due to soil acidification have become problems for cropping sandy soils in south-western Australia. *Aust. J. Exp. Agric.* 44, 1031–1039.
- Bruce, S.E., Kirkegaard, J.A., Pratley, J., Howe, G., 2006. Growth suppression of canola through wheat stubble. I. Separating physical and biochemical causes in the field. *Plant Soil* 281, 203–218.
- Chalk, P.M., 1998. Dynamics of biologically fixed N in legume-cereal rotations: a review. *Aust. J. Agric. Res.* 49, 303–316.
- Chan, K.Y., Heenan, D.P., 1996. The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil Till. Res.* 37, 113–125.
- Christen, O., 1999. Sustainable Agriculture—From the History of Ideas to Practical Application. Institut für Landwirtschaft und Umwelt, Bonn.
- Christen, O., Hülsbergen, K.J., 2003. Environmental assessment of oilseed rape cropping systems. In: Proceedings of the 11th International Rapeseed Congress, Copenhagen, Denmark, pp. 820–821.
- Christen, O., Lovett, J.V., 1993. Effects of a short term p-hydroxybenzoic acid application on grain yield and yield components in different tiller categories of spring barley. *Plant Soil* 151, 279–286.
- Christen, O., Sieling, K., Hanus, H., 1992. The effect of different preceding crops on the development, growth and yield of winter wheat. *Eur. J. Agron.* 1, 21–28.
- Cook, R.J., 1986. Interrelationships of plant health and the sustainability of agriculture, with special reference to plant diseases. *Am. J. Altern. Agric.* 1, 19–24.
- Cook, R.J., 1990. Diseases caused by root-infecting pathogens in dryland agriculture. *Adv. Soil Sci.* 13, 214–239.
- Cook, R.J., Hagland, W.A., 1991. Wheat yield depression associated with conservation tillage is caused by root pathogens in soil not phytotoxins from the straw. *Soil Biol. Biochem.* 23, 1125–1132.
- Cook, R.J., Schillinger, W.F., Christensen, N.W., 2002. *Rhizoctonia* root rot and take-all of wheat in diverse direct-seed spring cropping systems. *Can. J. Plant Pathol.* 24, 349–358.
- Cotterill, P.J., Sivasithamparam, K., 1988. Reduction of take-all inoculum by rotation with lupin, oats or field pea. *J. Phytopath.* 121, 125–134.
- Cresswell, H.P., Kirkegaard, J.A., 1995. Subsoil amelioration by plant roots—the process and the evidence. *Aust. J. Soil Res.* 33, 221–239.
- Crews, T.E., Peoples, M.B., 2004. Legume versus fertilizer sources of nitrogen: ecological tradeoffs and human needs. *Agric. Ecosys. Environ.* 102, 279–297.
- Delroy, N.D., Bowden, J.W., 1986. Effect of deep ripping, the previous crop, and applied nitrogen on the growth and yield of a wheat crop. *Aust. J. Exp. Agric.* 26, 469–479.
- Dogliotti, S., Rossin, W.A.H., van Ittersum, M.K., 2003. ROTAT, a tool for systematically generating crop rotations. *Eur. J. Agron.* 19, 239–250.
- Dong, Z., Wu, L., Kettlewell, B., Caldwell, C.D., Layzell, D.B., 2003. Hydrogen fertilization of soils—is this a benefit of legumes in rotation? *Plant Cell Environ.* 26, 1875–1879.
- Evans, J., Herridge, D.F., 1987. In: Bacon, P.E., Evans, J., Storrier, R.R., Taylor, A.C. (Eds.), *Nitrogen Inputs and Utilisation in Crop Legumes in Nitrogen Cycling in Temperate Agricultural Systems*. Aust. Soc. Soil Sci. Inc., pp. 14–43.
- Evans, J., Fettel, N.A., Coventry, D.R., O'Connor, G.E., Walscott, D.N., Mahoney, J., Armstrong, E.L., 1991. Wheat response after temperate crop legumes in south-eastern Australia. *Aust. J. Agric. Res.* 42, 31–43.
- Evans, J., McNeill, A.M., Unkovich, M.J., Fettel, N.A., Heenan, D.P., 2001. Net nitrogen balances for cool-season grain legume crops and contributions to wheat nitrogen uptake: a review. *Aust. J. Exp. Agric.* 41, 347–359.
- Evans, J., Scott, G., Lemerle, D., Kaiser, A., Orchard, B., Murray, G.M., Armstrong, E.L., 2003. Impact of legume “break” crops on the yield and grain quality of wheat and relationship with soil mineral N and crop N content. *Aust. J. Agric. Res.* 54, 777–788.
- Fehmi, J.S., Krupinsky, J.M., Tanaka, D.L., Merrill, S.D., Hendrickson, J.R., Ries, R.E., Liebigs, M.A., Hanson, J.D., 2001. A Crop Sequence Calculator for designing dynamic cropping systems: translating science into practice. No. 210215-P. In: Annual Meeting Abstracts, October 21–25, Charlotte, NC, ASA-SSSA-CSSA, Madison, WI.
- Gan, Y.T., Miller, P.R., McConkey, B.G., Zentner, R.P., Stevenson, F.C., McDonald, C.L., 2003. Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid northern Great Plains. *Agron. J.* 95, 245–252.
- Gardner, P.A., Angus, J.F., Pitson, G.D., Wong, P.T.W., 1998. A comparison of six methods to control take-all in wheat. *Aust. J. Agric. Res.* 49, 1225–1240.
- Gregory, P.J., 1998. Alternative crops for duplex soils: growth and water use of some cereal, legume and oilseed crops, and pastures. *Aust. J. Agric. Res.* 49, 21–32.

- Gubbels, G.H., Kenaschuk, E.O., 1989. Effect of spring seedling residues on the agronomic performance of subsequent flax and barley seeded with and without prior tillage. *Can. J. Plant Sci.* 69, 151–159.
- Gupta, V.V.S.R., Roget, D.K., Coppi, J.A., 2004. Identification of a previously unrecognized biological constraint to yield in sequential wheat crops. In: Proceedings of the 3rd Australasian Soilborne Disease Symposium, Ophel Keller, K.M. and Hall, B.H. (Eds) SARDI, Adelaide 2004 pp. 15–16.
- Halvorson, A.D., Peterson, G.A., Reule, C.A., 2002. Tillage system and crop rotation effects on dryland crop yields and soil carbon in the Central Great Plains. *Agron. J.* 94, 1429–1436.
- Harris, R.H., Scammell, G.J., Muller, W.J., Angus, J.F., 2002. Crop productivity in relation to species of previous crops and management of previous pasture. *Aust. J. Agric. Res.* 53, 1271–1283.
- Heenan, D.P., 1995. Effects of broad-leaf crops and their sowing time on subsequent wheat production. *Field Crops Res.* 43, 19–29.
- Herdina, Yang, H.A., Ophel-Keller, K., 1997. Correlation of take-all disease severity and inoculum level of *Gaeumannomyces graminis* var. *tritici* using a slot-blot hybridization assay. *Mycol. Res.* 101, 1311–1317.
- Hocking, P.J., 2001. Organic acids exuded from roots in phosphorus uptake and aluminium tolerance of plants in acid soils. *Adv. Agron.* 74, 63–97.
- Hocking, P.J., Randall, P.J., 2001. Better growth and phosphorus nutrition of sorghum and wheat following organic acid secreting crops. In: Horst, W.J., et al. (Eds.), Proceedings of the 14th International Plant Nutrition Colloquium Germany. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 548–549.
- Hülsbergen, K.J., Feil, B., Biermann, S., Rathke, G.W., Kalk, W.D., Diepenbrock, B., 2001. A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agric. Ecosys. Environ.* 86, 303–321.
- Johnston, A.M., Tanaka, D.L., Miller, P.R., Brandt, S.A., Nielsen, D.C., Lafond, G.P., Riveland, N.R., 2002. Oilseed crops for semi-arid cropping systems in the northern Great Plains. *Agron. J.* 94, 231–240.
- Kalk, W.D., Hülsbergen, K.J., Biermann, S., 1998. Management-related material and energy balances for the rating of production intensity and environmental acceptability of land use. *Arch. Acker Pfl. Boden.* 43, 167–182.
- Karlen, D.L., Varvel, G.E., Bullock, D.G., Cruse, R.M., 1994. Crop rotations for the 21st century. *Adv. Agron.* 53, 1–45.
- Kay, B.D., 1990. Rates of change of soil structure under different cropping systems. *Adv. Soil Sci.* 12, 1–52.
- Khan, D.F., Peoples, M.B., Schwenke, G.D., Felton, W.L., Chen, D., Herridge, D.F., 2003. Effects of below ground nitrogen on N balances of field grown fababean, chickpea and barley. *Aust. J. Agric. Res.* 54, 333–340.
- Kirkegaard, J.A., Gardner, P.A., Angus, J.F., Koetz, E., 1994. Effect of *Brassica* break crops on the growth and yield of wheat. *Aust. J. Agric. Res.* 45, 529–545.
- Kirkegaard, J.A., Hocking, P.J., Angus, J.F., Howe, G.N., Gardner, P.A., 1997. Comparison of canola Indian mustard and Linola in two contrasting environments. II. Break-crop and nitrogen effects on subsequent wheat crops. *Field Crops Res.* 52, 179–191.
- Kirkegaard, J.A., Howe, G.N., Mele, P., 1999. Enhanced accumulation of mineral-N following canola. *Aust. J. Exp. Agric.* 39, 587–593.
- Kirkegaard, J.A., Sarwar, M., Wong, P.T.W., Mead, A., Howe, G., Newell, M., 2000. Field studies on the biofumigation of take-all by *Brassica* break crops. *Aust. J. Agric. Res.* 51, 445–456.
- Kirkegaard, J.A., Howe, G.N., Pitson, G., 2001. Agronomic interactions between drought and crop sequence. In: Proceedings of the 10th Australian Agronomy Conference Hobart.
- Kirkegaard, J.A., Simpfendorfer, S., Holland, J., Bambach, R., Moore, K.J., Rebetzke, G.J., 2004. Effect of previous crops on crown rot and yield of durum and bread wheat in northern NSW. *Aust. J. Agric. Res.* 55, 321–334.
- Kollmorgen, J.F., Griffiths, J.B., Walscott, D.N., 1983. The effects of various crops on the survival and carry-over of the wheat take-all fungus *Gaeumannomyces graminis* var. *tritici*. *Plant Pathol.* 32, 73–77.
- Krupinsky, J.M., Tanaka, D.L., Merrill, S.D., Liebig, M.A., Hendrickson, J.R., Anderson, R.L., Hanson, J.D., Ries, R.E., 2002. Crop sequences influence crop seed production and plant diseases. In: Proceedings of the 24th annual Manitoba-North Dakota Zero Tillage Farmers Association Workshop, Minot, North Dakota, January 29–30, pp. 13–19.
- Krupinsky, J.M., Tanaka, D.L., Hanson, J.D., Merrill, S.D., Liebig, M.A., Hendrickson, J.R., 2003. Dynamic cropping systems and the distribution of research information: crop sequence calculator. In: Hanson, J.D., Krupinsky, J.M. (Eds.), Proceedings of the Dynamic Cropping Systems: Principles, Processes, and Challenges. Bismarck, ND, pp. 174–178.
- Krupinsky, J.M., Tanaka, D.L., Lares, M.T., Merrill, S.D., 2004. Leaf spot diseases of barley and spring wheat as influenced by preceding crops. *Agron. J.* 96, 259–266.
- Krupinsky, J.M., Tanaka, D.L., Merrill, S.D., Liebig, M.A., Hanson, J.D., 2006. Crop sequence effects of 10 crops in the northern Great Plains. *Agric. Syst.* 88, 227–254.
- Larney, F.J., Lindwell, C.W., 1995. Rotation and tillage effects on available soil water for winter wheat in a semi arid environment. *Soil Till. Res.* 36, 111–127.
- Leather, G.R., Einhellig, F.A., 1986. Bioassays in the study of allelopathy. In: Putnam, A.R., Tang, C.S. (Eds.), *The Science of Allelopathy*. Wiley and Sons, New York, pp. 133–145.
- Lemke, R.L., Zhong, Z., Campbell, C.A., Zentner, R., 2007. Can pulse crops play a role in mitigating greenhouse gases from North American agriculture. *Agron. J.* 99, 1719–1725.
- Lupwayi, N.Z., Kennedy, A.C., 2007. Grain legumes in the Northern Great plains: impacts on selected biological soil processes. *Agron. J.* 99, 1700–1709.
- McCallum, M.H., Kirkegaard, J.A., Green, T.W., Cresswell, H.P., Davies, S.L., Angus, J.F., Peoples, M.B., 2004. Improved subsoil macroporosity following perennial pastures. *Aust. J. Exp. Agric.* 44, 299–307.
- McCully, M.E., Shane, M.W., Baker, A.N., Huang, C.X., Ling, L.E.C., Canny, M.J., 2000. The reliability of cryosem for the observation and quantification of xylem embolisms and quantitative analysis of xylem sap in situ. *J. Microsc.* 198, 24–33.
- McEwen, J., Darry, R.J., Hewitt, M.V., Yeoman, D.P., 1989. Effects of field beans, fallow, lupins, oats, oilseed rape, peas, ryegrass, sunflowers and wheat on nitrogen residues in soil and on the growth of a subsequent wheat crop. *J. Agric. Sci. (Cambridge)* 115, 209–219.
- Mead, J.A., 1992. Rotations and farming systems—the current situation. In: Murray, G.M., Heenan, D.P. (Eds.), *Rotations and Farming Systems*. NSW Agriculture, Wagga Wagga, NSW, pp. 5–10.
- Miller, P.R., Holmes, J.A., 2005. Cropping sequence effects of four broadleaf crops on four cereal crops in the northern Great Plains. *Agron. J.* 97, 189–200.
- Miller, P.R., Waddington, J., McDonald, C., Derksen, D.A., 2002. Cropping sequence affects wheat productivity on the semiarid northern Great Plains. *Can. J. Plant Sci.* 82, 307–318.
- Miller, P.R., Gan, Y., McConkey, B.G., McDonald, C.L., 2003. Pulse crops for the northern Great Plains. II. Cropping sequence effects on cereal, oilseed, and pulse crops. *Agron. J.* 95, 980–986.
- Nielsen, D.C., Vigil, M.F., Anderson, R.L., Bowman, R.A., Benjamin, J.G., Halvorson, A.D., 2002. Cropping system influence on planting water content and yield of winter wheat. *Agron. J.* 94, 962–967.
- Norwood, C.A., 2000. Dryland winter wheat as affected by previous crops. *Agron. J.* 92, 121–127.
- Olofsson, S., 1993. Influence of preceding crop and crop residues on stand and yield of winter wheat (*Triticum aestivum* L.) in different tillage systems, including zero tillage. *Crop Prod. Sci.* 18 Swedish University of Agricultural Science.
- Panse, A., Mavid, F.X., Dennert, J., Brunner, H., Fishbeck, G., 1994. Ertragsbildung von getreidereichen Fruchtfolgen und Getreidemonokulturen in einem extensiven und intensiven Anbausystem. *J. Agron. Crop Sci.* 173, 160–171.
- Passioura, J.B., 2002. Soil conditions and plant growth. *Plant Cell Environ.* 25, 311–318.
- Peoples, M.B., Craswell, E.T., 1992. Biological nitrogen fixation: investments, expectations and actual contributions to agriculture. *Plant Soil* 141, 13–39.
- Peoples, M.B., Herridge, D.F., Ladha, J.K., 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production? *Plant Soil* 174, 3–28.
- Peoples, M.B., Hauggaard-Nielsen, H., Jensen, E.S., 2008. The potential environmental benefits and risks derived from legumes in rotations. In: Emerich, D.W., Krishnan, H.B. (Eds.), *Nitrogen Fixation in Crop Production*, ASA, CSSA, SSSA (2008).
- Pierret, A., Moran, C.J., Pankhurst, C.E., 1999. Differentiation of soil properties related to the spatial association of wheat roots and soil macropores. *Plant Soil* 211, 51–58.
- Prew, R.D., Beane, J., Carter, N., Church, B.M., Dewar, A.M., Lacey, J., Penny, A., Plumb, R.T., Thorne, G.N., Todd, A.D., 1986. Some factors influencing the growth and yield of winter wheat grown as a third cereal with much or negligible take-all. *J. Agric. Sci. Cambridge* 107, 639–671.
- Purvis, C.E., 1990. Differential response of wheat to retained crop stubbles. I. Effect of stubble type and degree of decomposition. *Aust. J. Agric. Res.* 41, 225–242.
- Reeves, T.G., Ellington, A., Brooke, H.D., 1984. Effect of lupin-wheat rotations on soil fertility, crop disease and crop yields. *Aust. J. Exp. Agric. Anim. Hus.* 24, 595–600.
- Reus, J., Leendertse, P., Bockstaller, C., Fomsgaard, I., Gutsche, V., Lewis, K., Nilsson, C., Pussemier, L., Trevisan, M., Van der Werf, H., Alfaro, F., Blümel, S., Isart, J., McGrath, D., Seppälä, T., 2002. Comparison and evaluation of eight pesticide environmental risk indicators developed in Europe and recommendations for future use. *Agric. Ecosys. Environ.* 90, 177–187.
- Rovira, A.D., Elliot, L.F., Cook, R.J., 1990. The impact of cropping systems on rhizosphere organisms affecting plant health. In: Lynch, J.M. (Ed.), *The Rhizosphere*. Wiley, Chichester, UK, pp. 389–436.
- Rowland, I.C., Mason, M.G., Hamblin, J., 1988. Effect of lupins and wheat on the yield of subsequent wheat crops grown at several rates of applied nitrogen. *Aust. J. Exp. Agric.* 28, 91–97.
- Rumberger, A., Marschner, P., 2003. 2-Phenylethylisothiocyanate concentration and microbial community composition in the rhizosphere of canola. *Soil Biol. Biochem.* 35, 445–452.
- Rumberger, A., Marschner, P., 2004. 2-Phenylethylisothiocyanate concentration and microbial community composition in the rhizosphere of field-grown canola. *Funct. Plant Biol.* 31, 623–631.
- Ryan, M.H., Angus, J.F., 2003. Arbuscular mycorrhizae in wheat and field pea crops on low P soil: increased Zn-uptake but no increase in P-uptake or yield. *Plant Soil* 250, 225–239.
- Ryan, M.H., Graham, J.H., 2002. Is there a role for arbuscular mycorrhizal fungi in production agriculture? *Plant Soil* 244, 263–271.
- Ryan, M.H., van Herwaarden, A.F., Angus, J.F., Kirkegaard, J.A., 2005. Reduced growth of autumn-sown wheat in a low P soil is associated with high colonisation by arbuscular mycorrhizal fungi. *Plant Soil* 270, 275–286.
- Ryan, M.H., Norton, R.M., Kirkegaard, J.A., McCormick, K.M., Knights, S.E., Angus, J.F., 2002. Increasing mycorrhizal colonisation does not improve growth and nutrition of wheat on Vertosols in south-eastern Australia. *Aust. J. Agric. Res.* 53, 1173–1181.
- Ryan, M.H., Kirkegaard, J.A., Angus, J.F., 2006. *Brassica* crops stimulate soil mineral N accumulation. *Aust. J. Soil Res.* 44, 367–377.

- Sands, G.R., Podmore, T.H., 2000. A generalized environmental sustainability index for agricultural systems. *Agric. Ecosys. Environ.* 79, 29–41.
- Sarwar, M., Kirkegaard, J.A., Wong, P.T.W., Desmarchelier, J.M., 1998. Biofumigation potential of brassicas. III. In vitro toxicity of isothiocyanates to soil-borne fungal pathogens. *Plant Soil* 201, 103–112.
- Schönhammer, A., Fischbeck, G., 1987a. Investigations on cereal crop rotations and monocultures. I. Differences in yield under 15 rotations. *Bayerisches Landwirt. Jahrb.* 64, 175–191.
- Schönhammer, A., Fischbeck, G., 1987b. Investigations on cereal crop rotations and monocultures. III. Changes in soil properties. *Bayerisches Landwirt. Jahrb.* 64, 681–694.
- Schultz, J.E., 1995. Crop production in a rotation trial at tarlee South Australia. *Aust. J. Exp. Agric.* 35, 865–876.
- Sieling, K., Stahl, C., Winkelmann, C., Christen, O., 2005. Growth and yield of winter wheat in the first three years of a monoculture under varying N fertilisation in NW Germany. *Eur. J. Agron.* 22, 71–84.
- Simpfendorfer, S.A., Kirkegaard, J.A., Heenan, D.P., Wong, P.T.W., 2002. Reduced early growth of direct-drilled wheat in southern New South Wales—role of root inhibitory *Pseudomonads*. *Aust. J. Agric. Res.* 53, 323–331.
- Smiley, R.W., Ingham, R.E., Uddin, W., Cook, G.H., 1994. Crop sequences for managing cereal cyst nematode and fungal pathogens of winter wheat. *Plant Dis.* 78, 1142–1149.
- Smiley, R.W., Collins, H.P., Rasmussen, P.E., 1996. Diseases of wheat in long-term agronomic experiments at Pendleton. *Oregon. Plant Dis.* 80, 813–820.
- Smith, B.J., Kirkegaard, J.A., Howe, G.N., 2004. Impacts of *Brassica* break crops on soil biology and yield of following wheat crops. *Aust. J. Agric. Res.* 55, 1–11.
- Soon, Y.K., Clayton, G.W., 2002. Eight years of crop rotation and tillage effects on crop production and N fertilizer use. *Can. J. Soil Sci.* 82, 165–172.
- Soon, Y.K., Clayton, G.W., Rice, W.A., 2001. Tillage and previous crop effects on dynamics of nitrogen in a wheat-soil system. *Agron. J.* 93, 842–849.
- Stevenson, F.C., van Kessel, C., 1996. A landscape-scale assessment of the nitrogen and non-nitrogen rotation benefits of pea. *Soil Sci. Soc. Am. J.* 60, 1797–1805.
- Tanaka, D.L., Bauer, A., Black, A.L., 1997. Annual legume cover crops in spring wheat-fallow systems. *J. Prod. Agric.* 10, 251–255.
- Tang, C.S., Waiss, A.C., 1978. Short-chain fatty acids as growth inhibitors in decomposing wheat straw. *J. Chem. Ecol.* 4, 225–232.
- Tennakoon, S.B., Bell, C.J., 1998. DACS: a knowledge-based decision support system for dryland agriculture crop sequencing. In: *Proceedings of the 9th Australian Agronomy Conference*, Wagga Wagga.
- Thompson, J.P., Owen, K.J., Clewett, T.G., 2001. Pre-cropping with canola decreases vesicular-arbuscular mycorrhiza and growth of wheat in low P soil. In: *Proceedings of the 2nd Australasian Soil-Borne Root Disease Symposium Lorne 2001*. pp. 150–151.
- Thyssen, I., 2000. Agriculture in the information society. *J. Agric. Eng. Res.* 76, 297–303.
- Van Herwaarden, A.F., Farquar, G.D., Angus, J.F., Richards, R.A., Howe, G.N., 1998. "Haying-off", the negative grain yield response of dryland wheat to nitrogen fertilizer. I. Biomass, grain yield and water use. *Aust. J. Agric. Res.* 49, 1067–1081.
- Van Kessel, C., Hartley, C., 2000. Agricultural management of grain legumes: has it led to an increase in nitrogen fixation? *Field Crop Res.* 65, 165–181.
- Walley, F.L., Clayton, G.W., Miller, P.R., Carr, P.M., Lafond, G.P., 2007. Nitrogen economy of pulse crop production in the Northern Great Plains. *Agron. J.* 99, 1710–1718.
- Watt, M., McCully, M.E., Kirkegaard, J.A., 2003. Soil strength and rate of root elongation alter the accumulation of *Pseudomonas* spp. and other bacteria in the rhizosphere of wheat. *Funct. Plant Biol.* 30, 483–491.
- Watt, M., Kirkegaard, J.A., Rebetzke, G.J., 2005. A wheat genotype developed for rapid leaf growth copes well with the physical and biological constraints of unploughed soil. *Funct. Plant Biol.* 32, 695–706.
- Watt, M., Hugenholz, P., White, R., Vinall, K., 2006a. Numbers and locations of native bacteria on field grown wheat roots quantified by fluorescence *in situ* hybridization (FISH). *Environ. Microbiol.* 71, 1291–1299.
- Watt, M., Kirkegaard, J.A., Passioura, J.B., 2006b. Rhizosphere biology and crop productivity: a review. *Aust. J. Soil Res.* 44, 299–317.
- Widdowson, F.V., Penny, A., Gutteridge, R.J., Darby, R.J., Hewitt, M.V., 1985. Tests of amounts and times of application of nitrogen and sequential sprays of aphicides and fungicides on winter wheat, and effects on take-all (*Gaeumannomyces graminis* var. *tritici*) on two varieties at Saxmundham Suffolk 1980–3. *J. Agric. Sci. (Cambridge)* 105, 97–122.
- Wilson, J.M., Hamblin, J., 1990. The effects of fumigation, rotation with lupins and nitrogen application on plant growth and common root rot of wheat at Geraldton Western Australia. *Aust. J. Agric. Res.* 41, 619–631.
- Wright, A.T., 1990. Yield effect of pulses on subsequent cereal crops in the northern prairies. *Can. J. Plant. Sci.* 70, 1023–1032.
- Wright, S.F., Anderson, R.L., 2000. Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. *Biol. Fert. Soils* 31, 249–253.
- Zentner, R.P., Campbell, C.A., Biederbeck, V.O., Miller, P.R., Selles, F., Fernandez, M.R., 2001. In search of a sustainable cropping system for the semiarid Canadian prairies. *J. Sust. Agric.* 18, 117–136.
- Zentner, R.P., Wall, D.D., Nagy, C.N., Smith, E.G., Young, D.L., Miller, P.R., Campbell, C.A., McConkey, B.G., Brandt, S.A., Lafond, G.P., Johnson, A.M., Derksen, D.A., 2002. Economics of crop diversification and soil tillage opportunities in the Canadian prairies. *Agron. J.* 94, 216–230.
- Zhu, Y.G., He, Y.Q., Smith, S.E., Smith, F.A., 2002. Buckwheat (*Fagopyrum esculentum* Moench) has high capacity to take up phosphorus (P) from a calcium (Ca)-bound source. *Plant Soil* 239, 1–8.