

Break crop benefits in temperate wheat production

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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 yield benefits of up to 20% or more. Much is known about the key 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.

Media summary

Break crops underpin sustained yield improvements in dryland wheat crops throughout the world. New technologies assist our understanding of the processes involved and how to apply them on farms.

Key Words

disease, structure, soil biology, sequence, rotation, preceding crop

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 deliberately avoid detailed consideration of the longer term effects of set crop rotations, but focus on the more immediate impacts of preceding crops on subsequent wheat.

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. In northern Europe, the average yield response is around 20 % but ranges from -7 % to 57 % in individual studies (Prew et al. 1986; McEwen et al. 1989; Christen et al. 1992; Sieling et al. 2004). A compilation of data from 26 experiments in southern Australia showed the average

yield benefit following canola was also 20%, but varied from -16 % to 197 % (Angus et al. 2001). In different areas of North America the average yield response of wheat to a previous break crop also falls close to 20% (Arshad et al. 2002; Krupinsky et al. 2002; Miller et al. 2002, 2003; Smiley et al. 1994, 1996; Soon and Clayton 2002), although responses can range from -10 % (Cook et al. 2002) to 62% (Stevenson and vanKessel 1996). Responses are notably less reliable and generally smaller in semi-arid areas (Gan et al. 2003; Zentner et al. 2001) and may be negative where break crops replace fallow. 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). 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”.

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 (eg *Rhizoctonia solani*, Cook et al. 2003) 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.

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 (Kollmorgen et al. 1983; Kirkegaard et al. 1994; Gardner et al. 1998), and averages 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 Figure 1a. The magnitude of the disease effect (D) 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. In some cases the disease reduction can extend beyond the first year and result in yield benefits in a second successive wheat crop (13% reported by Kirkegaard et al. 1997). For many diseases including take-all, seasonal conditions dictate the extent to which disease influences crop growth, as inoculum survival, pathogen infection and disease expression are influenced by rainfall patterns.

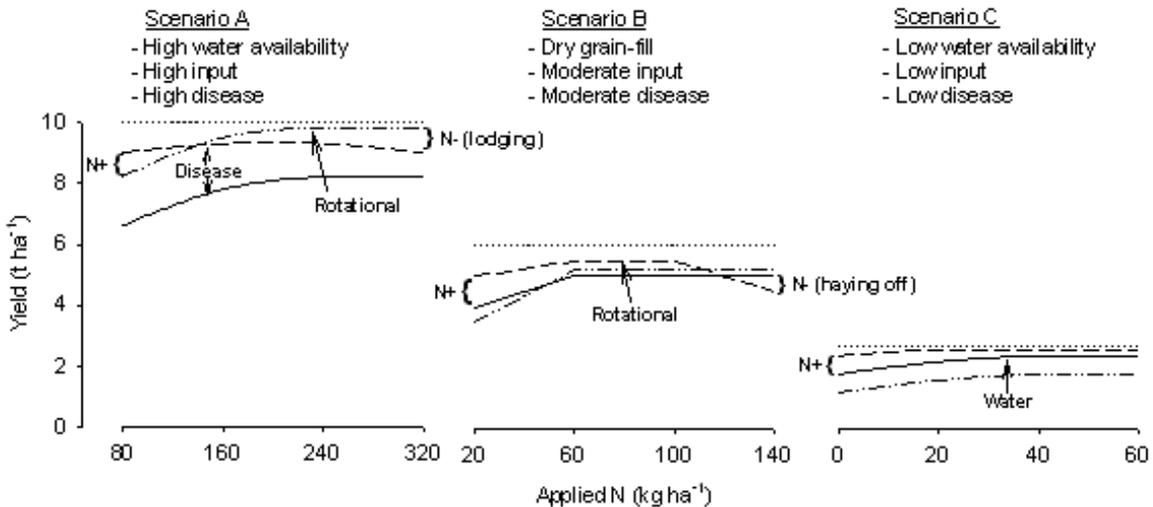


Figure 1. Typical response of wheat to previous wheat (solid), legume (dashed) and oilseed (dot-dash) break crops under different scenarios. The dotted line shows the potential yield. The mechanisms causing responses to differ between previous crops are shown (N = nitrogen, +/- denotes yield increase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

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 Figure 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 – 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-B² 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 Figure 1a and 1b, depending on seasonal conditions and disease development.

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) it appears these effects do not persist to influence the levels of disease on wheat in a subsequent season.

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 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 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 Sch?nhammer and Fischbeck (1987) and Sieling et al. (2004) concluded that only minor parts of the 10 – 25% wheat response to previous rapeseed crops (similar to those shown in Figure 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.

Residual water and nutrients

Residual nitrogen

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. Clearly the disease-break benefits of legume crops can be as important as the N benefits, as represented in Figure 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. 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” are generally thought to overestimate the N benefits of legumes (Chalk 1998; Peoples and Craswell 1992), 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). 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 (spared 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 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. Generally the N benefits of the legume break crops

are evident at lower rates of applied fertiliser N (shown as N⁺ in Figure 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 C:N ratio of the residues (Kirkegaard et al. 1999). Too much residual N can also reduce the yield of subsequent cereals. 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 Figure 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 "haying 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 Figure 1b following legumes at higher rates of applied N. The distribution of residual N within the profile following break crops may also influence both the yield and protein content of subsequent wheat crops (Evans et al. 2003).

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. The persistence of these effects and the magnitude of yield benefits to following cereals 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).

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. 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 19.9% and 9.9%, respectively compared with corn or sorghum. Nielson et al. (2002) showed that increasing cropping intensity to two crops in three years had little impact on 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 Lindwall (1995) found that the starting available soil water content at the establishment of winter wheat was least after canola (45mm), followed by continuous wheat (59mm), lentils/linseed (74mm) and fallow (137mm). The impact of these differences in residual water on subsequent wheat crops in semi-arid environments is depicted in Figure 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. 2004).

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). 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. 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. Two examples of soil biological changes associated with break crops are considered below.

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. 2004). 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 unexplained reasons, as depicted in Figure 1a at optimum N rates.

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 5000L 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) make it possible to detect ever more subtle changes in rhizosphere microbial populations, the challenge will be to identify changes which are agronomically significant in order to use them to improve crop sequence.

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 Andersen 2000). These impacts on soil characteristics 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. 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 (Sch?nhammer and Fischbeck 1987).

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 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 [Plate 1]. 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. 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 no-till, controlled traffic farming systems.

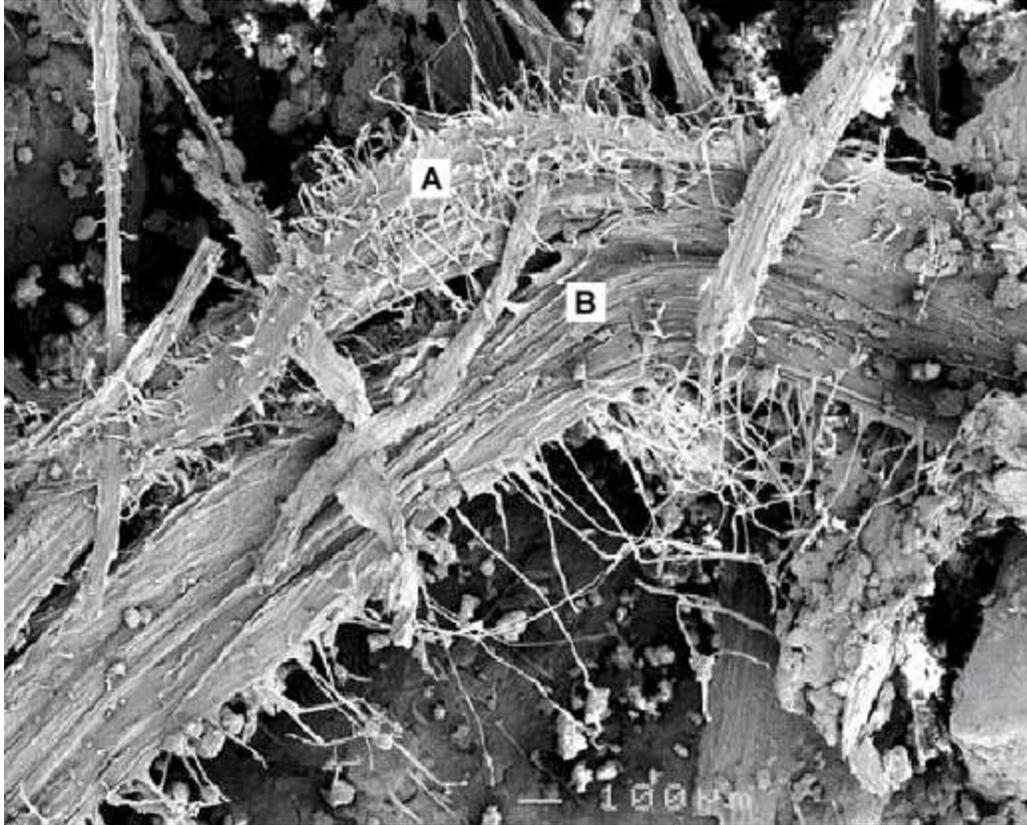


Plate 1. Cryo-SEM image of, (A) a wheat root 1 month after harvest, in close association with a root of a previous canola crop (B) within a structural biopore at a depth of 60 cm. Cryo-SEM allows visualisation of such intact associations of soil structure, biology and roots in field-grown samples providing 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]

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. 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. (2004) used a *Lemna* bioassay on soil extracts from different crop sequences to suggest a possible role for allelochemicals in reduced growth of wheat in 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 allelopathy from other impacts of retained residues in the field including increases in soil-borne pathogens (Cook and Haglund 1991), or the changes in the microclimate of emerging seedlings (Bruce 2003).

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

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 2001), other studies failed to identify the source of significant benefits, referring to a “rotation effect” depicted in Figure 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. While the measured parameters (such as soil structure and allelopathy) provide plausible explanations for some crop responses, others 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 approaches which focus on field-based assessments of less well defined changes in soil biology, structure and allelochemicals will shed light on these mechanisms.

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. peas) which can increase the risk of wind or water erosion particularly after grazing by sheep. The N benefits of legume break crops are often considered to constitute an environmental benefit in that they replace a N input 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 managed carefully. 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.

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 ten crops grown in any two-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 of the agricultural community. 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 2002) 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; H?lsbergen 2001; Christen und H?lsbergen 2003). The consideration of interactions between 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 (H?lsbergen 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.

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 (Angus et al. 2001; Zentner et al. 1996, 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 JF, Kirkegaard JA and Peoples MB (2001). Rotation, sequence and phase: research on crop and pasture systems. 10th Australian Agron. Conf. www.regional.org.au/au/asa/2001/plenary/4/angus.htm

Angus JF, Gardner PA, Kirkegaard JA and Desmarchelier JM (1994). Biofumigation: Isothiocyanates released from *Brassica* roots inhibit the growth of the take-all fungus. *Plant and Soil* 162, 107-112.

Arshad MA, Soon YK and Azooz RH (2002). Modified no-till and crop sequence effects of spring wheat production in northern Alberta, Canada. *Soil Till. Res.* 65, 29-36.

Arp DJ (1992) In "Biological Nitrogen Fixation", (Eds Stacey RH et al) pp 432-460 Chapman & Hall, New York.

Bailey KL, Gossen BD, Lafond GP, Watson PR and Derksen DA (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.

Bailey KL, Gossen BD, Derksen DA and Watson PR (2000). Impact of agronomic practices and environment on disease of wheat and lentil in southeastern Saskatchewan. *Can J Plant Sci* 80, 917-927.

Bourgeois L and Entz MH. (1996). Influence of previous crop type on yield of spring wheat: analysis of commercial field data. *Can. J. Plant Sci.* 76, 457-459.

Bowen GD and Rovira AD (1999). The rhizosphere and its management to improve plant growth. *Adv. Agron.* 66, 1-102.

Brennan RF, Bolland MDA and Bowden JW (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* (in press)

Bruce S (2003). Poor growth of canola in retained wheat stubble – causes consequences and control. PhD Thesis, Charles Sturt University, Australia.

Chalk PM (1998). Dynamics of biologically fixed N in legume-cereal rotations: a review. *Aust. J. Agric. Res.* 49, 303-16.

Chan KY and Heenan DP(1996). The influence of crop rotation on soil structure and soil physical properties under conventional tillage. *Soil Till Res.* 37, 113-125.

Christen O, Sieling K and Hanus, H (1992) The effect of different preceding crops on the development, growth and yield of winter wheat. *Europ. J. Agron.* 1, 21-28

Christen O, Lovett JV (1993) Effects of a short term p-hydroxybenzoic acid application on grain yield and yield components in different tiller categories of spring barley. *Plant and Soil* 151, 279-286

Christen O. (1999) Sustainable Agriculture – From the history of ideas to practical application. Institut für Landwirtschaft und Umwelt, Bonn

Christen O and H?Isbergen, KJ (2003) Environmental Assessment of oilseed rape cropping systems. Proceedings of 11th International Rapeseed Congress, Copenhagen, Denmark, pp 820-821.

Cook RJ (1986) Interrelationships of plant health and the sustainability of agriculture, with special reference to plant diseases. *Amer. J. Altern. Agric.* 1, 19-24.

Cook RJ (1990) Diseases caused by root-infecting pathogens in dryland agriculture. *Adv. Soil Sci.* 13, 214-239.

Cook RJ and Hagland WA (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 RJ, Schillinger WF and Christensen NW (2002). *Rhizoctonia* root rot and take-all of wheat in diverse direct-seed spring cropping systems. *Can. J. Plant Pathol.* 24, 349-358.

Cotterill PJ and Sivasithamparam K (1988). Reduction of take-all inoculum by rotation with lupin, oats or field pea. *J. Phytopath.* 121, 125-134.

Cresswell HP and Kirkegaard JA (1995). Subsoil amelioration by plant roots – the process and the evidence. *Aust. J. Soil Res.* 33, 221-39.

Dogliotti S Rossin WAH and van Ittersum MK (2003). ROTAT, a tool for systematically generating crop rotations. *Europ. J. Agron.* 19:239-250.

Dong Z, Wu L, Kettlewell B, Caldwell CD and Layzell DB (2003) Hydrogen fertilization of Soils – Is this a benefit of legumes in rotation? *Plant, Cell and Env.* 26: 1875-1879.

Evans J and Herridge DF (1987). Nitrogen inputs and utilisation in crop legumes In *Nitrogen Cycling in Temperate Agricultural Systems* (Eds PE Bacon, J Evans, RR Storrier and AC Taylor) Aust. Soc. Soil Sci. Inc pp 14-43.

Evans J, McNeill AM, Unkovich MJ, Fettell NA and Heenan DP (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 GM and Armstrong EL (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 JS, JM Krupinsky, DL Tanaka, SD Merrill, JR Hendrickson, RE Ries, MA Liebig, and JD Hanson (2001). A Crop Sequence Calculator for designing dynamic cropping systems: Translating Science into Practice. No. 210215-P In: *Annual Meeting Abstracts, October 21-25, 2001, Charlotte, NC, ASA-SSSA-CSSA, Madison, WI.*

Gan YT, Miller PR, McConkey BG, Zentner RP, Stevenson FC and CL McDonald (2003). Influence of diverse cropping sequences on durum wheat yield and protein in the semiarid northern Great Plains. *Agron. J.* 95:245-252.

Gardner PA, Angus JF, Pitson GD, Wong PTW (1998). A comparison of six methods to control take-all in wheat. *Aust. J. Agric. Res.* 49, 1225-1240.

Halvorson AD, Peterson GA and Reule CA (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 RH, Scammel GJ, Muller WJ and Angus JF (2002) Crop productivity in relation to species of previous crops and management of previous pasture. *Aust. J. Agric. Res.* 53, 1271-1283.
- Herdina, Yang HA and 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 PJ (2001) Organic acids exuded from roots in phosphorus uptake and aluminium tolerance of plants in acid soils. *Adv. Agron* 74, 63-97.
- Hocking PJ and Randall PJ (2001). Better growth and phosphorus nutrition of sorghum and wheat following organic acid secreting crops. In Proc. 14th International Plant Nutrition Colloquium Germany Eds W.J. Horst et al pp 548-549 (Kluwer Academic Publishers: Dordrecht, The Netherlands).
- H?lsbergen KJ, Feil B, Biermann S, Rathke GW, Kalk WD and Diepenbrock (2001). A method of energy balancing in crop production and its application in a long-term fertilizer trial. *Agric., Ecosys. Envir.* 86, 303-321
- Johnston AM, Tanaka DL, Miller PR, Brandt SA, Nielsen DC, Lafond GP and Riveland NR (2002). Oilseed crops for semi-arid cropping systems in the northern Great Plains. *Agron. J.* 94, 231-240.
- Kalk WD, H?lsbergen KJ and Biermann (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
- Kay BD (1990). Rates of change of soil structure under different cropping systems. *Adv. Soil Sci.* 12, 1-52.
- Khan DF, Peoples MB, Schwenke GD, Felton WL, Chen D, and Herridge DF (2003). Effects of below ground nitrogen on N balances of field grown fababean, chickpea and barley. *Aust. J. Agric. Res.* 54, 333-340.
- Kirkegaard JA, Gardner PA, Angus JF and Koetz E (1994). Effect of *Brassica* break crops on the growth and yield of wheat. *Aust. J. Agric. Res.* 45, 529-545.
- Kirkegaard JA, Sarwar M, Wong PTW, Mead A, Howe G, Newell M (2000). Field studies on the biofumigation of take-all by *Brassica* break crops. *Aust. J. Agric. Res.* 51, 445-56.
- Kirkegaard JA, Hocking PJ, Angus JF, Howe GN and Gardner PA (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 JA, Simpfendorfer S, Holland J, Bambach R, Moore KJ, Rebetzke GJ (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.
- Kirkegaard JA, Howe GN and Mele P (1999). Enhanced accumulation of mineral-N following canola. *Aust. J. Exp. Agric.* 39, 587-593.
- Kirkegaard JA, Howe GN and Pitson G (2001). Agronomic interactions between drought and crop sequence. Proc. 10th Austr. Agron. Conf. Hobart 2001.
- Kollmorgan JF, Griffiths JB, Walscott DN (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 JM, Tanaka DL Merrill SD Liebig MA Hendrickson JR Anderson RL Hanson JD and Ries RE (2002). Crop sequences influence crop seed production and plant diseases. In, Proc. of the 24th annual Manitoba-North Dakota Zero Tillage Farmers Association Workshop. January 29-30, Minot, North Dakota, p. 13-19.

Krupinsky JM, Tanaka DL Hanson JD Merrill SD Liebig MA and Hendrickson JR (2003). Dynamic cropping systems and the distribution of research information: Crop Sequence Calculator. pp. 174-178. In: Proc. of Dynamic Cropping Systems: Principles, Processes, and Challenges, (Eds JD Hanson and JM Krupinsky), Bismarck, ND.

Larney FJ and Lindwell CW (1995). Rotation and tillage effects on available soil water for winter wheat in a semi arid environment. *Soil Till. Res.* 36, 111-127.

Leather GR and Einhellig FA (1986) Bioassays in the study of allelopathy. In "The Science of Allelopathy" (Eds AR Putnam and CS. Tang).pp 133-145. (Wiley and Sons, New York).

McCully ME, Shane MW, Baker AN, Huang CX, Ling LEC and Canny MJ (2000). The reliability of cryoSEM for the observation and quantification of xylem embolisms and quantitative analysis of xylem sap in situ. *J. Microscopy* 198, 24-33.

McEwen J, Darry RJ, Hewitt, MV, Yeoman DP (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 JA (1992) Rotations and farming systems – the current situation. In:"Rotations and farming Systems" (Eds GM Murray and DP Heenan) pp 5 – 10. (NSW Agriculture, Wagga Wagga, N.S.W.).

Miller PR, Gan Y, McConkey BG and McDonald CL (2003). Pulse crops for the northern Great Plains: II. Cropping sequence effects on cereal, oilseed, and pulse crops. *Agron. J.* 95, 980-986.

Miller PR, Waddington J, McDonald C and Derksen DA (2002). Cropping sequence affects wheat productivity on the semiarid northern Great Plains. *Can. J. Plant Sci.* 82, 307-318.

Nielsen DC, Vigil MF, Anderson RL, Bowman RA, Benjamin JG and AD Halvorson (2002). Cropping system influence on planting water content and yield of winter wheat. *Agron. J.* 94, 962-967.

Norwood CA (2000). Dryland winter wheat as affected by previous crops. *Agron. J.* 92, 121-127.

Passioura JB (2002). Soil conditions and plant growth *Plant, Cell Envir.* 25, 311-318.

Peoples MB, Herridge DF and Ladha JK (1995). Biological nitrogen fixation: An efficient source of nitrogen for sustainable agricultural production? *Plant and Soil* 174, 3-28

Peoples MB and Craswell ET (1992). Biological nitrogen fixation: Investments, expectations and actual contributions to agriculture. *Plant and Soil* 141, 13-39.

Pierret A, Moran CJ and Pankhurst CE (1999). Differentiation of soil properties related to the spatial association of wheat roots and soil macropores. *Plant Soil* 211, 51-58.

Purvis CE (1990) Differential response of wheat to retained crop stubbles I. Effect of stubble type and degree of decomposition. *Aust. J. Agric. Res.* 41, 225-42.

Prew RD, Beane J, Carter N, Church BM, Dewar AM, Lacey J, Penny A, Plumb RT, Thorne GN and Todd AD (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.

Reeves TG, Ellington A, Brooke HD (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, Alfarroba F, Blümel S, Isart J, McGrath D and Seppälä T. (2002). Comparison and evaluation of eight pesticide environmental risk indicators developed in Europe and recommendations for future use. Agric., Ecosys. and Envir. 90, 177–187

Rovira AD, Elliot LF, Cook RJ (1990). The impact of cropping systems on rhizosphere organisms affecting plant health. In "The rhizosphere" (Ed JM Lynch) pp 389-436 (Wiley: Chichester, UK)

Rumberger A and Marschner P (2003). 2-phenylethylisothiocyanate concentration and microbial community composition in the rhizosphere of canola. Soil Biol. Biochem. 35, 445-452.

Ryan MH and Angus JF (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 MH and Graham JH (2002). Is there a role for arbuscular mycorrhizal fungi in production agriculture? Plant Soil 244, 263-271.

Ryan MH, van Herwaarden AF, Angus JF and Kirkegaard JA (2004). Colonisation by arbuscular mycorrhizal fungi is associated with reductions in biomass of wheat in a low-P soil under field conditions. Plant Soil (in press).

Sands GR and Podmore TH (2000). A generalized environmental sustainability index for agricultural systems. Agric. Ecosys. and Envir. 79, 29-41

Sarwar M, Kirkegaard JA, Wong PTW and Desmarchelier JM (1998). Biofumigation potential of brassicas III. In vitro toxicity of isothiocyanates to soil-borne fungal pathogens Plant Soil 201, 103-112.

Schäpperclaus A and Fishbeck G (1987) Investigations on cereal crop rotations and monocultures. III Changes in soil properties. Bayerisches Landwirtschaftliches Jahrbuch 64, 681-694.

Sieling K, Stahl C, Winkelmann C and Christen O (2004). Growth and yield of winter wheat in the first three years of a monoculture under varying N fertilisation in NW Germany. Europ. J. Agron. (*in press*)

Simpfendorfer A, Kirkegaard JA, Heenan DP and Wong PTW (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 RW, Ingham RE, Uddin W, and Cook GH. 1994. Crop sequences for managing cereal cyst nematode and fungal pathogens of winter wheat. Plant Dis. 78, 1142-1149

Smiley RW, Collins HP, and Rasmussen PE (1996). Diseases of wheat in long-term agronomic experiments at Pendleton, Oregon. Plant Dis. 80, 813-820.

Smith BJ, Kirkegaard JA and Howe GN (2004). Impacts of *Brassica* break crops on soil biology and yield of following wheat crops Aust. J. Agric. Res. 55, 1-11.

Soon YK and Clayton GW (2002). Eight years of crop rotation and tillage effects on crop production and N fertilizer use. Can. J. Soil Sci. 82, 165-172.

Soon YK, Clayton GW and Rice WA (2001). Tillage and previous crop effects on dynamics of nitrogen in a wheat-soil system. Agron. J. 93, 842-849.

Stevenson FC and van Kessel C (1996). A landscape-scale assessment of the nitrogen and non-nitrogen rotation benefits of pea. *Soil Sci. Soc. Amer. J.* 60, 1797-1805.

Tanaka DL, Bauer A, and Black AL (1997). Annual legume cover crops in spring wheat-fallow systems. *J. Prod. Agric.* 10, 251-255.

Tang CS and Waiss AC (1978). Short-chain fatty acids as growth inhibitors in decomposing wheat straw. *J. Chem. Ecol.* 4, 225-232.

Tennakoon SB and Bell CJ (1998). DACS: A knowledge-based decision support system for dryland agriculture crop sequencing. Proc. 9th Australian Agronomy Conference, Wagga Wagga.

Thompson JP, Owen KJ and Clewett TG (2001). Pre-cropping with canola decreases vesicular-arbuscular mycorrhiza and growth of wheat in low P soil. Proc. 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 AF, Farquar GD, Angus JF, Richards RA and Howe GN (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, 1067-81.

Watt M, McCully ME, Kirkegaard JA (2003). Soil strength and rate of root elongation alter the accumulation of *Pseudomonas* spp. And other bacteria in the rhizosphere of wheat. *Func. Plant Biol.* 30, 483-491.

Wright SF and Anderson RL (2000). Aggregate stability and glomalin in alternative crop rotations for the central Great Plains. *Biol. Fert. Soils* 31, 249-253.

Zentner RP, Campbell CA, Biederbeck VO, Miller PR, Selles F and Fernandez MR (2001). In search of a sustainable cropping system for the semiarid Canadian prairies. *J. Sustainable Agriculture.* 18:117-136.

Zentner RP, Wall DD, Nagy CN, Smith EG, Young DL, Miller PR, Campbell CA, McConkey BG, Brandt SA, Lafond GP, Johnson AM, Derksen DA (2002). Economics of crop diversification and soil tillage opportunities in the Canadian prairies *Agron. J.* 94, 216-230.