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Crop Updates 2000 - Cereals part 1

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- Western Australia

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Compiled by Christine Zaicou-Kunesch and Nicole Kerr

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Foreword

Over the past four years the Crop Updates has become the key extension event on the grains industry calendar.

Agriculture Western Australia and Grains Research and Development Corporation, have an on-going commitment to the Crop Updates. The Crop Updates allow the rapid transfer of research information to growers, which provides assistance in increasing production efficiency. This has an impact on wealth in regional areas of Western Australia.

This initiative draws together the primary communicators of agricultural information at a two-day event where they interact with leading researchers and discuss the results and implications of the research for the coming season.

The event is becoming more effective each year and all those involved in organising the event must be congratulated on their continual effort and success.

Personally, I always enjoy the opportunity to be updated on the latest research information and also the opportunity to meet key industry people.

I wish everyone an informative updates and a prosperous 2000.

Sean Powell
CHAIRMAN
CEREALS PARTNERSHIP GROUP

Acknowledgments

Coordinating the Cereals day for Crop Updates can at times feel like the most frustrating job on earth, but when everything comes together in the end it is very rewarding and worth every additional strand of grey hair we now have.

We would like to gratefully acknowledge the fantastic effort of all the Cereals authors. Some of our deadlines were tight which put people under pressure, but they managed to meet them. We would especially like to thank our plenary session experts - Tim Reeves, Bob McIntosh, Rob Loughman, Peter King, Bill Bowden and Terry Piper.

Last, but not least, we wish to acknowledge the support of the Crop Updates Working Group, particularly Lisa Blacklock, John Blake, Clinton Revell and Vanessa Stewart; and Shelly Ford who is an absolute whiz at formatting booklets.

Nicole Kerr and Christine Zaicou-Kunesch
CEREALS CONVENORS

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uses does not constitute a recommendation for that use. All pesticide use must be in accord with the registered uses for that product.
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New Wheats for a Secure, Sustainable Future

Timothy G. Reeves, Sanjaya Rajaram, Maarten van Ginkel, Richard Trethowan, Hans-Joachim Braun, and Kelly Cassaday, International Maize and Wheat Improvement Centre (CIMMYT)

At the same time that we are witnessing a proliferation of agricultural innovations unlike any seen previously, hunger and poverty—often the result of unemployment and low purchasing power—remain the defining conditions of life for hundreds of millions of people.

New agricultural knowledge and technologies are announced almost daily. The shifting alliances and the achievements of transnational seed-chemical-pharmaceutical companies are minutely analysed in the media. It is easy to forget that this frenetic activity occurs in a sobering context—a world of persisting hunger.

Even a small number of facts are sufficient to demonstrate the gravity of the world food situation. More than 800 million people in developing countries—20% of the population—cannot be certain that they will get enough to eat, because they lack the resources to grow or purchase sufficient food. The downward spiral of hunger and poverty remains serious in many regions and countries. An estimated 1.3 billion people live in households earning US$1 per day or less per person. Asia has 73% of the world’s poor people (World Bank 1997), and as we move into the new millennium South Asia will continue to be the home of half of the world’s poor. Though Asia will have the highest absolute number of poor people, the number of poor people in Sub-Saharan Africa (which currently has 17% of the world’s poor) will grow by 40% between 1990 and 2000, and the number of undernourished people will rise by 70% between 1988–90 and 2010 (World Bank 1997; Reeves, Pinstrup-Andersen, and Pandya-Lorch 1997).

Developing countries are projected to increase their demand for cereals by about 80% between 1999 and 2020 (Pinstrup-Andersen and Pandya-Lorch 1997). Rosegrant et al. (1997) report that over the next two decades global demand for wheat and maize could rise by 40% and 47%, respectively. By 2020, it is expected that 67% of the world’s wheat consumption and 57% of the world’s maize consumption will occur in developing countries.

Even if food crop productivity in developing countries remains at current levels, by 2020 developing countries will be importing 138 million tons of wheat and 62 million tons of maize every year. In these circumstances, how will we ensure food security for the poorest of the poor?

AGRICULTURE: AN AGENT OF CHANGE

The role of more productive, profitable maize and wheat systems in fostering food security, generating local employment, raising local incomes, and thus alleviating poverty must not be underestimated. A recent report (UNDP 1997) emphasises that agricultural research is the central means of achieving those goals: ‘About three-quarters of the world’s poorest people live in rural areas, dependent on agricultural activities for their livelihoods. For these people, pro-poor growth means raising agricultural productivity, efficiency, and incomes’. The report points out why agriculture can succeed where other initiatives might fail: ‘Raising the productivity of small-scale agriculture does more than benefit farmers. It also creates employment on the farm and off-and reduces food prices. The poor benefit most, because about 70% of their consumption is food, mostly staples, and regular supplies and stable prices can greatly reduce the vulnerability of the poor. Strong support to small-scale agriculture was at the core of the most successful cases of poverty reduction—such as China in 1978–85, Malaysia since 1971, and India in the early 1980s’. 
In these circumstances, the challenges for research—and the opportunities to alleviate much human suffering—are clear. We will have to develop the innovations that make it possible for people to benefit from more efficient, low-cost systems for food production. These systems must function without mining the natural resources on which agriculture depends. They are needed urgently in favoured as well as less favoured agricultural areas.

In this paper, we review strategies used by the International Maize and Wheat Improvement Center (CIMMYT) and its partners to develop sustainable wheat production systems for favoured and marginal areas. These strategies aim to achieve an optimal combination of the best genotypes (G), in the right environments (E), under appropriate crop management (M), and appropriate to the needs of the people (P) who must implement and manage them (Reeves 1998, 1999). Each variable in this GxE,MxP ‘sustainability equation’ is addressed in the sections that follow. After further defining what we mean by ‘sustainable technology’ we:

• review new options for raising wheat yield potential;
• discuss research on disease and stress tolerance, which is aimed at protecting yield potential in farmers’ fields. We give special emphasis to drought tolerance;
• describe advances in durum wheat yield potential which may prove particularly valuable in marginal environments;
• provide an overview of other wheat research initiatives for marginal environments;
• review the role of biotechnology in wheat improvement;
• describe recent research on wheat quality. For many poor farmers, an increase in wheat quality means a corresponding increase in income;
• briefly review recent initiatives in crop and natural resource management research in wheat.

We conclude by summarising the latest data on the global impacts of our wheat research and by discussing trends that could affect whether and how this impact is maintained into the future.

**Prerequisites for Sustainable Agriculture**

To be sustainable, farming systems must be biologically sensible, economically viable, environmentally sound, socially acceptable, and politically supportable (Reeves 1998, 1999):

• Sustainable farming systems must be biologically sensible. For example, the choice of crop(s), their management, and the level of intensification must be consistent with the biophysical realities of the farming system.
• Sustainable farming systems must be economically viable at the farm and national levels. Poor farmers cannot invest in systems that will not produce reasonable yields and (even better) cash income, now and in the future. At the national level, the reality in most developing countries is that economic well-being and development are almost invariably based on productive and profitable agriculture, the ‘engine room’ of subsequent industrialisation.

• Sustainable farming systems must be environmentally sound. Economic success in agriculture cannot come at the expense of our soils, air, water, landscapes, and indigenous flora and fauna.

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1 In this paper we focus on strategies related to wheat, although CIMMYT’s research mandate encompasses maize as well. We also give greater attention to wheat improvement research than to crop and natural resource management research, but readers should be advised that CIMMYT engages in a great deal of crop and resource management research, for wheat as well as maize. For a general overview, see our annual report, *CIMMYT in 1998-99*. 

• Sustainable farming systems must be socially acceptable. They must be appropriate to the people who, relying on their own meager resources, are responsible for implementing and managing them. The need for socially acceptable systems implies the need for a better understanding of farmer and community needs and values, as well as better targeting of technology to meet local conditions.

• Finally, sustainable farming systems must be politically supportable. Political support depends largely on successfully meeting the first three requirements of sustainability. If economic growth is catalysed by agriculture within an environmentally sound, socially acceptable framework, politicians will continue to view agriculture as justifying support.

All of these components combine to form the whole: sustainable agriculture. If one is neglected, it can seriously reduce the rate and extent of progress towards sustainability and food security.

BREEDING WHEATS FOR LASTING FOOD SECURITY

CIMMYT’s wheat breeding methodology is tailored to develop widely adapted, disease resistant germplasm with high and stable yield across a wide range of environments-favourable as well as marginal. To focus this work, we have grouped wheat production areas in developing countries into 12 ‘mega-environments’. A mega-environment is a broad but not necessarily contiguous geographical area, usually international and frequently transcontinental. Mega-environments are defined in terms of the type of wheat cultivated (spring, facultative, or winter wheat), the amount of water available to the crop, temperature regime, mineral toxicity in the soil, and the major diseases and pests that limit food production.

CIMMYT wheat breeders, through collaboration with national wheat research programs and genebanks, scour the world for new and different sources of yield potential and other traits of interest. We give the utmost attention to genetic diversity within CIMMYT germplasm to minimise the risk of genetic vulnerability, since our breeding materials are used in research programs worldwide, and the numerous varieties developed from those breeding materials are grown by hundreds of millions of farmers. We also believe that the use of genetically diverse material is mandatory for future increases in yield potential and yield stability. At CIMMYT, parental groups of lines for crossing in any year consist of 500–800 lines. Twice a year around 30% of parental stocks are replaced with outstanding introductions. In addition, commercial cultivars from NARSs and non-conventional sources (e.g. durum wheat and alien species) are used to incorporate desired traits by recombination or translocation. The introductions are mostly used as the female parent to preserve cytoplasmic diversity.

OPTIONS FOR INCREASING YIELD POTENTIAL

Like most wheat improvement programs, the CIMMYT wheat improvement program has many reasons for seeking to raise-and protect-genetic yield potential. High yield potential, assessed in breeders’ trials, is positively associated with superior crop performance in farmers’ fields, even in stressed environments. Another consideration is that most farmers readily adopt and share improved wheat seed, even in areas where problems with infrastructure and lack of farmer support services frustrate the adoption of other agricultural inputs and practices. Those may be regarded as the ‘humanitarian’ reasons for seeking higher yields, but it is important to remember that there are also compelling environmental reasons to break yield barriers. We must be realistic about changing land use patterns and their implications for agriculture. There is limited scope to open new land for crop production, and there is an even more urgent need to protect land (in particular, marginal land) from inappropriate uses. In recent decades developing countries have fortunately relied more on increased yields than on an expansion of cropped area to feed their populations. Between 1961 and 1990, yield increases accounted for 92% of the additional cereal
production in the developing world (Reeves, Pinstrup-Anderson, and Pandya-Lorch 1997). When farmers in stable, high production environments obtain better yields, the need to intensify production in fragile agricultural systems is reduced, offering a much more sustainable approach to meeting long-term demand for cereal production in developing countries. Because higher yielding lines are frequently bred to use inputs such as nutrients and water more efficiently, higher yields are not obtained at a higher cost to the environment. As our colleague Norman Borlaug has said, 'The only way for agriculture to keep pace with population and alleviate world hunger is to increase the intensity of production in those ecosystems that lend themselves to sustainable intensification, while decreasing intensity of production in the more fragile ecologies' (Borlaug and Dowswell 1997).

The selection of segregating populations and consequent yield testing of advanced lines is paramount for identifying high yielding, input responsive wheat genotypes. The increase in yield potential of CIMMYT cultivars developed since the 1960s is shown in Figure 1 (Rees et al. 1993). Sayre et al. (1997) concluded that from 1964 to 1990, yield potential in CIMMYT-derived cultivars increased by 67 kg/ha/yr, or 0.88% per year. The data do not indicate that we are approaching a yield plateau, and the performance of recently released lines such as Attila and Baviacora, and of Lr19-derived Veery, indicates that yield potential has been further enhanced.

![Figure 1](image_url)

**Figure 1.** Mean grain for the historical series of bread wheat varieties for the years 1990-93 at Cd Obregón, Mexico.

Source: Rees et al. (1993)

With yield, a complex trait still not well understood genetically or physiologically, the use of proven, high yielding sources, as well as genetically diverse germplasm, will continue to be paramount for increasing yield potential. Genetic diversity and the opportunity for its recombination through crossing will be important to break undesired linkages and increase the frequency of desirable

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2 For example, if India were suddenly required to produce its current wheat harvest using the technologies of 30 years ago, Indian farmers would have to bring more than 40 million hectares of additional land into production. The wheat varieties developed in the past three decades were instrumental in preventing damage to areas that are not well suited to agriculture.
alleles. Future breakthroughs in yield potential are likely to come from such genetically diverse crosses. Examples are given below, along with a description of other efforts to raise both spring and winter wheat yield potential.
GENE POOLS OF WINTER AND SPRING HEXAPLOID WHEATS

The variability currently available among spring and winter hexaploid wheats is still extensive. New high yielding sources from within the CIMMYT Bread Wheat Program and from around the world are identified and intercrossed. For example, high yielding spring wheat lines from South Asia and China are regularly intercrossed with the highest yielding lines identified in Mexico, followed by selection for types superior to either parent, carrying all desirable genes. Likewise elite winter wheats are intercrossed. Considerable progress can still be made in this way as yield is controlled by many genes and the optimal combinations of these genes for any particular environment may not yet have been realised.

Introgressing Spring and Winter Wheat Gene Pools

By introgressing genetic variability from winter wheats, breeders have considerably augmented the yield potential of spring wheats. The Veery wheats, developed from crosses of CIMMYT spring wheats and Russian winter wheat, represented a quantum leap in spring wheat yield and wide adaptation during the 1970s and 1980s (their contribution to drought tolerance is discussed later). More recently, the spring bread wheat Attila, developed from crosses with western European and US winter wheats, has rapidly gained ground on the Indian subcontinent. New evidence indicates that yield potential in winter wheat may also benefit from crosses with high yielding spring wheats.

CHINESE WHEATS: A WELLSPRING OF DIVERSITY

Before the mid-1980s, only a limited amount of wheat germplasm from outside China was available to Chinese breeders. Since the mid-1980s, CIMMYT and Chinese scientists have worked together to benefit from the diversity in each others’ wheat germplasm. More than 100 Chinese varieties contain CIMMYT germplasm, and up to 20% of new CIMMYT spring wheats have Chinese wheats in their pedigrees. Apart from its resistance to biotic pests such as scab and Karnal bunt, modern Chinese germplasm offers new alternatives for raising the yield potential of wheat; yields of elite Chinese wheats in China can exceed 10 t/ha.

HYBRID WHEATS

The expression of heterosis for yield in wheat can be high. Although it has been well documented, heterosis has not been exploited commercially to any great extent. Hybrids offer the unique opportunity of combining different gene pools in the production of the F1 hybrid. Because heterosis is, to some extent, a function of genetic distance, CIMMYT is well positioned to exploit this need for genetic diversity. During the past three years, CIMMYT hybrids have produced yields that are 15–20% higher than those of commercially grown cultivars in Mexico, and levels of heterosis of a similar maximum size have been reported. The difficulty of producing F1 seed in a cost-effective way remains the greatest limitation to the exploitation of such hybrids, but CIMMYT breeders expect to resolve this issue by introgressing outcrossing traits.

LANDRACES

Many high yielding CIMMYT wheats have a considerable number of landraces in their pedigrees. A coefficient of parentage analysis reveals that on average CIMMYT advanced lines contain as many as 50 landraces in their genetic history. Breeding programs have still not exploited all of the yield-controlling genes available in landraces. Landraces may also provide novel sources of adaptation, which will allow breeders to select more stable, high yielding lines. As yields increase, consumer preferences will also turn to increased quality and taste. Here, locally preferred landraces can play a very new and exciting role.

Improved Plant Ideotype

CIMMYT breeders are using increased knowledge of the physiological bases of yield to define a range of optimal wheat plant ideotypes. We are examining plants with large spikes, which contain many grains per spikelet. The optimisation of source-sink relationships is also being examined with a
view to obtaining a better balance of grain-filling characters. The hexaploid wheat and other gene pools are
being searched for examples of extreme expression of these characters. We believe advances of yield potential on the order of at least 20% in optimum conditions can still be realised by fine-tuning the source-sink relationships in wheat.

PHENOLOGICAL TRAITS

By manipulating photoperiod and vernalisation genes, we are attempting to tailor genotypes to specific environments. Photoperiod and vernalisation genes optimise the timing and duration of flowering and grain-filling, thereby influencing the wheat plant’s eventual yield. New and different sources of these genes are being exploited through the use of high-latitude germplasm from Central Asia and Canada.

PHYSIOLOGICAL TRAITS

A strong body of evidence now indicates that physiological traits may complement early-generation phenotypic selection in wheat. Genetic progress in increasing yield potential is closely associated with increased photosynthetic activity (Rees et al. 1993). Photosynthetic activity as well as yield potential have increased over the past 30 years by some 25%. These findings may have major implications for CIMMYT’s future selection strategy, since there is evidence that wheat genotypes with higher photosynthesis rates have lower canopy temperatures, a characteristic that can be measured easily, quickly, and cheaply. Canopy temperature depression (CTD) is the cooling effect exhibited by a leaf as transpiration occurs. Canopy temperature depression and stomatal conductance, measured on sunny days during grain filling, have shown a strong association with yields of semidwarf wheats grown under irrigation, in both temperate (Fischer et al. 1998) and subtropical environments (Reynolds et al. 1994). In addition, CTD measured on large numbers of advanced breeding lines in irrigated yield trials was a powerful predictor of performance, not only at the selection site but also for yield averaged across 15 international sites. Canopy temperature depression has been shown to be associated with yield differences between homozygous lines in warm environments, indicating a potential for genetic yield gains under conditions of heat in response to selection for CTD (Reynolds et al. 1998). Breeders have found CTD to be highly correlated with yield under heat conditions among elite lines (van Ginkel and Trehowman, unpublished), and the technique may be particularly useful for more efficiently selecting wheat genotypes adapted to environments where heat is a production constraint.

SYNTHETIC WHEATS: DELIVERING DIVERSITY TO PLANT BREEDERS

Synthetic wheats are the result of a cross between two relatives of putative progenitors of wheat, *Triticum turgidum* and *T. tauschii*, with subsequent chromosome doubling. Historically (10,000 to 8,000 years ago), this cross has probably occurred on only a few occasions. As a result, the genetic resources of these two species have been sampled in only a limited way in the development of bread wheat. CIMMYT holds a large number of *T. tauschii* accessions from which many new synthetic hexaploid wheats have been made (about 650 to date). These synthetics possess a range of positive traits, including resistance to such diseases as Karnal bunt, fusarium head scab, and helminthosporium leaf blotch, and tolerance to heat, drought, waterlogging, and late frost at flowering. They are spring types that are highly crossable to advanced bread wheats, which means that they may be used easily in breeding programs. Through this approach, CIMMYT breeders have not only been able to take advantage of the new variation from *T. tauschii*, but have also found a new way to introgress traits from elite durum wheats into bread wheat. Synthetics or their derivatives may also prove useful in the production of hybrid wheat and the improvement of bread wheat quality.

*Alien substitutions and translocations*

The 1B/1R translocation (discussed also in the section on drought tolerance) led to a revolution in the broad adaptation of wheat. This translocation from rye increased wheat biomass, harvest index, and—especially—wide adaptation, which spurred improvements in wheat yield in most spring wheat environments. More recently, a translocated segment from *Agropyron* sp. containing the leaf rust resistance gene *Lr19* has been linked with a 5–10% increase in yield in adapted backgrounds. Other alien sources of higher yield are also currently under evaluation.
PROTECTING YIELD POTENTIAL: THE ROLE OF RESISTANCE TO PATHOGENS AND PESTS

Over the past few decades, the gains from breeding for disease resistance are likely to have been at least as important as the gains from breeding for increased yield potential (Byerlee and Moya 1993). A recent survey of wheat breeders in developing countries indicated that among the types of materials used in crossing (including the breeder's own advanced lines, advanced lines obtained from other countries, wild relatives, and landraces), materials from CIMMYT international nurseries are the most frequently crossed in pursuit of disease resistance goals (Rejesus, van Ginkel, and Smale 1996). CIMMYT’s global effort to breed wheats with diverse and durable resistance will protect global food security by reducing the incidence of disease epidemics. It will also protect the environment and farmers’ incomes, by reducing dependence on pesticides for disease and pest control. In CIMMYT’s target mega-environments, important obligate fungal diseases of wheat caused by obligate parasites include the rusts (one or more of which are the most economically important diseases in most wheat production environments), powdery mildew, and the bunts and smuts. Widespread diseases caused by facultative fungal parasites include septoria tritici blotch, septoria nodorum blotch, spot blotch, tan spot, head scab, and a suite of root rots.

The obligate parasites are highly specialised, and significant variation exists in the pathogen population for virulence to specific resistance genes. The evolution of new virulence (races) through migration, mutation, and recombination of existing virulences and their selection is more frequent in rust and powdery mildew fungi. For this reason, these diseases have required constant vigilance and attention from breeders. Physiological races are also known to occur for most bunts and smuts, although evolution and selection of new races is less frequent. Because most bunts and smuts are easily controlled by chemical seed treatment, little effort is currently placed on breeding for resistance, except for resistance to Karnal bunt. Successful changes in pathogen races are even less frequent in the facultative parasites mentioned earlier.

Since wheat cultivars derived from CIMMYT germplasm are grown over a large area and are exposed to a variety of pathogens under conditions that may favour disease development, our strategy has been to utilise resistance sources that are as diverse as possible and have shown durability. Genetic diversity and durability of resistance against diseases caused by pathogens such as the rust pathogens are vital for long-term food security. Resistances caused by race-specific genes become ineffective in a short time (in five years on average at the global level and in three years for leaf rust, *Puccinia recondita*, in Mexico). In contrast, cultivars with durable resistance have shown stable resistance for over 50 years at the global level. Consider the resistance to stem rust (*P. graminis*). McFadden in the US transferred the *Sr2* gene complex from a tetraploid emmer wheat to hexaploid bread wheat in the 1920s (McFadden 1930). Borlaug in Mexico used this source of resistance in his breeding program in the 1940s, and since then this gene, in concert with several known and unknown major and minor genes, has formed the basis of durable resistance to stem rust in CIMMYT wheat germplasm.

Following the lesson learnt from stem rust research, CIMMYT’s wheat breeding in the last three decades has focused on utilising diverse sources of slow rusting resistance to *P. recondita* and yellow rust (*P. striiformis*). Genetic analyses of durable resistance indicate that effective disease control can be achieved by combining from three to five minor, slow rusting genes in a single cultivar. Such resistance is expected to provide sufficient protection to farmers’ crop against all biotypes over a long period. Currently we are also attempting to identify molecular markers for each of the slow rusting genes present in CIMMYT wheats. If this strategy is successful, breeding programs will be able to incorporate known combinations of minor genes, develop a global strategy for their deployment, and at the same time enhance genetic diversity in farmers’ fields.
Recent analysis of trials conducted in northwestern Mexico confirms that progress in protecting yield potential through genetic resistance to leaf rust is about three times as great as advances in yield potential itself (R.P. Singh and K.D. Sayre, pers. comm.). The economic benefits of CIMMYT’s strategy of incorporating non-specific, durable resistance to leaf rust into modern bread wheats have been estimated using data on resistance genes identified in cultivars, trial data, and area sown to cultivars in northwestern Mexico. Even under the most conservative scenario, the gross benefits
generated in this region on about 120,000 ha of wheat from 1970 to 1990 were US$ 17 million (in 1994 real terms) (Smale et al. 1998). At the global level, where a considerable area is sown to cultivars carrying non-specific resistance, the benefits must be correspondingly large.

Resistance to the diseases caused by facultative parasites, such as Septoria tritici and Fusarium graminearum, also involves genes that have additive effects. Tremendous progress has been made at CIMMYT in developing semidwarf wheats that have adequate resistance to Septoria tritici. Sources contributing to resistance include wheats from France, Brazil, China, and Russia. More recently we have identified synthetic wheats (T. turgidum x T. tauschii) possessing good resistance to septoria tritici blotch. This new genetic diversity is currently being transferred to CIMMYT wheats.

**Moving beyond marginal yields in marginal environments**

Limited water availability is probably the most common stress that affects farmers in marginal environments, but they also have to contend with factors such as diseases, acid soils, extreme cold and heat, waterlogging, and mineral deficiencies and toxicities. A region is defined as marginal when wheat production drops to 70% of optimal yield levels, as in, for example, the highland areas from Turkey to Afghanistan, the dryland areas of West Asia and North Africa (WANA), much of Ethiopia, and the dryland areas of central and southern India (Table 1).³

Our discussion of CIMMYT’s research directed at marginal areas begins with a review of the methods used in breeding drought tolerant wheats. Next, we describe achievements in durum wheat breeding, given the considerable amount of durum wheat grown in marginal areas. We conclude with an overview of specific research initiatives in regions where marginal environments present a series of challenges to wheat production. As the following sections indicate, CIMMYT researchers and their collaborators are implementing a combination of strategies to ensure that farmers in marginal areas are no longer destined to obtain marginal yields.

### Table 1. Portions of wheat producing regions of the world that are defined as marginal

<table>
<thead>
<tr>
<th>Region</th>
<th>Total wheat area (000 ha)</th>
<th>Percent marginal</th>
</tr>
</thead>
<tbody>
<tr>
<td>WANA</td>
<td>28,300</td>
<td>65</td>
</tr>
<tr>
<td>Central Asia and the Caucasus</td>
<td>15,000</td>
<td>80</td>
</tr>
<tr>
<td>South Asia (Subcontinent)</td>
<td>34,500</td>
<td>35</td>
</tr>
<tr>
<td>East Asia (including China)</td>
<td>30,100</td>
<td>13</td>
</tr>
<tr>
<td>Eastern Africa</td>
<td>1,500</td>
<td>27</td>
</tr>
<tr>
<td>Southern Africa</td>
<td>1,300</td>
<td>91</td>
</tr>
<tr>
<td>Southern Cone of South America</td>
<td>7,400</td>
<td>60</td>
</tr>
<tr>
<td>Andean Region of South America</td>
<td>300</td>
<td>18</td>
</tr>
<tr>
<td>Mexico/Central America</td>
<td>900</td>
<td>43</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>119,300</strong></td>
<td><strong>45</strong></td>
</tr>
</tbody>
</table>

### BREEDING FOR DROUGHT TOLERANCE

The annual gain in genetic yield potential in drought environments is only about half (0.3–0.5%) of that obtained in irrigated, optimum conditions. Many investigators have attempted to produce wheat adapted to semiarid environments but with limited success. The CIMMYT Wheat Program follows a system of breeding for drought tolerance in which yield responsiveness is combined with adaptation to drought conditions. Because most semiarid environments differ significantly in annual precipitation distribution, and because water availability also differs across years in these environments, it is prudent to construct a genetic system in which plant responsiveness provides a bonus whenever higher rainfall improves the production environment. With such a system, improved moisture is immediately translated into greater yield gains for farmers. Why do we believe that this can be done?

³ Note that, although improved varieties have a role to play in these areas, considerable gains will also result from improved crop and resource management, especially measures to conserve and utilise moisture more efficiently in rainfed areas. Some of these practices are discussed later in this paper.
One compelling piece of evidence comes in the form of Veery S, which combines high yield performance in favourable environments and adaptation to drought in more marginal areas. When Veery S was tested in 73 environments in the early 1980s, its performance differed from that of other high yielding varieties. It yielded better than other cultivars not only in high yielding environments but also under reduced irrigation (Table 2). What made this line different was that it carried the 1B/1R translocation from rye. By 1990, 63% of the dryland wheat area in developing countries was sown to semidwarf wheats (Byerlee and Moya 1993). Many of these wheats possessed the 1B/1R translocation, which had been incorporated into hundreds of genetically different backgrounds and made available to breeders throughout the world.

We have conducted several experiments to compare the performance of the newest and most widely adapted wheat germplasm to the performance of commercial cultivars from countries in three marginal, low rainfall mega-environments, under conditions simulating those environments (Calhoun et al. 1994; van Ginkel et al. 1998; Tables 3 and 4). The most widely adapted CIMMYT lines yielded better than the commercial cultivars in all of the simulated environments. Recent adoption of CIMMYT germplasm in those environments supports the model of combining input efficiency and input responsiveness.

Table 2. Effect of the 1BL/1RS translocation on yield characteristics of 28 random F2-derived F6 lines from the cross Nacozari/Seri 82 under reduced irrigation

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>1BL/1RS</th>
<th>1B</th>
<th>Mean difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield (kg/ha)</td>
<td>4,945</td>
<td>4,743</td>
<td>202 *</td>
</tr>
<tr>
<td>Above-ground biomass at maturity (t/ha)</td>
<td>12,600</td>
<td>12,100</td>
<td>500 *</td>
</tr>
<tr>
<td>Grains m²</td>
<td>14,074</td>
<td>13,922</td>
<td>152 NS</td>
</tr>
<tr>
<td>Grains/spike</td>
<td>43.5</td>
<td>40.6</td>
<td>2.9 *</td>
</tr>
<tr>
<td>1,000 grain weight (g)</td>
<td>37.1</td>
<td>36.5</td>
<td>0.5 *</td>
</tr>
</tbody>
</table>

Source: Villareal et al. (1995).
Note: NS = not significant; * = significant at the 0.05 level.

Table 3. Wheat genotypes representing adaptation to different moisture environments

<table>
<thead>
<tr>
<th>Mega-Environment (ME)</th>
<th>Genotype</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME1 (Irrigated environment)</td>
<td>Super Kauz, Pavon 76, Genaro 81, Opata 85</td>
</tr>
<tr>
<td>ME4A (Mediterranean Region)</td>
<td>Almansor, Nesser, Sitta, Siete Cerros</td>
</tr>
<tr>
<td>ME4B (Southern Cone, S. America)</td>
<td>Cruz Alta, Prointa Don Alberto, LAP1376, PSN/BOW CM69560</td>
</tr>
<tr>
<td>ME4C (South Asian Subcontinent)</td>
<td>C306, Sonalika, Punjab 81, Barani</td>
</tr>
</tbody>
</table>

Source: Calhoun et al. (1994)
Table 4. Grain yields of selected wheat genotypes grouped by adaptation and tested under moisture regimes in the Yaqui Valley, Mexico, 1989/90 and 1990/91

<table>
<thead>
<tr>
<th>Adaptation group</th>
<th>Full irrigation&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Late drought&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Early drought&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Residual moisture&lt;sup&gt;d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>ME (Irrigated environment)</td>
<td>6,636&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4,198&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4,576&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3,032&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>ME4A (Mediterranean Region)</td>
<td>6,342&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3,990&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>4,390&lt;sup&gt;b&lt;/sup&gt;</td>
<td>3,032&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>ME4B (Southern Cone, S. America)</td>
<td>5,028&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3,148&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>4,224&lt;sup&gt;b&lt;/sup&gt;</td>
<td>2,359&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>ME4C (South Asian Subcontinent)</td>
<td>4,778&lt;sup&gt;c&lt;/sup&gt;</td>
<td>3,245&lt;sup&gt;bc&lt;/sup&gt;</td>
<td>3,657&lt;sup&gt;c&lt;/sup&gt;</td>
<td>2,704&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Source: Calhoun et al. (1994).

Note: Means in the same column followed by the same letter are not significantly different at P = 0.05.

<sup>a</sup> Received 5 irrigations.
<sup>b</sup> Received 2 irrigations early, before heading.
<sup>c</sup> Received 1 irrigation for germination and 2 post-heading.
<sup>d</sup> Received 1 irrigation for germination only.

Another piece of evidence is Nesser, an advanced line with superior performance in drought conditions. Nesser was bred at CIMMYT—Mexico and identified by the CIMMYT Mediterranean program located at the International Center for Agricultural Research in the Dry Areas (ICARDA) in Syria. The cross combines the high yielding CIMMYT variety Jupateco 75 and the drought tolerant Australian variety W3918A. The performance of Nesser in the dryland environments of West Asia and North Africa (WANA) has been widely publicised (ICARDA 1993), and the line is considered to represent a uniquely drought-tolerant genotype. This line was selected at CIMMYT/Mexico under favourable conditions, and it carries a combination of input efficiency and high yield responsiveness. In the absence of rust, its performance is quite similar to that of Veery S.

A breeding scheme to achieve the combination of yield responsiveness and drought tolerance in wheat is presented in Table 5. This method is supported by research on wheat as well as other crops, in which testing and selecting in a range of environments, including well-irrigated ones, has identified superior genotypes for stressed conditions (see, for example, Ehdaise, Waines, and Hall 1988; Duvick 1990, 1992; Bramel-Cox et al. 1991; Uddin, Carver, and Clutter 1992; Zavala-García et al. 1992; and Cooper, Byth, and Woodruff 1994). The approach results in the selection of germplasm that is adopted by farmers because it translates improved environmental conditions into yield gains. The traditional methodology of selecting only under drought conditions and narrowly relying on landrace genotypes does not move yield levels significantly beyond those usually obtained, and it does not provide the farmer with a bonus in years when rainfall is higher.
Table 5. Methodology for breeding drought-tolerant wheat that is also responsive to favourable environmental conditions

<table>
<thead>
<tr>
<th>Generation</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F1</strong></td>
<td>Crosses involving widely adapted germplasm, representing yield potential, yield stability, and input responsiveness, with lines carrying proven drought tolerance in the setting of the respective drought mega-environments (ME4A, ME4B, or ME4C), and input (water) use efficiency. Winter wheat and synthetics are emphasised.</td>
</tr>
<tr>
<td><strong>F2</strong></td>
<td>Individual plants are raised under irrigated and optimally fertilised conditions, and inoculated with a wide spectrum of rust virulence. Only robust and horizontally resistant plants are selected. These plants may represent adaptation and responsiveness to favourable environmental conditions.</td>
</tr>
<tr>
<td><strong>F3</strong></td>
<td>The selected F2 plants are evaluated as F3s in a modified pedigree/bulk breeding system (Rajaram and van Ginkel 1995) under rainfed conditions or very low water availability. The selection is based on such criteria as spike density, biomass/vigour, and grains/m², among others (van Ginkel et al. 1998). This index helps identify lines that may adapt to conditions in which water is limited (that is, lines that are input efficient).</td>
</tr>
<tr>
<td><strong>F4</strong></td>
<td>Selected lines from F3 are further evaluated under optimum conditions, as for the F2.</td>
</tr>
<tr>
<td><strong>F5</strong></td>
<td>As F3.</td>
</tr>
<tr>
<td><strong>F6</strong></td>
<td>As F4.</td>
</tr>
<tr>
<td><strong>F7, F8</strong></td>
<td>Simultaneous evaluations under low and intermediate (representing the higher rainfall years in marginal drought environments) water regimes. Selection of those lines showing outstanding performance under both conditions. Further evaluation in international environments is carried out for verification.</td>
</tr>
</tbody>
</table>

**HIGHER YIELDING DURUM WHEATS**

Although durum wheat is not cultivated as widely as bread wheat, it occupies a special niche in the developing world. Durum wheat is generally sown in marginal environments subject to great climatic fluctuations during the growing season. The durum crop may experience heat and drought at different times during its growth cycle. Most of the developing world durum area is concentrated in the countries of West Asia and North Africa, but durum is also grown in central and south India, Ethiopia, Mexico, Argentina, Peru, Kazakhstan, Azerbaijan, and Ukraine. Often the crop is grown by poor people who rely on it for a high proportion of calories in the diet or for income—as durum in some areas fetches a premium in the local market. Short-cycle, semidwarf durum wheat varieties recently tested in northwestern Mexico produced a remarkable 89 kg of grain per hectare per day, for a final tally of 11.7 t/ha at harvest (W. Pfeiffer, pers. comm.). This is an increase of more than 20% over the previous generation of durum wheats. Generally average yields of durum wheat in farmers’ fields in northwestern Mexico are 6 t/ha, and the world average is 2–3 t/ha. If these recently tested wheats retain some of their yield advantage in marginal conditions, they may prove to be a valuable asset for breeding programs.

Regional Research on Wheat for Marginal Environments

**West Asia and North Africa.** About one-third of the area planted to wheat in the developing world is located in marginal environments plagued by drought and soil problems. These problems are frequently exacerbated by a lack of infrastructure and farmer support services. Most of the world’s drought-prone wheat area is concentrated in the WANA region (Table 1). Wheat is the principal food source for people in WANA, who on average consume more than 145 kg/cap/yr, one of the highest levels of per capita consumption in the world.

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4 In parts of India, durum production is relegated to the hottest and driest environments.
CIMMYT efforts aimed at improving wheat production in WANA are conducted in conjunction with ICARDA. The CIMMYT Mediterranean and ICARDA Joint Dryland Wheat Program for West Asia and North Africa seeks to increase wheat productivity by developing spring bread and durum wheats that are better adapted to the WANA region. Wheats developed or identified by the program are widely adapted and possess enhanced disease and insect resistance, as well as better tolerance to the prevalent abiotic stresses. This is why our partners in the region increasingly select them for use in their own breeding programs. Farmer adoption of CIMMYT- and CIMMYT/ICARDA-derived varieties in WANA continues to increase, with more than 90 wheat varieties released in 21 countries in the region over the past 10 years.

The Turkey/CIMMYT/ICARDA International Winter Wheat Improvement Program (IWWIP) based in Ankara, Turkey, came into existence 11 years ago with the purpose of generating winter wheats for developing countries, particularly in the WANA region. Over the past two years, IWWIP has expanded its collaboration with winter wheat programs in the developing world. New research partnerships with colleagues from Central Asian and the Caucasus has greatly increased the number of cooperators.

The program is devoting particular attention to improving resistance to yellow rust, which is the most serious winter wheat disease in WANA. It conducts trials using artificial inoculation in Ankara, Konya, and Eskisehir (Turkey), Aleppo (Syria), and Iran. It is also conducting research on micronutrients aimed at identifying zinc-efficient wheats to be used in crosses and alien materials that may be potential sources of zinc efficiency. At present, rye and triticale seem to be the best sources, but other alien species are also being tested at Turkey’s Çukurova University.

Central Asia and the Caucasus. The republics of Central Asia and the Caucasus are relatively diverse in climate, agricultural production, and population. What these eight countries (Armenia, Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Tadjikistan, Turkmenistan, and Uzbekistan) have in common is that they are all in transition from being centrally planned economies to becoming market-oriented ones. Nearly 15 million hectares are planted to wheat in the region, but with the exception of Kazakhstan, all countries have to import wheat to satisfy domestic demand. A major objective of their governments is to become self-sufficient in wheat.

In 1992, after the political situation changed, CIMMYT re-established contacts with research programs in the region. In 1998, CIMMYT was mandated by the CGIAR to address the needs for wheat germplasm in this region. Breeders and research administrators from the region have visited IWWIP in Ankara or CIMMYT in Mexico, and CIMMYT scientists have visited several of the newly independent nations. In 1998 CIMMYT opened a regional office in Kazakhstan. There is now active exchange of germplasm and information. In the future, CIMMYT will initiate shuttle breeding programs with the region. A joint CIMMYT/Kazakhstan breeding program to combine quality, drought tolerance, and disease resistance in high latitude spring wheat is in the planning stages. If successful, it would contribute to the food security not only of Kazakhstan, but of the whole region.

Eastern Africa. Now in its fourth phase, the CIMMYT/Canadian International Development Agency Eastern Africa Cereals Program (EACP) has as its main objective to increase maize and wheat production and productivity in eastern Africa. During its third phase, the wheat component of the program focused heavily on developing sustainable production systems for the major wheat growing environments in the region and on strengthening national program commitment and capacity for long-term experimentation. During 1993–96, Kenya, Ethiopia, and Uganda released 13 CIMMYT-related bread wheat and durum wheat varieties. Studies conducted by the EACP in collaboration with Ethiopia and Kenya found that reduced or zero tillage produced either the same or better yields than conventional tillage systems. The EACP also developed agronomic recommendations to improve yields and nitrogen use efficiency in areas that experience waterlogging problems. An encouraging fact brought to light in a recent report by the EACP is that several decades of breeding durum and bread wheats from CIMMYT semidwarf wheats in Ethiopia have resulted in annual increases of 1.5–2.0% in yield potential based on rainfed experiments.

**Improvements in wheat quality**

Often wheat quality is perceived to be important only to large-scale farmers dedicated to commercial production. In fact, traits related to quality in wheat are even more important for many poor farmers, whose incomes may increase if they can produce wheat that receives a price premium for its quality characteristics.

Several studies have concluded that wild diploid species carrying A- and D-genomes have greater allelic variation than cultivated wheat for gene loci controlling glutenin subunits (Waines and Payne...
1987; Lagudah and Halloran 1988; Ciaffi et al. 1992; Lafiandra, Ciaffi, and Benedetelli 1993; William, Peña, and Mujeeb-Kazi et al. 1993). These alien genes offer a potential means of expanding the number of allelic variants controlling proteins with desirable quality effects in wheat. Several of the synthetic hexaploids developed from accessions of diploid Triticeae species (T. tauschii, T. boeoticum, T. monococcum, and T. urartu) and durum wheat have been examined in relation to grain characteristics associated with end-use quality of bread and durum wheats. The analyses revealed that T. tauschii may be used for substantially increasing the number of high molecular weight glutenin (HMWG) subunits present in bread wheat (HMWG subunit composition is implicated in the definition of gluten strength in both bread wheat and durum wheat) (Payne et al. 1981; Pogna et al. 1990).

We have also examined variability for quality (grain hardness, protein content, and SDS-sedimentation) as well as the relationship between quality and HMWG and low molecular weight glutenin (LMWG) subunit composition (SDS-PAGE) in 137 accessions of T. dicoccon. Results confirm previous findings that T. dicoccon has more diverse genetic variability for alleles involved in the synthesis of gluten-type proteins than cultivated wheat. T. dicoccon should be considered a good potential source for improving gluten strength in bread and durum wheat.

In the past three years, the frequency of high quality CIMMYT bread wheats has increased dramatically. A modification of the crossing strategy, emphasising high quality parents, was implemented in the early 1990s. Quality testing of advanced generation breeding materials was increased over the past few years. Now these two strategies have come to fruition. In the near future, about 75% of CIMMYT’s new bread wheat germplasm will be competitive for quality standards in the marketplace.

BIOTECHNOLOGY AND WHEAT IMPROVEMENT: AN EXAMPLE OF COLLABORATION

By drawing on the power of biotechnology, CIMMYT seeks to make plant breeding more efficient and, in some cases, to improve wheat in ways that have eluded conventional breeding approaches. The comparative genetic mapping of cereal genomes has identified a vast amount of conserved linearity of gene order (Devos and Gale 1997). This observation is likely to accelerate the application of quantitative trait loci (QTL) in wheat, as well as aid in the identification of genes required for introgression from alien species. Given the low number of loci tagged at present in wheat, the problems related to developing a high-density map for wheat (Snape 1998), and the limited progress to identify QTL for yield in wheat, we believe that the impact from this linearity on wheat improvement will be significant.

An extremely positive development in CIMMYT’s efforts to apply biotechnology to wheat improvement is participation as a core partner in the Cooperative Research Centre (CRC) for Molecular Plant Breeding, established and supported under the Australian government’s Cooperative Research Centres Program. The CRC collaboration features two main projects. The first projects aims to identify molecular markers for resistance to leaf rust and yellow rust. In line with the rust resistance breeding strategy described previously, researchers from CIMMYT and Australia are looking for minor genes to create durable resistance. For CIMMYT’s partners in the international wheat improvement system, the value of this project is clear. For Australia, this work will prove valuable in the event that rust resistance in its wheat varieties (largely based on major genes) breaks down, as has occurred on occasion in the past.

The second project in the CRC collaboration focuses on introducing, via transgenics, resistances to some fungal pathogens of wheat and then characterise their effects. An important aspect of this work was to increase transformation efficiencies, which were low at the outset. Rates of
transformation have been significantly increased (efficiency was 0.2–0.4% before; now it averages about 1% and may reach 5% in the near future), and researchers are proceeding with the other objectives.

By collaborating with the many institutes involved with the CRC that are leaders in molecular genetics in wheat, CIMMYT can tap into their expertise in ways that will greatly benefit many of our partners in the international wheat improvement system. Australia will also see positive results from the collaboration. According to the last annual report of the CRC for Molecular Plant Breeding, ‘CIMMYT’s global field program provides CRC scientists with the opportunity to evaluate germplasm and populations in a wide range of environments. This makes it much easier for researchers to develop molecular approaches to the isolation of traits than if they were limited solely to Australia’s agro-ecological environments’ (CRC for Molecular Plant Breeding 1998). Many globally important diseases are not yet present in Australia, but resistance to them is present in CIMMYT germplasm, and the current research on molecular markers could one day play a key role in protecting Australian agriculture and varieties.

CROP AND NATURAL RESOURCE MANAGEMENT RESEARCH

When combined with robust, highly productive crop varieties, it is not uncommon for improved management practices to raise farmers’ yields twice and even three times. Strategic research on crop and natural resource management leads to improved farming practices and more sustainable maize and wheat production systems. Such research involves a complex iteration of field studies, crop and soil modeling, the use of geographic information systems, and remote sensing. At CIMMYT, agronomists are examining nutrient auditing and strategic fertiliser use; appropriate strategies for replenishing soil organic matter (such as green manures and crop residues); the development of suitable crop rotations; reduced tillage; and integrated pest and weed management. Some of these strategies are described in the sections that follow.

IMPROVED INPUT USE EFFICIENCY

Combining input efficiency with high yield potential in new cultivars will allow a farmer to benefit from these cultivars over a wide range of input levels. Selection for yield potential under medium to high levels of nitrogen has indirectly increased the efficiency of N uptake in CIMMYT wheats. Recently released CIMMYT bread wheat cultivars require less N to produce a unit of grain than cultivars released in previous decades (Ortiz-Monasterio et al. 1997). The increase in nitrogen use efficiency is shown in Figure 2. Under low N levels in the soil, N use efficiency increased mainly due to a higher N uptake efficiency—the ability of plants to absorb N from the soil—whereas under high N levels, the N utilisation efficiency—the capacity of plants to convert absorbed N into grain yield-increased.

![Figure 2. Grain yield of the historical series of bread wheats at Cd Obregón, Mexico at 0 and 300 kg/ha N application.](image_url)
A study initiated in 1994 evaluated changes in soil nutrients and gas emission before and after fertiliser applications and compared alternative ways of applying nitrogen, including the farmers’ common practice (Matson, Naylor, and Ortiz-Monasterio 1998). The experiment compared the common practice of Yaqui Valley farmers with alternatives that included reducing the amount of nitrogen applied and changing the timing of its application. The researchers found that with the farmers’ practice, relatively high levels of nitrogen were lost into the atmosphere when nitrogen came into contact with irrigation water, even before the wheat crop was in the ground. The best practice reduced the amount of nitrogen (from 250 to 180 kg/ha, one-third applied at planting and two-thirds six weeks later) and produced yields and grain quality similar to those obtained under the farmers’ practice. The best alternative practice also saved US$ 55-76/ha (equivalent to saving 12–17% in after-tax profits). The study shows that it is possible to reduce nitrogen gas emissions and fertiliser losses through appropriate agronomic practices and at the same time maintain yields.

BED PLANTING SYSTEMS
A reduced tillage system developed by farmers and researchers in Mexico’s Yaqui Valley is showing its potential there and in other irrigated wheat production environments. In this system, a crop is grown on raised beds that are divided by furrows for irrigation. No soil inversion tillage is used on the beds. Crop residues are chopped and left on the surface of the beds. The system has several advantages for farmers and the environment, including:

- Nitrogen can be applied when and where the wheat plants can use it most efficiently. Yields improve, and nitrogen losses into the environment are significantly reduced.
- Water conservation improves. As water for agriculture becomes more scarce in the years to come, water conservation practices will become more important for farmers. Researchers in South Asia report a 30% savings in water use from using bed planting and improved weed control.
- Weeds can be controlled by cultivating between the beds-reducing costs and the need for herbicide.
- Residues are returned to the soil without burning, which is beneficial to the environment.
- The beds can be used cycle after cycle. Farmers avoid the financial and environmental costs of making repeated passes with a conventional plow during land preparation.

Prototype machinery specifically for this bed planting system has been designed and tested in Mexico and in Asia. The prototypes are modifications of standard agricultural equipment and are expected to be affordable for poor farmers. Mexican farmers reportedly save 30% on their production costs when they use the bed planting system. Some 10,000 farmers are thought to use the system in Mexico, and the number of farmers who are using bed planting is growing in South Asia and China as well. In fact, in parts of China some farmers find the technology so valuable that in the absence of equipment they form the beds by hand.

FARMER PARTICIPATORY RESEARCH
Over the past few years, CIMMYT has significantly increased its investment in farmer participatory research for natural resource management (that is, in the development of productivity-enhancing, resource-conserving practices for maize and wheat systems, with beneficial impacts on soils, water, and agroecosystem diversity). Farmer participatory research is a tool for a purpose: the development of sustainable practices that improve resource quality while raising system productivity. CIMMYT is moving aggressively to mainstream the use of this tool for these important ends. For example, in irrigated areas in northern Mexico, CIMMYT has long collaborated with farmers in the development of the bed planting systems described earlier.
In Asia, CIMMYT works with the other members of the Rice-Wheat Consortium for the Indo-Gangetic Plains to foster farmer experimentation on reduced and zero tillage strategies for establishing wheat after rice. Farmer groups have assessed alternative tillage and sowing implements and wheat establishment strategies, and they have been encouraged to develop their own innovations and adaptations. Minimum tillage practices are spreading in Bangladesh, and farmers in the western part of the Indo-Gangetic Plains are beginning to use zero tillage. Farmers report earlier sowing, higher yields with lower levels of inputs, and improved possibilities for diversifying cropping patterns away from a continuous rice-wheat rotation—with numerous agroecological benefits.

In Bolivia, we are collaborating with farmer groups to develop zero tillage/mulch systems suitable for smallholders (2−5 ha) in the high inter-Andean valleys. These farmers produce one crop of wheat each year in monoculture or in rotation with potatoes, faba beans, peas, and/or barley. Research focuses on evaluation of straw cover to increase rainfall use efficiency. Results are extremely encouraging: crop residue retention generally increases yields and reduces risk, two important objectives for Bolivia’s small-scale, subsistence farmers. Researchers also participate in a project to develop a small, animal-drawn, no-till seed drill for sowing cereals into surface residues, and results are very positive (CIMMYT 1999).

INFORMATION MANAGEMENT TOOLS FOR SUSTAINABLE SYSTEMS

Researchers have always believed in the value of sharing information more widely, but the limitations of information technology have not made this easy. CIMMYT now offers a widening array of information management tools to researchers in many disciplines.

For example, the International Wheat Information System (IWIS) is a relational database available on CD which gives each genotype a unique identifier and provides extensive pedigree and performance data. The Genetic Resources Information Package (GRIP), designed in conjunction with Australian partners, allows IWIS users to locate seed samples in wheat germplasm stocks in a number of collections around the world and provides an abbreviated version of the IWIS pedigrees. The International Crop Information System (ICIS) is a data management tool that builds on IWIS. It contains information on several crops in addition to wheat. The core of ICIS is a relational database structure that stores data on plant genetic resources, pedigrees, field and laboratory evaluations (including molecular information), and auxiliary data on locations, institutions, and people. Simple geographic information functions are being incorporated into ICIS, and a tool for exporting data to crop simulation models is also under development.

One challenge to sharing information more widely is to provide access to cutting-edge geographic information system (GIS) tools for non-GIS users, especially those in Africa. African researchers need spatially referenced data on climate, soils, infrastructure, crop distribution, and the natural resource base, in part to ascertain the extent to which their site-specific research may have relevance to larger areas. The Africa Country Almanacs contain such base data, along with the most commonly requested maps, plus search and viewing tools, on a single compact disc. Almanacs have been developed for 12 African countries, some of which have requested follow-on demonstrations and training for their research staff. Now all researchers can have access to these powerful GIS tools, not just a few specialists in a central office.

The Spatial Characterisation Tool (SCT) developed by CIMMYT and Texas A and M University goes a long way towards addressing the problem of ‘site specificity’ in natural resources management research. Site researchers can now quickly perform ‘site similarity analysis’, identifying areas with

5 Including three important wheat producing nations: Ethiopia, Kenya, and Zimbabwe.
environments resembling that of their site. When applied to sites in Bolivia, this analysis uncovered environmentally similar areas within Bolivia; in neighbouring countries (e.g., Chile, Brazil); within the Americas (e.g., Mexico); and even in other regions of the world (Ethiopia, Lesotho). Scientists in these diverse locations find that they have much to share about technology performance and the consequences of technical change for system productivity and sustainability.

These information management tools help encourage research integration, explore the prospective performance of new technologies, and overcome site specificity. However, like all information management tools, they need data. A final challenge is how to preserve, organise, and make available to researchers the rich array of data often generated by research, particularly in natural resource management research. CIMMYT is developing an answer to this set of challenges: the Sustainable Farming Systems Database (SFSD). Non-governmental organisations are using the SFSD prototype to organise information on the global experience with green manure cover crops. As the SFSD matures, its uses will be virtually infinite.

CONCLUSIONS

The strategies we have just outlined could make the difference between a sustainable future, with food and economic opportunity available for the majority, and a future of scarcity, with survival seriously compromised for most people. Successful, sustainable agriculture can help create the purchasing power and employment that will ensure food security and help eradicate poverty. We believe that the risks of ignoring agricultural development will be far higher than the risks of deciding to create a sustainable future for us all.

The world has faced a similar choice before, when a decision was made to sow the new semidwarf wheats in India in the hope that their higher yields would prevent a famine on the order of the devastating Bengal famine of 1943. That decision transformed agriculture and the way that agricultural research was conducted. Today CIMMYT and its partners join forces in one of the world’s most ambitious endeavours: we participate in a global wheat improvement system that continues to better the lives of millions of poor farmers and consumers in developing countries. The impact of that system is well documented (Byerlee and Moya 1993; Maredia and Byerlee 1999; CIMMYT 1999). In the most recent period, 1991–97, almost 90% of the spring bread wheat varieties released by national agricultural research systems had CIMMYT ancestry (Figure 3). Virtually all (98%) of the spring durum wheats released by national programs in 1991–97 had CIMMYT ancestry (Figure 4). Farmers now plant almost 80% of the developing world’s spring bread wheat area to CIMMYT-related wheats (Figure 5).
Figure 3. Ancestry of spring bread wheat varieties released by national programs, 1991-1997.
Source: CIMMYT wheat impacts database.

Figure 4. Ancestry of spring durum wheat varieties released by national programs, 1991-1997.
Source: CIMMYT wheat impacts database.
Figure 4. Ancestry of spring durum wheat varieties released by national programs, 1991-1997.

Source: CIMMYT wheat impacts database.

Figure 5. Area planted to spring bread wheat in developing countries, 1997.

Source: CIMMYT wheat impacts database.
A New Research Paradigm for New Research Impacts

These research impacts are reassuring, but much remains to be done. When our colleague Norman Borlaug accepted the Nobel Peace Prize for his achievements in bringing about the Green Revolution in wheat, he cautioned that the Green Revolution ‘has not transformed the world into Utopia. None are more keenly aware of its limitations than those who started it and fought for its success . . . . Above all, I cannot emphasise too strongly the fact that further progress depends on intelligent, integrated, and persistent effort’ (CIMMYT 1970).

Borlaug’s observation remains true. If we are to make progress toward sustainable food security, we must take his advice and change the way we plan, conduct, and communicate about research. We must blend very specialised research disciplines in teams of scientists seeking appropriate outcomes that have an immediate impact in farmers’ fields. It is from these fields that food supplies must come for the foreseeable future. The farmer is the ultimate systems-oriented operator, juggling biological, economic, environmental, and social factors. In such circumstances, isolated interventions are of limited value at best; all too often, they make things worse.

These interventions will be based on a new, integrative research paradigm that focuses on the elements of the G×E×M×P equation mentioned earlier: the best genotypes (G), in the right environments (E), under appropriate crop management (M), generating appropriate outcomes for people (P). Everyone who seeks to foster sustainable agriculture in developing countries should recognise the interdependence of these factors, because most organisations by themselves cannot contribute fully to each aspect of G×E×M×P. Partnerships and consortia that assemble the best possible teams to execute the G×E×M×P approach will underpin the timely and successful achievement of sustainable farming systems and future food security.

The shape of things to come

Given these requirements, what will agricultural research look like in the new millennium? Every member of the international wheat improvement system—and the farmers and consumers who depend on it—will be affected by changes in international research in the years to come. Which forces are likely to shape the way that research is done—either by contributing to or detracting from the integrative research paradigm we have just described?

For decades, collaboration has been the mainspring of the international wheat improvement system. None of the achievements described in this paper could have been attained without it. Gains from conventional breeding will continue to be significant in the next two decades or more (Duvick 1996), but these are likely to come at a higher cost than in the past. Research managers and policy makers are increasingly concerned that the very open, collaborative networks that have sustained the wheat improvement system will become far more circumscribed in coming years.

Rasmussen (1996) has stated that nearly half of the progress made by breeders in the past can be attributed to germplasm exchange. In recent surveys of wheat breeders (Braun et al. 1998; Rejesus, van Ginkel, and Smale 1996), more than 80% of respondents expressed concern that plant variety protection (PVP) and plant or gene patents will restrict access to germplasm, with deleterious consequences for future breeding achievements. Regional and international nurseries are an efficient, low-cost means of gathering data from varied environments and exposing germplasm to diverse pathogen selection pressures, while providing access to germplasm and promoting germplasm exchanges. Breeders use cooperative nurseries extensively in their crossing programs, but the number of such nurseries has been greatly reduced during the past decade, partly because of increasing restrictions on germplasm exchange.

Recent developments in biotechnology for plant improvement have motivated much of the concern over PVP and other forms of intellectual property rights (IPR), as well as concern over germplasm exchange and developing nations’ access to novel agricultural technologies. That debate promises
to pale in comparison to another biotechnology-inspired debate, however, that has been prominent in the media.

The debate over the ethical uses of biotechnology has shifted to the agricultural sector. A furor over genetically modified plants (focusing on uncertainty over their potential effects on human health and the environment) has swept across Europe, where ‘the public’s perception of risk far outweighs its view of the possible benefits’ (The Economist, 19 June, 1999). Within development circles, some argue that it is too risky to use genetic engineering to solve poor people’s problems because we may be unaware of future side effects. Others question whether it is ethical to withhold solutions to problems that cause millions of children to die from hunger and malnutrition. Clearly we must seek acceptable levels of biosafety before releasing products from modern science, but it is critical that the risks associated with the solutions be weighed against the ethics of not making every effort to solve food and nutrition problems.

These highly public-and highly charged-debates make it easy to lose sight of another trend in the research environment that is almost more worrying. For a host of reasons, many national agricultural research systems have become weaker over the past two decades rather than stronger. At the international level, public support for broad research initiatives, such as CIMMYT’s improvement of wheat germplasm for the major environments in the developing world, has diminished as public research investments have increasingly focused on more narrowly targeted projects. Under these circumstances, can we reasonably expect the public sector to be an effective advocate on behalf of the poorest constituents of society? Will the declining resources commanded by the public sector interfere with germplasm testing and exchange even more than the trends described earlier? Given the vast resources commanded by private research organisations, what is the future role of the public sector in crop improvement research?

Despite these uncertainties in the research environment, our ultimate objective remains clear. We know that to ensure food security in the 21st century, the sustainable intensification of agriculture in farmers’ fields is essential. With 200 people added each minute to our population, and with all of us, rich and poor alike, dependent on a shrinking agricultural resource base, sustainable intensification is the only practical and appropriate choice for the foreseeable future. The new millennium holds out incredible promise-superior technology, unprecedented access to information, economic growth—but if these serve only to widen the gap between the ‘haves’ and ‘have-nots’, between the North and South, then what will we have gained? Of the many issues surrounding the future of international agriculture, this is perhaps the most important. It is the central issue that motivates CIMMYT’s research agenda, and it will remain at the forefront of all of our future efforts.

REFERENCES


Managing Cereal Rusts - National Perspective
R.A. McIntosh, University of Sydney Plant Breeding Institute, New South Wales

SUMMARY
The cereal rusts are known as ‘social’ diseases because the individual farmer is subject to air-borne spores from areas beyond the farm and part of any inoculum produced on farm is dispersed to others. Control of rust diseases must therefore be addressed at the community level, preferably through the widespread use of resistant varieties. Control of out-of-season host material is an important aspect of delaying infection. Chemicals can be used as seed dressings to control early infection or as foliar applications, but must be timely applied. Knowledge of the rust pathotypes and the predicted responses to those pathotypes is important in variety choice. There is always the threat of new resistance-breaking pathotypes either from mutational change locally or from elsewhere in Australia or overseas. Wheat stripe rust is yet to appear in Western Australia.

INTRODUCTION
The rusts are among the most important diseases of cereals worldwide. The cereal rusts are caused by fungal pathogens that are highly specialised and restricted largely to single host species. Although most of them have alternate hosts on which they complete a sexual cycle, the alternate hosts are not common in this country. The uredospores must recycle on green hosts plants, usually the specific cereal host (Table 1).
Uredospores are airborne and can disperse over long distances, usually following predominant weather patterns. However, movement of people and goods has become increasingly important. For these reasons the rusts can be described as ‘social’ diseases - national problems where a particular farmer can play only a partial role in control, but a single grower with a susceptible crop can be destructive. A concerned grower can adopt resistant varieties and control self sown cereals over summer, but they can still be affected by incoming inoculum from neighbours, or indeed from rusted crops far removed from their property.

Table 1. Cereal rusts, their cereal hosts and other host species

<table>
<thead>
<tr>
<th>Rust</th>
<th>Cereal Host</th>
<th>Other hosts</th>
<th>Likely significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat stem rust</td>
<td>Wheat¹</td>
<td>Barley², some grasses</td>
<td>Moderate, low</td>
</tr>
<tr>
<td>Wheat leaf rust</td>
<td>Wheat¹</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wheat stripe rust</td>
<td>Wheat¹</td>
<td>Barley grass³, some grasses</td>
<td>Moderate</td>
</tr>
<tr>
<td>Oat stem rust</td>
<td>Oat</td>
<td>Wild oats</td>
<td>High</td>
</tr>
<tr>
<td>Oat leaf rust</td>
<td>Oat</td>
<td>Wild oats</td>
<td>High</td>
</tr>
<tr>
<td>Barley leaf rust</td>
<td>Barley</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rye leaf rust</td>
<td>Rye</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rye stem rust</td>
<td>Rye</td>
<td>Barley², some grasses</td>
<td>Moderate, low</td>
</tr>
</tbody>
</table>

¹ Although usually resistant, triticale may be infected with certain pathotypes of the wheat rust group.
² Out of season, late sown or early sown barley can be very susceptible to stem rust, therefore barley can be important in rust survival.
³ See also comments on barley grass stripe rust.
⁴ The alternate host occurs in a small area of South Australia.
EPIDEMIOLOGY IN AUSTRALIA

On-farm/local. A rust epidemic can be compared to a bushfire.

- Sparks Initial inoculum
- Fuel Susceptible varieties
- Temperature/wind Climatic conditions/moisture

The presence of resistant varieties in an epidemic is like green fuel to a fire - it will have effect but there will be scorching in a big one.

The farmer can reduce the likelihood of on-farm rust survival by control of self-sown cereals and by having (more) resistant varieties. However they have little control over off-farm situations.

Pathogens/pests have an added dimension; their ability to undergo genetic change in order to overcome the protection provided by resistant varieties. In the absence of sexual reproduction this occurs either from mutation or from introduction of new pathotypes. New mutants overcome resistance in varieties that have the same genes for resistance - hence the need for genetic diversity.

Regional/national. The long term patterns of rust movement in Australia are north to south as the crop matures and west to east with the dominating weather patterns, but local effects are also important. With the greater likelihood of summer rainfall in the north, self sown plants and rust survival is increased. All coastal and highland areas are potential over-summering areas. However, summer storm activity on a local basis, or the presence of cereals (or susceptible grasses such as wild oats) in irrigated areas may be adequate to ensure survival of some rust on a more or less random basis. Since the control of wheat rusts in Queensland and northern NSW with the widespread use of resistant varieties, both the frequency and intensity of rust epidemics in eastern Australia have declined.

Western Australia is characterised by a hot dry summer, however over recent years leaf rust has survived. The areas more likely to be involved are the north, and coastal areas in the south. The 1999-2000 summer seems likely to be another year for widespread rust survival. Wheat stripe rust has not appeared in Western Australia some 20 years after its occurrence in the east.

Crop losses

The rusts cause losses in grain yield. Severe rusting, in oats for example, can lead to low palatability for grazing animals. Actual grain losses depend on the duration and intensity of the epidemic and on the degree of susceptibility of particular varieties. In extreme cases, stem rust causes complete losses, and leaf rusting or stripe rusting losses can exceed 50%.

Rust control

Control can be achieved by resistant varieties, or with chemicals. Farm/public hygiene measures may have some value in delaying the epidemic depending on the extent of inoculum carry-over. From the point of view of both farmers and public, resistant varieties should be the most economic procedure but chemicals are certainly a worthy backup. Chemicals must be applied at the correct time. Stem rust is more difficult to control than other rusts. Seed dressings may be useful in delaying early infection.

Types of resistance. Resistance is often described as major gene or minor gene but a number of other contrasting descriptions are used. Major gene resistance works throughout the lifecycle of the plant, and is often highly effective, but is considered vulnerable to mutational change in the pathogen. Most of the resistances we use in Australia are of this type. Minor gene resistance is usually less effective, operates at adult plant stages and may be influenced by environmental factors such as nutrition and temperature. Minor gene resistances are often based on multiple genes and are considered to confer more durable resistance. In some cases minor genes can be combined or 'pyramided' by breeders to provide very effective levels of resistance (especially useful for stripe rust).

Extension workers in Western Australia have attempted to promote the small differences in varietal response to leaf rust as a means of addressing the recent problems. However, as rust builds up on more susceptible varieties there is a considerable ‘scorching’ effect on the less susceptible types.
National Cereal Rust Control Program (NCRCP). Because the rusts are community (social) problems requiring national solutions, much of the rust work in Australia has been concentrated at the University of Sydney Plant Breeding Institute, Cobbitty, about 60 km south west of Sydney. The NCRCP has three primary functions:

(i) Pathogenicity surveys

Rust samples collected throughout the country by staff and collaborators are tested to determine pathotypes, their frequencies and distribution. This enables us to monitor the movement of pathotypes and to predict the responses of varieties. Significant findings can be communicated to breeders and the community. Some examples from the 1999 survey:
- The wheat stem rust pathotypes in Western Australia (34-2, 34-2,7, and 1 sample 34-2,7,8,9,10) were different from those in Victoria (predominantly 98-1,2,3,5,6). Consequently the variety responses are different.
- New pathotypes of wheat leaf rust affected long season wheats in Victoria (104-1, 2, 3, (6), (7), 11, 12, 76-1, 3, 5, 10,12 and 53-1, (6), (7), 10, 11, 12). Pathotype 104-1, 2, 3, (6), (7), 11 occurred in Western Australia as well as the east. The ‘Triller’ pathotype (104 -1, 2, 3, (6), (7), 9, 11) predominated in NSW and appeared on Mawson wheat in Queensland.
- Two isolates of stripe rust virulent on Yr 17 were obtained from research stations in NSW. The Western Australia cultivar Camm is one of several Australian wheats that carry Yr 17.
- Oat leaf rust with virulence for Pc68 attacking Graza 68 and Moola in Queensland.
- Barley leaf rust with virulence for Rph12 in Tallon, Lindwall, Franklin and Fitzgerald is now present in all states.
- ‘Barley Grass’ stripe rust is now present throughout eastern Australia and appears to be a threat to some varieties of barley.

(ii) Germplasm surveys and genetic and cytogenetic studies on the basis of resistance

As the rust pathogens evolve to neutralise genes for resistance, we must continue to introduce further genes for resistance. To do this we must identify new sources of resistance and establish through genetic studies that they are determined by new genes (or new gene combinations) that can be successfully integrated into breeding programs. Screening often must be done using key pathotypes identified in the pathogenicity survey. Molecular technologies have (will have) an increasing role in establishing gene identity and in aiding the combination of genes into single cultivars.

(iii) Germplasm screening and enhancement

The NCRCP provides seedling and field testing services for all breeding organisations in Australia (30-40,000 lines tested annually). The data obtained are used for line selection by breeders and in establishing expected cultivar responses for recommendation purposes. New genes are introduced into lines recommended by breeders as a means of enhancing resistance in existing materials - the aim is to stay ahead of the pathogen.

Table 2 provides the expected responses to four stem rust pathotypes and to the predominant leaf rust pathotype in Western Australia. Given that the main stem rust pathotypes in 1999 were 34-2 and 34-2,7 farmers can select appropriate resistant varieties for planting in 2000. The other two stem rust pathotypes have been found in Western Australia but the likelihood of them appearing in 2000 is less. Farmers who want to avoid all risks should select cultivars with R or MR ratings to all four pathotypes. The opportunities for choice of leaf rust resistance among this group of varieties are much less.

The Threat of Wheat Stripe Rust in Western Australia
When stripe rust first appeared in the east (probably Victoria) in 1979, it quickly spread to SA and Qld and reached New Zealand in 1980. We predicted its early arrival in Western Australia - either airborne or wind-borne, but this has not eventuated. However, the risk remains and some cultivars grown in Western Australia are very susceptible. Meanwhile Western Australia breeders have utilised opportunities for cultivar and line testing/selection at Cobbitty and Horsham, Vic. We also know that adult plant resistance is available and is preferable to seedling resistance.

Since 1979 stripe rust has undergone a number of changes, some of which affected the responses of commercial cultivars (e.g. Avocet, (Yr A), Millewa and Bindawarra (Yr 6)). More serious and different changes occurred in New Zealand where a wider range of major resistance genes were used.

Over the years we observed increasing infection of barley grass by stripe rust and actually demonstrated the breakdown of resistance in some barley grass genotypes. In 1998 a new form of stripe rust appeared on barley grass. This new rust is only poorly infective on wheat, but has been sampled from some barleys, especially Skiff and its derivatives. Barley breeders in the east have expressed sufficient concern that funds are likely to be allocated to firstly address the potential threat of barley grass stripe rust (BGYR) to barley, and secondly to undertake anticipatory breeding of barley for resistance to ‘true’ barley stripe rust (BYR) that does not occur in Australia. For this second aspect there will be dependence on a foreign collaborator for screening services. Australian barleys, generally, are susceptible to BYR.

BGYR and BYR are equally threats to Western Australia

**Exotic threats**

The threat of diseases we do not have (such as BYR) are easily recognised. However the threat of foreign pathotypes of disease pathogens that we have already is even greater. There is evidence from our wheat leaf rust work that foreign incursions are more frequent than earlier believed. For example, on close examination, leaf rust pathotype 104-2, 3, (6), (7), 11 was found to be much more distinct from the pre-existing 104-2, 3, 6, (7) than suggested by the respective names. This led us to suggest new introductions but our knowledge of global variability does not allow us to pinpoint an origin. The problem with imported pathotypes is that it is much more difficult to predict overall variety responses than it is to predict their responses to single gene mutants of existing pathotypes.

**Table 2. Wheat variety choice based on stem rust and leaf rust responses to Western Australian pathotypes**

<table>
<thead>
<tr>
<th>Cultivar</th>
<th>% Area</th>
<th>Relevant Sr gene(s)</th>
<th>Response to pathotype</th>
<th>Relevant Lr Gene(s)</th>
<th>Response to 104-34-2, 34-2, 7, 34-2, 7, 8, 9, 10, 343-1, 2, 3, 5, 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Westonia</td>
<td>10.3</td>
<td>S¹</td>
<td>SR, SR, MR</td>
<td>1 or 3</td>
<td>S</td>
</tr>
<tr>
<td>Arrino</td>
<td>9.8</td>
<td>30*</td>
<td>MR, MR, S, MR</td>
<td>3?, 23</td>
<td>S</td>
</tr>
<tr>
<td>Stiletto</td>
<td>9.7</td>
<td>12, 13</td>
<td>M, M, M, M, S</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Spear</td>
<td>8.0</td>
<td>9b, 17</td>
<td>R, R, R, R, S, 1*</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Carnamah</td>
<td>7.7</td>
<td>2, 12, 30</td>
<td>R, R, MR, R</td>
<td>27 + 31</td>
<td>MS-S</td>
</tr>
<tr>
<td>Amery</td>
<td>5.8</td>
<td>-</td>
<td>S, S, S, S</td>
<td>23</td>
<td>S</td>
</tr>
<tr>
<td>Eradu</td>
<td>5.6</td>
<td>2, 8a+</td>
<td>MR, MR, MR, MR</td>
<td>3</td>
<td>S</td>
</tr>
<tr>
<td>Brookton</td>
<td>5.3</td>
<td>30+</td>
<td>MR, MR, S, MR</td>
<td>-</td>
<td>S</td>
</tr>
<tr>
<td>Machete</td>
<td>5.1</td>
<td>2, 13</td>
<td>R, R, R, R, R</td>
<td>23</td>
<td>S</td>
</tr>
<tr>
<td>Cascades</td>
<td>5.0</td>
<td>8a, 9b, 12, 15</td>
<td>R, R, R, M, R</td>
<td>20</td>
<td>S</td>
</tr>
<tr>
<td>Halberd</td>
<td>5.0</td>
<td>6</td>
<td>R, R, R, S</td>
<td>-</td>
<td>MR</td>
</tr>
<tr>
<td>Calingiri</td>
<td>3.1</td>
<td>30</td>
<td>MR, MR, S, MR</td>
<td>-</td>
<td>MS</td>
</tr>
<tr>
<td>Variety</td>
<td>Rating</td>
<td>Genes</td>
<td>Susceptible</td>
<td>Moderately Susceptible</td>
<td>Moderately Resistant</td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>-------</td>
<td>-------------</td>
<td>------------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td>Tincurrin</td>
<td>2.4</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>-</td>
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<tr>
<td>Cunderin</td>
<td>2.1</td>
<td>9b, 12, 30</td>
<td>R</td>
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<td>R</td>
</tr>
<tr>
<td>Perenjori</td>
<td>2.0</td>
<td>9b</td>
<td>R</td>
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<td>S</td>
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<td>2b</td>
<td>R</td>
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<td>R</td>
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<tr>
<td>Datatine</td>
<td>1.2</td>
<td>24</td>
<td>R</td>
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<tr>
<td>Wilgoyne</td>
<td>1.1</td>
<td>9g</td>
<td>S</td>
<td>S</td>
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</tr>
</tbody>
</table>

* Genetically heterogeneous.

1 S = susceptible, MS = moderately susceptible, MR = moderately resistant, R = resistant, M = MR to MS.

GRDC Project No.: US 221
Managing cereal rusts in 2000, a regional imperative
R. Loughman, Agriculture Western Australia

KEY MESSAGE

- The extensive leaf rust and local stem rust epidemics of 1999 have resulted in the largest simultaneous buildup of wheat leaf and stem rust inoculum known in Western Australia. Wet harvest conditions and widespread heavy summer rains have provided ideal conditions for rust carryover.

- Rust will develop and impact on wheat production throughout all agricultural areas in 2000. Growing season conditions will determine local severity and overall impact.

- Assessments from the 1999 rust epidemic show important differences in varietal responses from those noted in previous years. The potential combination of leaf and stem rust will make varietal selection more critical.

- Summer volunteer weed control was largely ignored last year. Widespread uptake of this progressive crop management strategy is critical.

- Fungicide use, already at record levels in 1999, will continue to grow as farmers budget for increasingly available fungicide options.

INTRODUCTION

A general epidemic of leaf rust (Puccinia recondita f sp tritici) developed in wheat in 1999, commencing in the south east but spreading throughout the wheat belt by late spring. Stem rust (Puccinia graminis f sp tritici) also developed in the Esperance area and sporadically in the central and northern wheatbelt. Despite awareness of rust risk, inflexibility in sowing options resulted in large areas of susceptible varieties. Fungicide use was greatly increased. Initial estimates of lost production are around $20M.

Risk scenarios and predisposing factors in rust epidemics are well understood. Growers are becoming increasingly aware of yield losses that can result from major rust outbreaks. As a result many growers are adopting pre-seeding and post-seeding management strategies. These are designed to reduce risk in an environment that has traditionally not been affected by cereal rusts on a frequent basis (seven major epidemics this century). The need to re-tune crop management between years of low and high rust risk is a difficult task to achieve on a large scale. The limited options are constrained by complex farming systems and exacerbated by imprecise knowledge on economic benefit. For the first time in Western Australia's farming history growers have the challenge of successfully managing extreme risk of combined leaf and stem rust occurrence in wheat.

THE IMPACT OF THE 1999 EPIDEMIC

Experimental results in 1999 have confirmed the extent of yield losses associated with severe leaf rust development in Western Australia. Losses ranged from 10-30 per cent for susceptible varieties depending on severity. Leaf rust build up prior to winter had a greater impact than leaf rust developing later in the season. Losses for resistant or partially resistant varieties did not exceed 5-10 per cent. The extent of outbreaks indicate that leaf rust had greater impact overall than stem rust. As expected for stem rust, individual crop losses were greater with numerous crops in the Esperance, Lakes and Central wheatbelt that required fungicide or were severely affected. Where stem rust progress was late, yield losses around 10 per cent were observed. Losses of 40-50 per cent were measured in crops north of Esperance affected by stem or both leaf and stem rusts.
VARIETAL PERFORMANCE IN 1999

Most of the recent Western Australian varieties with partial resistance to leaf rust performed well. These were Brookton, Calingiri, Carnamah, Westonia, and Perenjori. Several of these varieties also combine useful resistance to other damaging leaf diseases. Generally these varieties had end of season leaf rust severities under 10 per cent which resulted in minimal losses. The contribution of partial leaf rust resistance to yield under severe disease is substantial (Figure 1.)

![Figure 1. Yield of two susceptible (left) and two partially resistant wheats (right) with and without fungicide protection from severe leaf rust, Mingenew 1999 (data of Bhathal and Loughman).](image)

Arrino proved more susceptible to leaf rust than expected. In some situations it behaved as moderately susceptible while in some cases it developed rapid leaf rust typical of a very susceptible variety. At Katanning Arrino wheat lost 24 per cent yield (0.8 t) while at Mingenew Arrino lost 20 per cent yield (0.7 t) when leaf rust became severe. The rust severities experienced indicate that fungicide will be important in use of this variety in 2000.

Ajana wheat (released 1998) and Karlgarin (released 1999), both proved to be very susceptible to leaf rust. Late leaf rust development in Ajana wheat caused around 11 per cent loss at Katanning while at Mingenew severe leaf rust contributed to 28 per cent yield loss. Ajana avoided problems with stem rust indicating its moderate resistance to stem rust remains effective.

While Westonia provided a useful level of resistance to leaf rust it was more susceptible to stem rust than expected and yield losses in one crop were measured at 46 per cent. The extent of stem rust development on Westonia in the Esperance area and the subsequent need for chemical control of these outbreaks indicate that Westonia is susceptible to the currently prevalent stem rust strains despite previously superior local performance.

Calingiri and Arrino wheats developed significant stem rust infection. Despite positive tests indicating the presence of partial resistance gene Sr30, infection was at times severe and these varieties are now considered susceptible. At present, pathotype testing undertaken by the National Cereal Rust Control Program indicates that virulence for Sr30 is very rare in Western Australia. Virulence changes do not explain the field performance of these varieties. Expression of Sr30 may be poor in these varieties due to a lack of other supporting resistance genes or Sr30 may actually be absent. It is clear that these varieties now need to be regarded as susceptible to stem rust in Western Australia.
Seven of the ten varieties most widely grown in 1999 are susceptible to either leaf or stem rust or both. Varieties such as Stilleto, which suffered 25 per cent loss when severely affected by leaf rust at Newdegate, will need to be de-emphasised in 2000. Approximately 50 per cent of wheat area sown in 1999 was to varieties with partial resistance to leaf rust (intermediate or better). Approximately 25 per cent of area sown was to varieties with combinations of some leaf and stem rust resistance (intermediate or better to both rusts). Among these, new rust resistant varieties such as Camm and Nyabing as well as established varieties Carnamah, Cunderdin, Datatine and Machete must be used to circumvent rust losses. Old stem rust resistance genes in varieties like Spear and Halberd, despite being rendered ineffective elsewhere in Australia, may have some value in Western Australia due to the current dominance of old stem rust pathotypes in the region.

FUNGICIDE CONTROL

In the 1999 season fungicide use has been greatly increased. This further develops the trend of broader adoption of in-crop fungicide in Western Australia, encouraged by greater availability of fungicides and more competitive prices. Fungicide will remain a key means of disease control in 2000.

Experimental results over a series of years indicate that around 70 per cent of the yield loss from leaf rust is prevented with a single standard rate fungicide spray and that this is generally the most economic means of preventing yield loss in susceptible infected varieties. In 1999 single sprays prevented 70-95 per cent of yield loss from leaf rust at Mingenew but only 50 per cent of loss at Newdegate under severe leaf rust pressure. In general, leaf rust control is readily achieved with fungicide and highly economic responses are frequently observed.

Control of stem rust with fungicide is difficult. The disease can develop quickly and should be controlled early, when first detected, for best results. Expensive highly effective fungicide treatments are required. Experiments with single high rates of fungicide application prevented almost 80 per cent of losses from leaf and stem rust in Amery and approximately 70 per cent of losses in Westonia and despite the expense, were highly profitable.

CONTROL OF WHEAT AND BARLEY VOLUNTEERS

Susceptible wheat varieties as well as summer barley can host wheat rusts out of season. Controlling these out of season hosts is an important factor in slowing early rust build-up. Response of growers to controlling self sown volunteers in 1999 was too little, too late. Growers in eastern and south eastern areas, where volunteers were most abundant, experienced very early rust infection. Such early infection requires expensive control options to prevent severe yield losses. Summer weed control is a progressive strategy for optimum crop production. Not only does it reduce the risk of severe early rust infection from local carryover, it also:

- reduces carryover of takeall, crown rot, root nematodes and cereal aphids;
- increases opportunities for early sowing by keeping cropping paddocks manageable and conserving soil moisture;
- augments management of herbicide resistant weeds through use of non-selective herbicides.

There is significant opportunity to improve uptake of this management strategy. However, it is difficult to encourage adoption by growers, particularly in stubble paddocks that are not intended to be cropped in the approaching season.

BARLEY AND OAT RUSTS

Barley has not been subject to attack by stem rust in Western Australia and represents a means of diversifying cropping to reduce exposure to wheat rusts. However a barley leaf rust pathotype virulent on Franklin, Gairdner and other barley cultivars was recognised in Western Australia in 1997 and
caused minor crop loss in 1998. Barley leaf rust became more widespread in 1999 but was not noted as being severe. While it could occur in 2000 it is likely that only with very favourable climatic situations would it induce losses similar to those of wheat leaf rust. Leaf and stem rusts remain significant constraints to oat production in epidemic years. Oaten hay crops appear vulnerable to leaf rust while grain crops are more vulnerable to attack by stem rust. Farm businesses heavily reliant on these crops should review cropping plans accordingly.
ARE RUSTS INCREASING IN IMPORTANCE?

Despite the irregularity of rust epidemics, rusts do have a history of impact in Western Australia as factors converge that result in exploding rust populations. The susceptibility of many Western Australian wheats has traditionally provided wheat rusts with ample host material. Combined with exceptional climatic factors of summer rain and wet springs, this has resulted in five major stem rust epidemics (1915-1963) and two major leaf rust epidemics (1992 and 1999). In addition 13 years can be identified between 1924 and 1992 when localised stem rust epidemics developed, an average interval of 1 in 5 years. From 1992-99 localised outbreaks of leaf rust have been more frequent, occurring in 1993, 1996 and 1997.

Changes to rust populations

A major factor in the current prominence of wheat rusts has been the occurrence and dominance of leaf rust pathotype (pt) 104-1, 2, 3, (6), (7), 11 in Western Australia since 1990. The reasons for the particular success of this pathotype, compared with other previous leaf rust strains, are unclear. In contrast, stem rust flora have remained comparatively stable over several decades and pathotype changes have not been a significant factor in recent stem rust occurrence.

Availability of susceptible hosts

The degree of susceptibility of popular varieties is an important factor in determining disease occurrence. Variety Canna generated stem rust outbreaks in northern wheatbelt areas in 1984. Current pathotype prevalence of stem rust pt 34-2, 7 appears to have resulted from a minor initial build up in 1992 in soft wheat areas, then as a consequence of outbreaks on var. Amery grown in rust-prone southern areas in 1997. In 1999 the degree of susceptibility of Amery (expected), Westonia and Arrino (not fully expected) provided the opportunity for stem rust development.

Varieties Kulin and Spear were dominant varieties generating abundant inoculum in the leaf rust epidemic of 1992. Spear, Stiletto and Amery have been important in maintaining leaf rust inoculum over the second half of this decade. These varieties, together with Arrino, contributed to epidemic development in 1999.

Changing farming systems

Evolving farming systems can contribute to increasing importance of rust. Early in the 1960s farming was expanding rapidly in the Esperance area and wheat, usually the first crop on new land, was unfenced and ungrazed. This provided large areas of self sown summer and autumn hosts. Carryover of newly virulent stem rust on these hosts set the scene for the subsequent 1963 stem rust epidemic.

Throughout the last decade significant changes to Western Australian farming systems have occurred. These include:

- historically low sheep numbers that have reduced demand for summer feed and diminished opportunity to control summer volunteer hosts through grazing;
- record high areas of wheat production, on average 30 per cent more wheat area compared with 10 years ago;
- significantly earlier sowing opportunities from direct drilling have shortened the interval between autumn rust survival and development of new crops.

These factors are likely to contribute to overall increased opportunity of rust occurrence.

NEED AND OPPORTUNITIES FOR IMPROVED MANAGEMENT

The frequency of local and epidemic stem rust indicate that chance factors interacting with intrinsic susceptibility have resulted in the current build-up and threat to this season's production. The high frequency of local and epidemic leaf rust in the last decade indicate that greater effort is required to reduce the success of this pathogen.
Immediate opportunities for improved management require the adoption of existing resistant varieties and the development of understanding and confidence in use of fungicides for susceptible varieties. With fungicide options and availability increasing growers have the opportunity to further adopt this technology and hone important skills in fungicide use.

Since the occurrence of wheat leaf rust in 1992 the Western Australian breeding program has undertaken activities to improve development of leaf rust resistance. The National Cereal Rust Control Program (NCRCP) helped identify resistance in Carnamah, Cunderdin, Nyabing and Perenjori. Datatine and Camm, backcross derivatives of Tincurrin and Spear, have been produced with the NCRCP. Medium term prospects are good as rust resistant derivatives of other currently popular wheats are being fast-tracked. While some progress has been made, displacement of currently susceptible varieties with new resistant or less susceptible varieties will be required to diminish importance of rusts in the future. An additional factor, potential for introduction of stripe rust (*Puccinia striiformis f. sp. tritici*), remains an important issue.

The CIMMYT wheat breeding program in Mexico has developed wheat with highly effective combinations of adult plant resistances to leaf rust and also stripe rust. Individually these genes produce slower rust development but in combination they are highly effective and produce near complete resistance. Such resistance is not reliant on individual genes and therefore is more likely to have durability. These resistances have not intentionally been transferred to Australian cultivars because they cannot be selected in wheats that are already resistant, hence many eastern Australian wheats do not provide appropriate backgrounds for their selection. Western Australian wheats are an appropriate choice for incorporating these important resistances because Western Australia has high yielding, high quality, but rust susceptible wheats to which these resistances could be effectively transferred. These resistances could improve the longer term prospects for diverse and stable rust resistance in Western Australia and elsewhere in Australia.

**ACKNOWLEDGEMENTS**

Assistance of J. Bhathal, K. Jayasena, R. Wilson, R. Dickie, A. Hills and J. Majewski, Agriculture Western Australia, in formulation of this paper is greatly appreciated. Agriculture Western Australia Research Support Units managed and assisted with field trials. Thanks also to R. Park and R. McIntosh, National Cereal Rust Control Program, University of Sydney and R. Singh, CIMMYT, Mexico for information and discussions. Research was supported by the Cereals Program, Agriculture Western Australia and the Grains Research and Development Corporation.

**GRDC Project No.:** DAW488, DAW589, DAW516
Is nutrition the answer to wheat after canola problems?

Ross Brennan1, Bill Bowden1, Mike Bolland1, Zed Rengel2 and David Isbister2

1 Agriculture Western Australia
2 University of Western Australia

BACKGROUND

Canola is viewed as a cleaning crop in cereal rotations as it provides a break in the cycle of the pests and diseases hosted by cereals, and it provides an opportunity for managing grass weeds. Yield potentials are expected to be higher in cereals following canola than in continuous cereal rotations. However, canola is also known as a voracious scavenger of nutrients. It has a cobweb of fine roots that allows it to explore a very wide range of soil pore spaces. This means that canola is very efficient at taking up nutrients, particularly the soil immobile ones such as copper, zinc and manganese and on some soils, phosphorus. This efficiency in feeding, linked with high nutrient contents in canola relative to other crops, means that canola/rape has a well-earned reputation for depleting soil nutrients.

Western Australia has a uniquely ancient and deeply weathered landscape; the soils are notoriously deficient in most of the essential plant nutrients. Most of the current chemical fertility in the agricultural soils has been provided from fertiliser inputs; even the nitrogen fertility has been built up by growing legumes fed nutrients from a bag. Our agriculture always has been carried out at marginal levels of chemical fertility. This means that any extraordinary perturbations in nutrient status such as larger than usual nutrient removals or problems with root growth and function, can be reflected in nutrient deficiency problems and yield losses.

Just such problems have been observed in cereal crops following canola in the Western Australia cropping areas in 1998 and again in 1999. Some growers who have been swathing their canola crops and then burning the stubble in the windrows, have been observing on the windrows, better growth in the following cereal crops. This wave effect has been particularly prevalent in the Great Southern districts. The problem is likely to become more widespread and be seen more frequently as canola is grown on increased hectares and as it is pushed into more marginal cropping districts. The table below shows that where wave patterns in crops were observed, the off-windrow areas were yielding as little as 25% of the on-windrow areas. While such yield losses can not be extrapolated across all cereal crops following canola, the losses can be disastrous for individual growers who are affected. Diagnosing the problem and providing a remedy is essential.

Crop responses to canola windrows

<table>
<thead>
<tr>
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<th>On</th>
<th>Off</th>
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<tr>
<td>1998 observations</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Packard, Badgebup</td>
<td>Grain yield</td>
<td>2230</td>
<td>1080</td>
</tr>
<tr>
<td>Henderson, Varley</td>
<td>Grain yield</td>
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<td>1933</td>
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<td>Hill, Holt Rock</td>
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<td>1999 observations</td>
<td></td>
<td></td>
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<tr>
<td>Hill, Holt Rock</td>
<td>Tops yield</td>
<td>572</td>
<td>189</td>
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<td>Mayfield, East Hyden</td>
<td>Tops yield</td>
<td>1387</td>
<td>597</td>
</tr>
<tr>
<td>Kukerin, wheat</td>
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<tr>
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<td>Measurement Type</td>
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<td>Value 2</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------</td>
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<td>---------</td>
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<tr>
<td>Kukerin, barley</td>
<td>Tops yield</td>
<td>570</td>
<td>176</td>
</tr>
<tr>
<td>Davies, South York</td>
<td>Grain yield</td>
<td>5248</td>
<td>2104</td>
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<td>Darkan, wheat</td>
<td>Grain yield</td>
<td>3380</td>
<td>1870</td>
</tr>
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Last year at the 1999 Crop Updates, we ran over the likely causes of the wave problem with calculations of amounts of nutrients being transferred into wind-rows. We also touched on the more generic problem of the changing nature of soil test critical levels in the context of the positional unavailability induced by no-till practices and the possibility of root pruning from various causes.

Following that paper, GRDC and Agriculture Western Australia (AGWEST) funded a three year project to investigate, in part, this problem. Our brief was to get more information on the amounts of nutrients being redistributed with different canola stubble management practices and to try to isolate the reasons for the wave effects. Ideally we would come up with suggested ways of managing the problem. This paper reports some findings from that work and a parallel honour’s project at the University of Western Australia Department of Soil Science and Plant Nutrition.

RESULTS FROM 1999 WORK

Updated stubble analyses

In order to calculate the amounts of nutrients being redistributed under various stubble management practices in Western Australia, we need to have a feel for the nutrient composition of stubbles grown under our notoriously deficient circumstances and compare these with literature standards. Preliminary results from some 1999 crops show that the macronutrients nitrogen, phosphorus and potassium run at levels as low as 40% of those reported for more fertile soils in eastern Australia. In other words, we move only about half as much nutrient in our stubbles as we calculated last year using literature standards. This helps explain the lower than expected differences in soil test potassium and phosphorus between on and off windrow samples. Laboratory studies showed that, depending on level of application from 60 to 80% of stubble potassium and from 0 to 30% of stubble phosphorus was recovered in soil test extractants following 9 week’s incubation of stubble in moist soil.

Calcium, magnesium and sulphur levels in canola straw from Western Australia were similar to those reported from in the literature. Copper levels were lower and zinc and manganese levels were higher in Western Australia samples. Obviously the results depend very much on the conditions under which the crops were grown, but we are accumulating valuable information.

The implications of these results are that we can now better estimate the changes in the plant availability of phosphorus and potassium (and to some extent, the other nutrients) given any redistribution pattern of canola stubbles

Field trials

Nutrient omission trials were put in at a couple of sites at seeding, which allowed phosphorus to be drilled with the seed. Other sites were chosen after waves of better growth became obvious in emerged crops. This meant that soil immobile phosphorus was not applied because it could not be drilled or banded into the soil to guarantee that it was positionally available. The other major nutrients; nitrogen, potassium and sulphur (all relatively soil mobile), were applied as soon as possible after site selection while the trace elements copper, zinc, molybdenum and manganese, were applied as sprays when there was sufficient ground cover to allow adequate uptake. These post-seeding remedies to the problem meant that there was always an observable response to the windrows because even the inter row areas which received full nutrients, suffered yield component reductions due to poor nutrition during the early growth stages of the cereal crops.
<table>
<thead>
<tr>
<th>Treatment</th>
<th>Holt Rock wheat tops Z45</th>
<th>Kukerin wheat tops</th>
<th>Kukerin barley tops</th>
<th>E hyden wheat tops Z53</th>
<th>Darkan wheat? grain</th>
<th>South York wheat grain</th>
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<tr>
<td>None</td>
<td>0.33</td>
<td>0.25</td>
<td>0.31</td>
<td>0.43</td>
<td>0.55</td>
<td>0.40</td>
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<td>0.46</td>
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<td>Minus Zn</td>
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<td>Minus Mo</td>
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<td></td>
<td>0.33</td>
<td>0.43</td>
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</tbody>
</table>

It is obvious that potassium deficiency is one of the main causes of the response patterns, but anecdotal evidence has implicated phosphorus, sulphur, molybdenum, copper and zinc.

Only preliminary results from the field trial work are available at the time of writing.

Further yield component, nutrient uptake and soil nutrient measures together with rigorous statistical analyses of the results, will let us discriminate which nutrients are important in causing the windrow effects.

At the South York site, an attempt was made to get a quantitative feel for the magnitude of the yield variation and responses across the site by carrying out grid sampling at harvest.
The six windrow areas show as high yield, horizontal strips while the ‘none’ and ‘minus K’ treatments show as vertical columns of lower yield. When treatment effects are averaged and plotted on a transect across the windrows, the ‘wave’ effect is dramatic, as is the variation in response to windrows and nutrient treatments across the site. This variation reflects the variation in growing conditions and nutrient status on the trial, the diagnosis of which, on a larger scale, is the subject of several precision agriculture studies.

**Glasshouse work**

As well as the recoveries of stubble nutrients to soil test extractants reported above, glasshouse studies showed marked potassium uptake and grain yield responses to levels of canola stubble application.
The figure above shows effect on the amount of wheat grain > 3.2 mm in size and the amount of grain < 3.2 mm (‘screenings’), of five different levels of canola chaff (equivalent to nil, 6, 12, 18 and 90 t/ha) and different nutrient treatments. All treatments received full basal nutrients except where phosphorus and potassium were omitted as indicated. Bars represent ± standard errors. The extra high chaff addition had early phytotoxic effects.

There were large responses to stubble potassium but little or no response to stubble phosphorus in these studies, probably because the pre-seeding incubations allowed any inorganic phosphorus released to be rendered unavailable by reaction with the soil.

CONCLUSIONS

Providing adequate nutrition will certainly overcome most of the problems associated with growing cereal crops following canola and will certainly remedy the causes of waves in such crops. The problem then becomes one of diagnosing if there is a problem, which nutrients are inadequately supplied and then working out how much and when to apply remedial dressings. There is nothing new in the technology required to do this; it has been the subject of nutritional decision making in Western Australia since agriculture began here. The new dimension from swathing canola and retaining stubble in windrows is that the paddock scale, strip trials so provided help with the diagnosis of otherwise sub-clinical nutrient deficiencies. It also presents both opportunities (for comparing paired samples) and hazards (by mixing high and low areas) for diagnosis through traditional soil and tissue testing services. It is imperative to sample on and off windrow areas separately.

Some simple practical options for growers, many of which are already being used are:

- Soil test the areas between the windrows of canola stubbles.
- Where appropriate, spread the stubbles rather than keeping them in windrows.
- Off set the windrows from harvest to harvest.
- If soil levels are marginal or you are in doubt, apply fertiliser potassium as an insurance policy.
- If in doubt about trace elements, you can apply insurance dressings for early crop requirements with your in crop herbicide sprays.
- If you see waves of better growth in your cereal crop following canola, then take soil and plant samples from on and off the waves, and get them tested separately.
- If in doubt, refer to a consultant/expert.

We are continuing our investigations and are also addressing the more generic problem of the increasing disparity between soil testing and tissue testing recommendations. This results from inefficiencies of nutrient uptake due to root pruning by bugs, pathogens, aluminium toxicity and some herbicide residuals. It can also occur where some nutrients are chemically available but become positionally unavailable in dry surface soils. The nutritional implications of using new crop sequences, tillage methods and herbicide regimes require continual research in Western Australia.

GRDC Project No.: DAW 635
Improved Sandplain Cropping systems by Controlled Traffic

Dr Paul Blackwell, Agriculture Western Australia

KEY MESSAGES

- Controlled Traffic (CT) cropping systems can improve gross margins for broadacre crop production on sandplain by about 20% or better. This equates to about $20/ha or better for current wheat prices. Most of this improvement comes from reducing compaction and increasing crop yield.

- Estimated benefits can be made for individual operations can be made with the help a computer model under development. The model combines the known effects of individual wheel types for different patterns of wheeling from current equipment or that modified or purchased for CT.

- Farmers experience of adaptation to CT has shown it can be practicable and simple. Marker arms and sprayers and spreader 2-3 times the width of seeders are the minimum requirement. Tracked tractors are better than multiple tyres. Improvements to bare tramlines are needed for better weed control. An innovation of ‘Fuzzy Tramlines’ will be tested this season.

- New methods of controlling herbicide resistant weeds in legumes should be possible within a CT cropping system. These methods use shielded sprays which allow knock-down herbicides to be used between rows of crop.

AIMS

1. To test and demonstrate Controlled Traffic farming systems on northern sandplain for more profitable and sustainable grain production, especially after a deep ripping operation.

2. To evaluate new technology, e.g. for weed control, which can be used with the help of CT.

METHODS

Large scale field trials using replicated blocks or covariate observations to compare yield, grain quality, overlap and forward speed for either a full scale Controlled Traffic system or a normal traffic system currently in farm use. Measurements of growth and yield in individual wheel tracks and unripped subplots provide data for a simplified model of effects of whole traffic systems on yield, especially in comparison to possible Controlled Traffic systems with the same equipment. Results of yield improvements and input reductions are used in a farm budget spreadsheet to calculate the effects on gross margins. Midas input for machinery costs and Farm Budget Guide 2000 for variable costs have been used, as well as representative yields, fertiliser and pesticide rates for low to medium rainfall sandplain in the Geraldton District. Total costs were about $150/ha for wheat, yields 2.5 t/ha.

RESULTS

Wheat yield in 1999 showed encouraging effects of a Controlled Traffic system which kept all spraying, seeding and spreading traffic to 2m track and 9m spaced bare tramlines.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Deep ripping</th>
<th>Yield (t/ha)</th>
<th>Protein (%)</th>
<th>Scrgs (%)</th>
<th>Hl Wt (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT for 3 yrs (A)</td>
<td>1997</td>
<td>2.77</td>
<td>9.9</td>
<td>1.6</td>
<td>81.7</td>
</tr>
</tbody>
</table>
Controlled Traffic (CT) gave the best yield benefit over normal traffic (NT) when maintained for three years after deep ripping in a wheat/lupin/wheat rotation (treatment A is 13% or 320 kg/ha better than treatment C). In the first year after deep ripping CT gave an 8% (199 kg/ha) yield benefit (treatment D). CT gave a 7% (196 kg/ha) benefit when applied to normally trafficked sand (treatment B).

Grain quality was most consistently effected by CT reducing screenings, by 0.3-0.4%. There was no clear effect on protein or hectolitre wt. Other measurements show more uniform head size for wheat grown by controlled traffic.

Measurements of overlap in the Tenindawa trials show a 3% reduction of seeding overlap and a 4% reduction of spraying overlap is possible with CT. Herbicide spraying in the newly ripped trial was also 10% quicker with CT than NT, due to reduced rolling resistance on the firm tramlines.

All these results in wheat are with bare tramlines for CT. The crop loss was often compensated by extra yield of the edge rows in the very good 1999 growing season; poorer growing seasons have shown less compensation. Bare tramlines led to extra weed growth and some erosion. ‘Fuzzy tramlines’, using a broad band of seed rolled in by a wheel, have been accidentally made and observed to reduce weed growth.

CONCLUSIONS

An 8-13% yield increase for wheat, a 3% reduction of seed and fertiliser and a 4% reduction of herbicide, as well as a 10% reduction of fuel use when spraying after ripping can improve gross margins by about 20% or better on an analysis for wheat production in a typical sandplain rotation. Such benefits of about $30/ha or better at current prices and yields can easily pay for the costs of marker arms and changing equipment to better matching widths and wheel tracks. A simple calculation of benefits and costs for only a 2000 ha wheat program result in a calculated ratio of $1.6 benefit for each dollar invested.

An estimate of possible yield benefits for equipment conversion to more controlled traffic can be made with a model which uses measured yield losses in wheelings and combines them to compare gross yields by different traffic systems. An example is shown in Figure 1.

![Figure 1. The yield and yield losses in two different traffic systems based on data from 1999 results.](image)
The figure on the left shows yields in wheelmarks from different normal traffic operations. The figure on the right shows the calculated losses of yield from the bare tramlines in CT, with some edge compensation, or the total losses from different operations in NT. The yield loss from the tramlines in CT is 7% less than the total yield loss in NT after deep ripping. This compares well with the measurements from whole plots in trial treatments D and E (Table 1).

KEY WORDS
controlled traffic, compaction, gross margins, deep ripping, weed control

GRDC project No.: DAW 505
Paper reviewed by: Bill Bowden
Raised bed farming for improved cropping of waterlogged soils

Derk Bakker¹, Greg Hamilton², David Houlbrooke¹, Cliff Spann³ and Doug Rowe³, Agriculture Western Australia

¹ Albany  
² South Perth  
³ Mount Barker Research Station

This paper is a summary of the results of the third year of a five-year project on the application of raised beds to waterlogged soils in the Great Southern. Eight sites varying in size and type of crop grown were used in 1999. Seeding was done with a new air seeder tailored for raised beds and equipped with John Walker disc openers. Good crop establishment was obtained at all sites. A wet start to the season and below average rainfall during June and July was experienced at all sites with a very dry July at Badgebup (Katanning) but average conditions in Esperance. Harvesting was done with a commercial harvester equipped with narrow dump truck tyres to fit the furrows.

All sites have been sampled for dry matter production at different stages of plant growth, see Table 1 but only the last sampling has been presented due to limited space.

Table 1. Dry matter content for the different sites, crops and positions in the crop

<table>
<thead>
<tr>
<th>Location</th>
<th>Crop</th>
<th>RB, bed t/ha, ←</th>
<th>RB furrow, t/ha ↑</th>
<th>RB total, t/ha →</th>
<th>Control, t/ha ↓</th>
<th>% diff ← &amp; ↓</th>
<th>% diff → &amp; ↓</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverley</td>
<td>Peas</td>
<td>5.14</td>
<td>0.89</td>
<td>3.93</td>
<td>4.04</td>
<td>27</td>
<td>-3</td>
</tr>
<tr>
<td>Woodanilling</td>
<td>Peas</td>
<td>5.18</td>
<td>2.12</td>
<td>4.31</td>
<td>4.03</td>
<td>28</td>
<td>7</td>
</tr>
<tr>
<td>Toolibin</td>
<td>Canola</td>
<td>5.83</td>
<td>0.99</td>
<td>4.45</td>
<td>4.91</td>
<td>19</td>
<td>-9</td>
</tr>
<tr>
<td>Badgebup</td>
<td>Canola</td>
<td>6.85</td>
<td>4.16</td>
<td>6.08</td>
<td>6.37</td>
<td>8</td>
<td>-5</td>
</tr>
<tr>
<td>Cranbrook</td>
<td>Wheat</td>
<td>7.01</td>
<td>1.42</td>
<td>5.41</td>
<td>4.68</td>
<td>50</td>
<td>16</td>
</tr>
<tr>
<td>MBRS</td>
<td>Canola</td>
<td>6.82</td>
<td>2.11</td>
<td>5.47</td>
<td>4.66</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td>South Stirling</td>
<td>Wheat</td>
<td>9.23</td>
<td>0.00</td>
<td>6.60</td>
<td>8.02</td>
<td>15</td>
<td>-18</td>
</tr>
<tr>
<td>Esperance</td>
<td>Wheat</td>
<td>6.87</td>
<td>3.48</td>
<td>5.90</td>
<td>4.95</td>
<td>39</td>
<td>19</td>
</tr>
</tbody>
</table>

At all sites the DM from the beds only (←) out yielded the control (↓) by up to 50% but the total DM yield from the beds was suppressed by the sometimes very low DM content in the furrows (i.e. 0.0 t/ha).

Harvesting proved to be a protracted exercise due to unseasonal weather along the South coast. Beverley was harvested in the middle of November whilst Cranbrook was not harvested until the end of January 2000. The results were in favour of the raised beds and are presented in Table 2.

Table 2. 1999 yields from demonstration and research sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Crop</th>
<th>Raised bed, t/ha</th>
<th>Control, t/ha</th>
<th>% diff</th>
<th>Area, ha</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beverley</td>
<td>Field peas</td>
<td>1.96</td>
<td>1.39</td>
<td>41</td>
<td>12</td>
</tr>
<tr>
<td>Woodanilling</td>
<td>Field peas</td>
<td>1.47</td>
<td>1.03</td>
<td>43</td>
<td>10</td>
</tr>
<tr>
<td>Toolibin</td>
<td>Canola</td>
<td>1.34</td>
<td>1.18</td>
<td>14</td>
<td>55</td>
</tr>
<tr>
<td>Badgebup</td>
<td>Canola</td>
<td>1.75</td>
<td>1.82</td>
<td>-4</td>
<td>45</td>
</tr>
<tr>
<td>Cranbrook</td>
<td>Wheat</td>
<td>2.41</td>
<td>2.04</td>
<td>18</td>
<td>10</td>
</tr>
<tr>
<td>MBRS</td>
<td>Canola</td>
<td>2.15</td>
<td>1.90</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>South Stirling</td>
<td>Wheat</td>
<td>3.43</td>
<td>3.39</td>
<td>1</td>
<td>66</td>
</tr>
<tr>
<td>EDRS</td>
<td>Wheat</td>
<td>3.64</td>
<td>2.71</td>
<td>34</td>
<td>6</td>
</tr>
<tr>
<td>------</td>
<td>-------</td>
<td>------</td>
<td>------</td>
<td>-----</td>
<td>-----</td>
</tr>
</tbody>
</table>

Yield maps have been obtained at all sites and will be analysed in greater detail at a later stage. The negative result in Badgebup is most likely due to the dry start of the growing season and the loose nature of the beds whilst the very poor crop establishment in the furrows at South Stirling depressed the final yield from the RB treatment. The yield therefore obtained in South Stirling from the RB treatment has been obtained solely from the beds.

The establishment and maintenance of good soil conditions in the raised beds are essential to maximise the benefits of raised beds. The beds should have a well-structured root zone to ensure rapid drainage and aeration shortly after rainfall. The saturated hydraulic conductivity as an indicator of soil structure was measured at different sites and at different times of the year and is presented in Table 3.

Table 3. Saturated hydraulic conductivity (mm/hr) at Cranbrook (sandy loam on gravel, beds two years old) and at Toolibin (shallow sandy loam on grey clay, beds 1 years old)

<table>
<thead>
<tr>
<th>Site</th>
<th>RB_Ungrazed</th>
<th>RB_Grazed</th>
<th>Control_Ungrazed</th>
<th>Control_grazed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranbrook</td>
<td>833</td>
<td>241</td>
<td>58</td>
<td>47</td>
</tr>
<tr>
<td>Toolibin</td>
<td>RB, Autumn</td>
<td>C, Autumn</td>
<td>RB, Winter</td>
<td>C, Winter</td>
</tr>
<tr>
<td></td>
<td>564</td>
<td>212</td>
<td>201</td>
<td>50</td>
</tr>
</tbody>
</table>

Even after 2 years the beds maintained a higher conductivity in the topsoil compared to the control. Summer grazing in Cranbrook affected the conductivity of the beds which still remained very high compared to the control areas. The reduction in the conductivity between autumn and winter is obvious in Toolibin in both the beds and the control but the conductivity of the beds remains high even during the winter months.

Deep drainage has been assessed with tensiometers at various depths in the raised beds and the control. The difference in pressure between two tensiometers placed at different depths, indicate the direction of the flow, a positive difference indicate a downward flow and a negative difference an upward flow. From Figure 1 it can be seen that during the winter little difference exists between the raised beds and the control. Both show a marginal negative difference, (i.e. very little upward movement) but the difference become more negative earlier in the beds than in the control which indicate an earlier development of the capillary rise. Results of shallow tensiometers (not depicted) indicated that the beds dried out faster than the control which would explain the earlier development of substantial capillary rise in the subsoil under the beds (Figure 1) and a further drying out of the profile.

![Figure 1. Difference between two tensiometers positioned at depths indicated in the legend as a function of time.](image-url)
Runoff was measured at Cranbrook, Mount Barker and Esperance (Table 3). The rain in 1999 came evenly spread with many little showers rather than several larger storms. Only one substantial rainfall event (18 mm in one day) in Cranbrook occurred on 10 September when the crop had a substantial canopy and little runoff was generated.
Table 3. Mean percentage rain-runoff from Cranbrook and Mt Barker with the standard deviation between brackets

<table>
<thead>
<tr>
<th>Location</th>
<th>Period</th>
<th>Rain, mm</th>
<th>RB, %</th>
<th>C, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cranbrook</td>
<td>Total: 22/07-22/10</td>
<td>145</td>
<td>9 (7)</td>
<td>13 (7)</td>
</tr>
<tr>
<td></td>
<td>Wet period: 10/11/09</td>
<td>45</td>
<td>13 (7)</td>
<td>13 (4)</td>
</tr>
<tr>
<td>Mt Barker</td>
<td>Total: 22/07-24/09</td>
<td>137</td>
<td>20 (7)</td>
<td>17 (4)</td>
</tr>
</tbody>
</table>

The percentage runoff from the Cranbrook site as well as the Mt Barker site has been low compared to the previous two years. The low intensity of the rainfall and the high infiltration rates of the raised beds resulted in a non-significant difference in percentage rainfall-runoff between the Control and the Raised Beds in Cranbrook and Mount Barker. The runoff from the Esperance site has been negligible.

**CONCLUSION**

For the third year in a row the raised beds have proven to be a robust soil management system producing yield advantages for a range of crops, climatic conditions and soil types. After three years soil conditions have remained such that rapid drainage of the beds is ensured to eliminate waterlogging and reduce the potential for recharge. It has also been established that raised beds not necessarily increase the runoff, which for a given site is affected by rainfall patterns, intensity and stage of the crop growth.

**GRDC Project No.:** DAW500

**Paper reviewed by:** Greg Hamilton
Banded Urea increased wheat yields
Patrick Gethin, Stephen Loss, Frank Boetel, and Tim O’Dea, CSBP futurefarm

KEY MESSAGE
Banding Urea 3-4 cm below and 2-3 cm to the side of the seed resulted in 8-15% more wheat yield than topdressed Urea in three trials during the wet 1999 season. Banding Urea directly below the seed reduced plant density by 21% at one site with a loamy clay soil. Banding Urea below and to the side virtually eliminated Urea toxicity to seedlings and N supply was better matched to crop demand.

BACKGROUND AND AIM
Urea is the most cost effective nitrogen (N) source and is traditionally topdressed before or after sowing. Under certain conditions, topdressed Urea is prone to volatilisation losses. Urea is also converted into nitrate, which can be leached past the root zone depending upon rainfall and soil texture. Applying Urea in a narrow band in the soil may eliminate volatilisation losses and slow down its conversion into leachable nitrate. Limited experiments conducted by CSBP futurefarm in 1998 showed little benefit (in some cases a small penalty) of banding Urea below and to the side the seed. The main aim of the three experiments conducted in 1999 was to compare the effects of Urea placement on N uptake, yield and protein of wheat.

METHODS
The three trials included three replicates and were a randomised block factorial design of 3 N rates with 3 Urea placements. At Carnamah and Buntine the placement treatments were topdressed and immediately incorporated with sowing, banded 3-4 cm below the seed, and banded below and 2-3 cm to the side of the seed. At the Ballidu site, the banded below the seed treatment was replaced with banded 2-3 cm to the side of the seed. Plastic-coated Urea (PCU, 2% plastic) was included in all placements at Ballidu and Carnamah, and was also drilled with the seed to test for toxicity. 70 kg/ha of Westonia seed was sown with a Conserva Pak seeding system on 22.5 cm row spacings with a basal fertiliser of 148 kg/ha ExtraPhos drilled with the seed. The experiments were sown into moist soil after large rainfall events in late May.

Table 1. Experimental site characteristics

<table>
<thead>
<tr>
<th></th>
<th>Ballidu</th>
<th>Carnamah</th>
<th>Buntine</th>
</tr>
</thead>
<tbody>
<tr>
<td>History</td>
<td>Wheat 97 Canola 98</td>
<td>Canola 98</td>
<td>Poor Legume Pasture</td>
</tr>
<tr>
<td>Soil description 0-10 cm</td>
<td>Brown sandy loam</td>
<td>Greybrown loamy clay</td>
<td>Greybrown sandy loam</td>
</tr>
<tr>
<td>P mg/kg</td>
<td>24</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>N (Nit) mg/kg</td>
<td>8</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>N (Amm) mg/kg</td>
<td>3</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>K mg/kg</td>
<td>49</td>
<td>87</td>
<td>69</td>
</tr>
<tr>
<td>S mg/kg</td>
<td>2.0</td>
<td>4.4</td>
<td>5</td>
</tr>
<tr>
<td>OC %</td>
<td>0.66</td>
<td>0.4</td>
<td>0.98</td>
</tr>
<tr>
<td>Fe Status</td>
<td>200</td>
<td>328</td>
<td>423</td>
</tr>
<tr>
<td>Salt Ds/M</td>
<td>0.024</td>
<td>0.25</td>
<td>0.66</td>
</tr>
<tr>
<td>Ph 1:5 CaCl₂</td>
<td>5.3</td>
<td>5.1</td>
<td>5.1</td>
</tr>
<tr>
<td>Sowing time</td>
<td>6 June</td>
<td>10 June</td>
<td>11 June</td>
</tr>
<tr>
<td>May-October Rain mm</td>
<td>373</td>
<td>429</td>
<td>414</td>
</tr>
</tbody>
</table>
### RESULTS

At Ballidu and Buntine, Urea placement had no effect on plant establishment at all N rates. At Carnamah, however, 90 kg/ha N as Urea banded below the seed reduced the plant density by 21% (P < 0.05, Figure 1). PCU appeared to be safer than Urea, but still reduced establishment by 14% at 90 kg/ha N when banded below. Drilling PCU with the seed caused a 28% reduction. In contrast, placing Urea below and to the side of the seed did not result in a significant reduction in plant density. At Ballidu there were significant effects of placement and N source on grain yields (P < 0.05, Figure 2). On average over all N rates, the below/side placement produced 10% more yield (335 kg/ha) than topdressed, and the side placement was also 5% superior to topdressed. On average, Urea produced 5% more grain yield (185 kg/ha) than PCU. Protein content (mean 9.5%) was unaffected by N rate, placement and source. Increasing N rate resulted in greater hectolitre weights (mean 80 kg/HL) and reduced screenings (mean 1.2%), but neither placement nor source had any effect.

At Carnamah, there was a significant effect of placement on grain yield (P < 0.05, Figure 3), however, there was no difference between the Urea and PCU. Over all N rates, the below/side placement produced 15% more grain yield (280 kg/ha) than the topdressed treatment. Despite the reduction in plant establishment with the Urea placed below the seed, yields were not significantly different to the topdressed treatment. Protein (mean 8.1%), hectolitre weights (mean 81 kg/HL) and screenings (mean 0.4%) were not affected by any of the treatments.

Over all N rates at Buntine, both the below/side and below treatments produced about 8% more grain yield (280 kg/ha) than the topdressed treatment (Figure 4). Increasing N rate increased grain protein (mean 10.5%), increased hectolitre weights (mean 83 kg/HL) and reduced screenings (mean 0.9%). Plant weight and N uptake data were also recorded during the season and these confirm the trends evident in the grain yield data.
CONCLUSIONS

Banding Urea below and to the side of the seed resulted in a better match between N supply and crop demand, and produced between 8-15% more yield than topdressing. Care should be taken before extending these results widely as seasonal and environmental conditions can influence the effects of fertiliser on plant establishment. The reduction in plant density with Urea banded below the seed at Carnamah is probably related to the release of ammonia around the band causing death of roots growing through this zone. These effects are common in medium or low rainfall seasons and normally make placing Urea close to the seed a risky option. The dissipation of ammonia away from the band may have been slow in the fine-textured soil at Carnamah, which could explain why no reduction in establishment was observed at the sandy Buntine and Ballidu sites. Banding Urea below and to the side may result in benefits that other N sources claim to deliver, but at a fraction of the cost.

KEY WORDS

nitrogen, fertiliser, plastic-coated Urea, placement
Flexi N is as effective as Urea on wheat and canola
Frank Boetel, Stephen Loss, Patrick Gethin, and Tim O’Dea CSBP futurefarm

KEY MESSAGE
Urea and Flexi N were equally effective at supplying nitrogen (N) to wheat and canola across a range of environments, rates and application times. In some cases, Flexi N was more effective when applications were split between sowing and 4-8 weeks after sowing (WAS) compared to all at sowing.

BACKGROUND AND AIM
Flexi N is a fertiliser solution of Urea and ammonium nitrate containing 32% N w/w. Similar liquid fertilisers are used widely in Europe, North America and South Africa for a range of crops. The main advantages of Flexi N over Urea are easy storage and handling, and application at the same time as some herbicides. Limited research over the past two years in Western Australia indicates Flexi N could be an efficient means of supplying N to crops. The trials reported here compare Flexi N and Urea as N sources for wheat and canola using several application strategies over various environments and yield potentials.

METHODS
The trials included three replicates and were a randomised block factorial design of two N sources (Urea, Flexi N), three N rates (generally 30, 60, 90 kg N/ha) and two or three application times (all immediately before sowing, split 50% before sowing + 50% at 4-6 WAS, and split 33% before sowing + 33% at 4-6 WAS + 33% 8-10 WAS). Flexi N was applied through an ATV bike mounted boomspray. Plots were 2.1 x 40 m long and were sown either with a Conserva Pak system on 22.5 cm row spacings or Agmaster points on 15 cm row spacings. A basal fertiliser of AllPhos, ExtraPhos or Agflow was drilled with the seed.

Table 1. Experimental site characteristics

<table>
<thead>
<tr>
<th></th>
<th>Mullewa</th>
<th>Wubin</th>
<th>Kalannie</th>
<th>Beverley</th>
<th>Tambellup</th>
</tr>
</thead>
<tbody>
<tr>
<td>History</td>
<td>Wheat 97</td>
<td>Wheat 97</td>
<td>Wheat 98</td>
<td>Barley 97</td>
<td>Good pasture</td>
</tr>
<tr>
<td></td>
<td>Lupin 98</td>
<td>Lupin 98</td>
<td></td>
<td>Canola 98</td>
<td>97 &amp; 98</td>
</tr>
<tr>
<td>Soil 0-10 cm</td>
<td>Grey brown</td>
<td>Grey brown</td>
<td>Grey brown</td>
<td>Grey brown</td>
<td>Grey sandy</td>
</tr>
<tr>
<td></td>
<td>loamy sand</td>
<td>loamy</td>
<td>sandy loam</td>
<td>loamy sand</td>
<td>loam</td>
</tr>
<tr>
<td>P mg/kg</td>
<td>16</td>
<td>17</td>
<td>32</td>
<td>30</td>
<td>41</td>
</tr>
<tr>
<td>N (Nit) mg/kg</td>
<td>11</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>N (Amm) mg/kg</td>
<td>5</td>
<td>12</td>
<td>12</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>K mg/kg</td>
<td>67</td>
<td>153</td>
<td>87</td>
<td>56</td>
<td>112</td>
</tr>
<tr>
<td>S mg/kg</td>
<td>3</td>
<td>3</td>
<td>12</td>
<td>18</td>
<td>8.6</td>
</tr>
<tr>
<td>OC %</td>
<td>0.42</td>
<td>0.59</td>
<td>1.00</td>
<td>2.27</td>
<td>0.88</td>
</tr>
<tr>
<td>Fe status</td>
<td>80</td>
<td>309</td>
<td>561</td>
<td>542</td>
<td>371</td>
</tr>
<tr>
<td>Salt dS/m</td>
<td>0.035</td>
<td>0.040</td>
<td>0.065</td>
<td>0.060</td>
<td>0.101</td>
</tr>
<tr>
<td>Ph 1:5 CaCl2</td>
<td>6.2</td>
<td>5.1</td>
<td>4.3</td>
<td>4.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Sowing time</td>
<td>18 May</td>
<td>20 May</td>
<td>26 May</td>
<td>15 June</td>
<td>2 June</td>
</tr>
<tr>
<td>Variety</td>
<td>Carnamah</td>
<td>Westonia</td>
<td>Westonia</td>
<td>Westonia</td>
<td>Carnamah</td>
</tr>
<tr>
<td>May-Oct rain mm</td>
<td>405</td>
<td>353</td>
<td>340</td>
<td>416</td>
<td>275</td>
</tr>
</tbody>
</table>
RESULTS

Grain yields (averaged over the application timing treatments) are presented in Figure 1. The least significant differences (lsd) are presented where the differences were statistically significant. There were good to excellent responses in grain yield to N application at all sites. Wheat yield varied from 1-5 t/ha, while canola yields were 0.4-1.5 t/ha. On average over all N rates and timing treatments there were no significant differences (P > 0.05) between the yields of the Urea and Flexi N at Wubin, Kalannie and Tambellup in the wheat trials and all three canola trials.

Overall, Flexi N produced 5% more wheat yield than Urea at Mullewa and the split Flexi N application strategies resulted in 4% less yield than applying all the Flexi N at sowing. On average at Beverley, Flexi N produced 3% less yield than Urea, however, when its application was split, Flexi N yields increased and were similar to Urea. The Tambellup trial was partially affected by frost damage which may account for the extra variability at this site and the poor performance of Urea at 30 kg N/ha. While there were significant increases in wheat protein content (up to 1.8% increase) with increasing N application, neither source nor application timings had significant effects at all sites.

Although there was no overall difference between the timing strategies in the canola trial at Moora, Flexi N did perform 15% better when applications were split. There was a reasonably heavy infection of blackleg in this trial which constrained yields. On average at Wyalkatchem, the split application treatments produced 38% more grain yield than when all the N was applied at sowing (1.4 vs 1.0 t/ha). Neither source nor timing of the N treatments had significant effects on yields at Pingaring. At this site Flexi N from the farmer’s paddock drifted over the trial which may account for the apparent poor N response. Oil contents increased by 1.0-2.2% with N application at Moora and Wyalkatchem, but were reduced by 1.8% at Pingaring. Source and timing of N application did not have a significant effect on oil content at any site.

The post-emergent application of Flexi N resulted in mild scorching of the tips of the older leaves at several sites, however, the plants rapidly grew through this damage and symptoms were difficult to find 7-10 days after application. Although plants were not suffering from moisture deficits at the time of Flexi N applications, damage appeared to be more evident during fine, warm conditions.
Plant weight and N uptake data were also recorded on several occasions during the growing season (data not presented) and in general these support the overall result that Flexi N was as effective as Urea.
CONCLUSIONS

In general, Flexi N was as effective as Urea at supplying N to wheat and canola over a wide range of environments and yield potentials. In some cases, split applications of Flexi N performed slightly better, than split applications of Urea and this may be due to foliar uptake during dry conditions after application. The fact that Flexi N can be safely applied with post-emergent herbicides, thereby saving one pass over the paddock, will encourage farmers to split N applications to more closely match N supply with plant demand and consequently reduce the risk of leaching losses. This also gives farmers the opportunity to alter N rates after sowing, depending upon rainfall and yield potential. At a few sites Flexi N was less effective than Urea when applied all at sowing which suggests that it is prone to greater leaching losses. This is not surprising given a significant proportion of the N in Flexi N is in the nitrate form. Split applications of N had virtually no effect on wheat grain protein and this can be partially attributed to the high yields at many sites. Lack of soil moisture was not a limitation for most of the year and the applied N was used to increase yield rather than protein. In these situations, very high rates of N application applied at or after flowering would be required to influence protein. Similarly, the split N applications increased canola yields but had no effect on oil content. About 15 farmers tested Flexi N on-farm in 1999. They identified the main advantages of Flexi N as ease of storage and handling, more accurate application and saving the cost of application when mixed with a herbicide. Flexi N was applied through a boomspray in these experiments. In Europe and North America liquid fertilisers are commonly applied in narrow band either near the row or between the rows, and can also be banded below the soil surface. These application techniques have implications for volatilisation and leaching losses and weed growth, and are worth investigating in Western Australia.

KEYWORDS

nitrogen, fertiliser, timing
Why potassium may reduce cereal leaf diseases
Noeleen Edwards, Agriculture Western Australia

KEY MESSAGE
There were a number of observations of increased leaf disease in cereal crops on light soils during the 1999 season, possibly associated with marginal plant potassium (K) levels. K is known to affect plant susceptibility to diseases by influencing biochemical processes and tissue cell structures. The modes of disease resistance are discussed in this article. In seasons when the risk of leaf disease is high, any management strategies that help lower the risk are worth pursuing.

1999 SEASON
During the 1999 growing season, there were observations that leaf rust appeared to be reduced by applications of K fertiliser. For example, there was no leaf rust in a crop of Cascades grown on a light soil east of Tambellup where 200 kg/ha of muriate of potash had been applied over 5 years. Also, crops where 50 kg/ha of muriate of potash was applied had reduced rust severity (D. Rees, pers. comm.). Similar observations have been made before with powdery mildew in barley. Crops with high nitrogen (N) status (unbalanced K nutrition) on poorer soils have suffered worse mildew.

At Gairdner River, two barley variety trials on different soil types in the same paddock showed contrasting levels of Spot Type Net Blotch. Plant tissue analysis showed that the plots that were heavily infected were marginally K deficient while the plots nearby grown on soil that supplied adequate K had negligible disease (K. Young, pers. comm.).

INFECTION PROCESSES AND DEFENCE MECHANISMS
There is an extensive literature on the interaction of nutrients and plant disease, with N and K being the most involved in plant health. Nutrition may alter crop resistance or tolerance to disease by changing growth patterns, plant morphology and anatomy, or chemical composition. As a regulator of enzyme activity, K is involved in nearly all cellular functions that influence disease severity. In K deficient plants large chemical changes occur, including an accumulation of soluble carbohydrates and soluble N compounds, and a decrease in starch. K seems to be most effective in increasing resistance against fungal and bacterial diseases (Perrenoud, 1977).

The germination of spores on leaf and root surfaces is stimulated by the presence of plant exudates. The rate of flow of exudates depends on the cellular concentration (Marschner, 1995). The concentrations of sugars and amino acids are high in leaves, for example, when K is deficient. Excess N also increases amino acid levels. These low molecular weight compounds are important food sources for many pathogens. The concentration of photosynthates in the apoplast and at the leaf surface depends on the permeability of the plasma membrane, and will affect the growth of parasites during the penetration and postinfection phases. K deficiency impairs polymer synthesis in cells and therefore affects membrane permeability.

Many pathogens need to penetrate the plant cuticle and epidermis. Plants well supplied with K have stronger cuticles and thicker outer epidermal walls which make it more difficult for conidia to penetrate the cell. Adequate K also enhances lignification of cell walls and deposition of silicon, another important element in disease resistance. While most pathogens use enzymatic degradation to invade the apoplasm, many cannot degrade lignin, so lignification of cell walls bars penetration.

Phenols have an important role in early infection of the leaf by pathogens, acting both as phytoalexins or as precursors of lignin and suberin biosynthesis (Marschner, 1995). Pathogens cause more damage in varieties with a low phenol content. Adequate K favours protein synthesis and helps preserve these toxic compounds. In contrast, high tissue N depresses phenol and lignin levels.
Adequate K levels can increase the ability of plants to escape disease. For example many rust fungi enter the plant through the stomata. Stomata remain open longer in K deficient plants, favouring infection (Beringer and Trolldenier, 1978). K can also influence how long a plant is susceptible to a particular pathogen. As K favours the onset of flowering, applying K to plants with a marginal K supply can enable them to escape an infection that is more severe in the vegetative phase. Vigorously growing plants with a good K (and N) supply will be more tolerant to diseases because they have a better capacity to compensate for losses of photosynthates or leaf surface area due to infection.

While adequate K results in stronger tissue and thicker leaf cell walls which are more resistant to disease penetration, N has the opposite effect. High N levels also increase the proportion of young to mature tissue, and promote closure of the crop canopy which increases humidity and therefore infection spread. So, balance between these nutrients is especially important in improving tolerance to diseases.

From the literature, incidence of cereal rusts decreased with K application, with fewer pustules being produced in high K nutrient solutions and delayed appearance of rust on plus K plots. The severity of stripe rust on 2 susceptible wheat varieties grown in water culture decreased with increasing K level (Table 1). There are observations of powdery mildew being decreased in both wheat and barley by K fertiliser and the incidence of both Septoria nodorum and S. tritici being reduced by high rates of K fertiliser.

<table>
<thead>
<tr>
<th>Cultivars</th>
<th>K-conc. mM/l</th>
<th>Top fresh wt. G/pot</th>
<th>% K in tops</th>
<th>Disease score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cumhur-75</td>
<td>0.2</td>
<td>166</td>
<td>1.18</td>
<td>70-S</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>232</td>
<td>1.61</td>
<td>50-S</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>300</td>
<td>3.43</td>
<td>40-S</td>
</tr>
<tr>
<td>Super-x</td>
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</tr>
<tr>
<td></td>
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<td>2.03</td>
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<tr>
<td></td>
<td>1.2</td>
<td>234</td>
<td>3.54</td>
<td>50-S</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

While many recorded observations about the effect of K fertiliser on plant diseases are from trials that were not designed to investigate a K and disease interaction, some general conclusions can be drawn. In most cases, K deficient plants are more susceptible than K sufficient plants, and beyond the optimal K supply for growth little further increase in resistance is achieved by increasing the K supply. There are a number of ways K deficiency may increase the level of cereal leaf diseases. K levels are more likely to be marginal on light soils, with the critical surface soil K level for wheat on sandplain and duplex soils being about 40 ppm. Deficiency symptoms may not be evident until significant yield losses occur. In situations where the risk of leaf disease is high or for susceptible varieties, crops with marginal K tissue levels are more likely to develop disease and the level of disease will be worse. There is potential for yield losses from both K deficiency and leaf disease.

**REFERENCES**

KEY WORDS
Potassium, leaf disease

Paper reviewed by: Ross Brennan
Trace elements
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\textsuperscript{1} CSBP futurefarm
\textsuperscript{2} Agriculture Western Australia

INTRODUCTION
Trace elements, in particular copper and zinc, have become fashionable nutrients in recent years. Given long and variable residual lives from past applications of these nutrients, any requirement for them should be objectively assessed on a paddock by paddock basis rather than applying them ad hoc to keep up with fashion.

The main cause of increased interest in copper and zinc is increased use of one-pass seeding equipment. Because copper and zinc are immobile in soils, availability to plants depends upon roots moving to the nutrients. To be most effective, copper and zinc need to be in the pathway of as many roots as possible. Traditionally cultivation has distributed the trace elements through the soil and increased the likelihood of roots ‘bumping’ into them. Where cultivation is now ‘not an option’ (although increased availability of trace elements could make it an infrequent option) there is limited physical distribution of the trace elements, hence the increased interest in them.

One suggestion has been to increase the concentration of copper/zinc in fertilisers. Evidence to date would suggest this is an unlikely solution because absorption depends chiefly on the number of ‘hits’ the whole root system makes with nutrients, rather than the size of ‘hits’ which some roots may make.

The presentation will briefly summarise key parts of past research on trace elements in south western Australia. Although conducted some time ago (at least to the younger author) and before the latest surge in reduced tillage, the research identified mechanisms and factors affecting absorption of trace elements. Because processes were understood, we believe the results are still relevant today and can be applied to various seeding and farming systems. Given an apparent willingness at present to accept information from different farming systems in different conditions on different soil types in different countries, there shouldn’t be any problem reviewing Western Australian results which are some years old.

A high number of trace element hits throughout the root zone increases the chances of roots intercepting nutrient. The distribution of these hits is more important than the concentration within the hit. Even with low analysis fertiliser, there is more than enough trace element in the hit to satisfy roots which happen to hit it. Using high analysis fertiliser won’t improve availability. It will just increase the trace element within the hit to more than ‘more than enough’. Roots which bump into a concentrated hit may be fine (and would have been fine with lower analysis fertiliser) but they can’t compensate for roots which fail to find hits.

Anything that improves physical mixing and distribution through the root zone will improve trace element availability. Gilkes \textit{et al.} (1975) mentioned ‘cultivation, erosion and the disturbances produced by plants and soil fauna’ as contributors to physical movement of fertiliser copper and zinc from the point of application. Gartrell, Brennan and Jarvis in Gartrell (1981) demonstrated that smaller granules, and therefore more of them, and better placement geometry, are more effective than larger granules (Figure 1). Availability improves with cultivation (Gartrell, Brennan and Jarvis in Gartrell (1981)), again because of better redistribution (Figure 2). Cultivation has the benefit of dividing one hit into many hits because trace elements adsorbed onto fine soil particles are further redistributed throughout the soil.
The ‘maintenance strategy’, where a little trace element is applied each year, has gained in popularity in recent years. It is a good idea because time can be used to distribute trace elements through soil. This is provided levels in the soil are already adequate and there is time to work on positional availability of freshly applied nutrient. The maintenance strategy will not overcome a deficiency in the first year (and possibly for many subsequent years) unless the nutrients are made positionally available to roots.

Figure 1. The effect of fertiliser granule diameter (and therefore number of fertiliser granules) on copper concentration in the youngest fully expanded leaves of wheat (Gartrell, Brennan and Jarvis in Gartrell (1981)).
Figure 2. Effect of pre-seeding cultivations on the effectiveness of 1.4 kg/ha Cu in banded fertiliser measured by copper concentration of barley leaves sampled nine weeks after germination (Gartrell, Brennan and Jarvis in Gartrell (1981)).
If the maintenance strategy works it will be because trace elements are applied in different positions each year (if tyres don’t follow previous workings) and mixed to some extent by subsequent workings, not because a high rate of trace element is applied over several years. Factors like sweep width, row spacing and degree of soil disturbance will probably have as much effect on the efficiency of fertiliser as the fertiliser itself. If high rates, particularly of copper, are applied for many years and are available to plants, we should be careful of nutrient imbalances and toxicities in plants and animals.

The maintenance strategy is difficult to evaluate experimentally because its whole purpose is to apply trace elements where they are not immediately required. It would take many years to test the strategy because it requires soil levels, which are adequate now, to be depleted to the extent that plants require the fresher maintenance applications. The only trial we are aware of where ‘maintenance’ copper was applied for many years was at Newdegate (Gartrell, 1976). Where copper was applied at 0.14 kg/ha for nine years, yields were lower compared to one-off applications

(Figure 3). We are unsure of the circumstances of this trial and why such a result was measured.

**Figure 3.** Effects on wheat grain yields of copper fertiliser applications in years prior to, and in the year of planting (66N14 Long Term Copper Trial, Newdegate Research Station, Gartrell (1976)).

Availability of trace elements and effectiveness of fertilisers depend on many seasonal and environmental conditions. Herbicides, soil moisture, soil temperature, soil pH, diseases and pests can all influence plant absorption. For this reason, and as valuable as it is, anecdotal evidence from one year to the next or from one situation to another needs to be treated with a degree of caution. Variability is the nature of the trace element beast!

**REFERENCES**


Historical Nutrient Balance at Paddock and Whole Farm scales for typical wheatbelt farms in the Dowerin - Wongan Hills area

M.T.F. Wong, K. Wittwer and H. Zhang
Precision Agriculture Research Group, CSIRO Land and Water

KEY MESSAGE

Nutrient imbalance occurs in wheat based farming systems

Analysis of historical farm records of fertiliser use and yield dating back to around 1960 shows that typical wheat/sheep farms in the Dowerin–Wongan Hills area have suffered continuous loss of potassium and magnesium. The stock of phosphorus, calcium and sulphur has gradually increased on these farms due to application of superphosphate. In paddocks with a long history of pasture use, the nitrogen balance is positive; in others, nitrogen reserves have been depleted. The results indicate the need to address the issue of potassium and magnesium depletion and illustrate the importance of pastures in the nitrogen economy of the farm. Long term positive nitrogen balance in paddocks suggests that the risk of nitrate leaching has increased and therefore soil acidification and water contamination are likely.

AIMS

Farming relies on the capture of water and applied nutrients and fixed nitrogen by the crops. Outflows of nutrients include crop removal in the form of harvested materials and leaching losses. The aims of this work was to determine whether the inputs matched the outputs and therefore to unravel potential onsite and offsite sustainability issues associated with soil degradation by nutrient depletion, acidification and possible water contamination by leaching.

METHODS

Historical balances were calculated for participating farmers and farm consultants who had the foresight to keep annual records for each paddock. The records used included annual fertiliser use, rotation phase, harvest yield and rainfall. In some instances, these records date back over forty years. Pasture production and input by nitrogen fixation were estimated using: (1) published relationships between rainfall and biomass production; (2) the average legume composition of pastures in the area; (3) the average nitrogen content of pasture legumes and the fraction of that nitrogen that is derived by fixation. In the case of legume crops, the average harvest index was used to calculate nitrogen returned to the soil.

RESULTS

The balance shows consistent losses of potassium and magnesium and accumulation of phosphorus, calcium and sulphur on-farm. The partial balance for nitrogen (fertiliser input minus removal in harvested materials) is negative but this situation is improved if the pasture phase in the system is taken into account (Table 1).
Table 1. Example of on-farm nutrient balance (kg/ha/yr) based on (a) continuous individual paddock records for the 1963-99 period and (b) records of varying length of time to take into account of acquisition and development of new paddocks in the 1963-99 period

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Nitrogen-Legumes not accounted</td>
<td>-8.8</td>
<td>-26.2</td>
</tr>
<tr>
<td>Nitrogen-Legumes accounted</td>
<td>3.4</td>
<td>23.0</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>5.0</td>
<td>7.5</td>
</tr>
<tr>
<td>Potassium</td>
<td>-2.0</td>
<td>-6.7</td>
</tr>
<tr>
<td>Calcium</td>
<td>10.9</td>
<td>15.1</td>
</tr>
<tr>
<td>Sulphur</td>
<td>7.2</td>
<td>30.5</td>
</tr>
<tr>
<td>Magnesium</td>
<td>-0.4</td>
<td>-1.5</td>
</tr>
</tbody>
</table>

The inclusion of new paddocks in the on-farm survey shows a positive potassium balance in some cases due to recent adoption of potassium fertilisers. The same happens with calcium as a result of recent increased use of lime after the ‘Time to Lime’ campaign. Those new paddocks are also rarely used for pastures and are more intensively cropped resulting in overall negative nitrogen.

CONCLUSION

The on-farm survey shows that many paddocks may experience problems due to long term positive nitrogen and phosphorus balance. Positive nitrogen balance may under certain conditions expose the paddocks to increased leaching, water contamination and soil acidification risks. Phosphorus accumulation may result in increased risks of transfer to water bodies but the main issue may be economic and the need to develop technologies to draw on the soil phosphate bank more efficiently. Soil fertility decline is expected to have occurred due to continuous depletion of potassium and magnesium from the farmland. The use of potassium is increasing rapidly and we expect the decline to slow.

KEY WORDS

nutrient, accumulation, depletion

ACKNOWLEDGEMENT

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Paper reviewed by: Heping Zhang