BETTER CROPS
WITH PLANT FOOD

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Focus Issue: Nutrient Management for Wheat

In This Issue...

...and much more

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BETTER CROPS WITH PLANT FOOD

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Our cover: Close up shot of wheat heads ripening in a field in Russia.
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Applying 4R Nutrient Stewardship to Wheat

By Terry L. Roberts and Rob Norton

Wheat is the most important grain of trade for human consumption. It is produced in a vast range of environments from central Russia to the great Indian and Chinese river valleys and across the Great Plains and Pampas of the Americas. Soils and climates vary and so do yield potentials, so that developing appropriate local nutrient management strategies is critical to ensure that yields are produced that give the most efficient use of fertilizers.

The principles of 4R Nutrient Stewardship—apply the right source of plant nutrient, at the right rate, at the right time, and in the right place—aim to use sound science to develop best management practices, producing good yields, providing good human nutrition, and keeping nutrients where they belong. The 4Rs underpin social, economic and environmental goals.

This special edition of *Better Crops with Plant Food* is focused on wheat and provides some examples of the science underpinning the 4Rs. This edition draws on examples of current best practice for nutrient management developed through IPNI's Nutrient Management Decision Support for Wheat Systems workgroup. It has examples from the major wheat production zones showing how the application of good science can improve yield and quality.

An important outcome from the work of the wheat group has been the development and refinement of *Nutrient Expert*, a decision support tool that provides growers with fertilizer recommendations based on nutrient removal. This has been extensively tested and reviewed in China and India and gives growers economic benefits compared to current nutrient management practices.

It is clear that cultivar selection has a big impact on fertilizer decisions—this is shown by the work from Russia with winter wheat as well as grain nutrient surveys. Matching the 4Rs to a variety may need to be considered given these differences – and this suggests that we will need a variety of specific agronomic packages which include nutrient management. Much of the current improvement in efficiency (such as reported in the Russian work) is due mainly to rising yield potentials, but the paper by Hawkesford shows that within the current germplasm there is a range of nutrient efficiencies—associated with different traits—that could become important in developing future nutrient efficient cultivars. This becomes even more important when we consider the article by Lam et al. that N demand will increase as atmospheric CO_2 levels rise, and this demand will not necessarily be met by increased efficiency of N acquisition by wheat, nor by increased N fixation by legumes. Strategic interventions will continue to be needed to improve yields and nutrient use efficiency. BC

Common abbreviations and notes: N = nitrogen; CO_2 = carbon dioxide.

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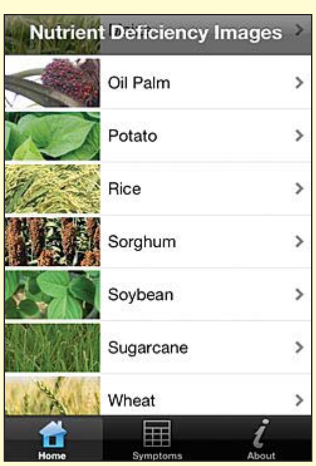
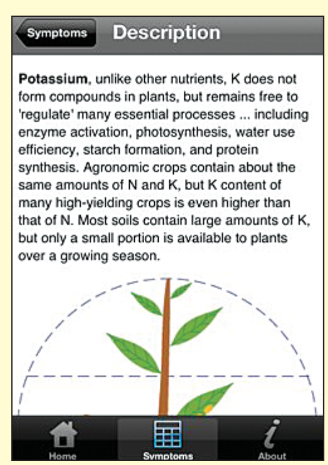
Nutrient Deficiency Photo Application for iPhone/iPad Released

IPNI has released a new Crop Nutrient Deficiency Photo Library app for your iPhone or iPad (see http://info.ipni.net/ndapp). The app contains key photos of classic nutrient deficiency documented from research plots and farm fields for 14 common crops. It also provides supporting text and illustrations of nutrient deficiencies. This mobile app will be a great tool for crop advisers, consultants, farmers, and anyone wanting help in identifying nutrient deficiency symptoms in common crops. BC





Global Wheat Production and Fertilizer Use

By Steve Phillips and Rob Norton

Global wheat production has risen over two and a half times since 1960 as the result of better farming practices, improved cultivars, and balanced nutrition. At the same time, fertilizer use in all agriculture has risen 4.3 times to keep up with growing food demand. It is estimated that growers use around 15% of the fertilizer consumed to produce the current 647 M t of wheat grain.

Global Wheat Production

Global production of the major cereal crops of wheat, corn, and rice is 647 M t, 814 M t, and 441M t, respectively (FAOStat, 2012). However, a large proportion of the corn crop is used for feed and fuel, while 93% of rice is consumed in the country where it is produced. Wheat is one of the most important food crops in the world, providing 20% of humanity's dietary energy supply and serving as the main source of protein in developing nations (Braun et al., 2010). There was around 135 M t traded annually from 2006 to 2010 (**Table 1**), 71% of which was sourced from the USA, France, Canada, Australia, Russia, and Argentina.

The demand for wheat follows rapidly growing populations and is expected to increase by 60% in the third world by 2050 (Rosegrant and Agcaoili, 2010). Over the past 20 years, the average growth in wheat production has been around 1.0% per year (**Figure 1**), but that is considerably less than the 3.3% annual increase between 1960 and 1990, the time of the

Common Abbreviations and Notes: M = million; N = nitrogen; P = phosphate; K = potassium.

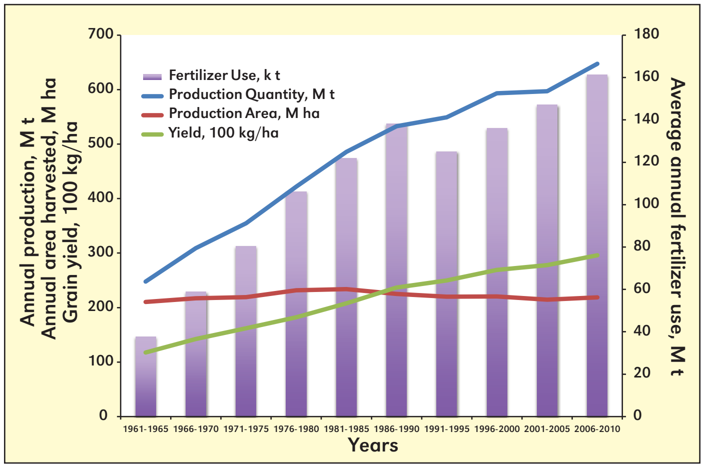


Figure 1. Global wheat production, area, yield, and total fertilizer use (1961 to 2010). (FAOstat, 2012; IFADATA 2012).

Table 1. Production, area, export, yield, and fertilizer use for the top 20 wheat-producing countries in the world (FAOStat, 2012; Heffer 2009, IFADATA 2012).

	Production, M t	Area, M ha	Exports, M t	Yield, t/ha	Fertilizer used in wheat (2006-2007) k t N	k t P_2O_5	k t K_2O	Total fertilizer used, k t nutrient
China	112.10	23.90	0.77	4.69	4,258	1,194	255	49,513
India	77.02	27.76	0.16	2.77	2,892	1,109	187	23,906
United States	58.70	20.32	27.11	2.89	1,604	568	224	18,795
Russian Federation	52.26	24.18	12.60	2.15	402	169	70	2,055
France*	36.73	5.31	16.03	6.92	619	240	206	3,249
Canada	24.79	9.25	17.01	2.67	591	173	36	2,770
Germany*	23.71	3.17	6.42	7.47	458	117	129	2,253
Pakistan	22.57	8.75	0.13	2.58	1,004	345	15	3,829
Turkey	19.06	8.15	0.27	2.34	584	252	15	1,925
Ukraine	18.30	6.31	6.43	2.86	**	**	**	955
Australia	17.92	13.04	13.88	1.36	263	284	28	1,908
United Kingdom*	14.83	1.93	2.36	7.66	549	89	87	1,462
Kazakhstan	13.83	12.98	4.09	1.07	**	**	**	55
Islamic Republic of Iran	13.40	6.47	0.06	2.05	414	179	48	1,614
Argentina	12.68	4.69	8.73	2.70	280	165	1	1,321
Poland*	8.79	2.26	0.76	3.87	591	176	140	1,968
Egypt	7.87	1.26	0.00	6.27	302	35	10	1,409
Italy*	7.29	2.00	0.21	3.65	190	141	81	1,128
Spain*	5.80	1.89	0.48	3.06	515	199	114	1,558
Romania*	5.35	2.05	1.14	2.59	150	24	7	397
World	647.30	218.60	134.78	2.96	16,614	6,261	1,617	161,313

*Fertilizer use in wheat for each EU27 country was estimated from mean fertilizer use by crop (Heffer, 2009) and the total fertilizer used in each country.
**No data available

Green Revolution. This production increase has come from a constant production area of around 215 M ha. So production increases have been largely due to higher grain yields (**Figure 1**). To satisfy the growing demand for wheat, annual production increases need to be closer to the rates observed following the Green Revolution (**Figure 1**). While some of this increase in production will be achieved using improved genetics; the rest will need to come from better agronomic practices, so that the gap between potential and actual yields becomes smaller.

Historical Production (1961 to 2010)

Since the period 1961-65, annual global wheat production increased 2.6 fold until 2010. From 1961 to 1980, the Soviet Union produced around 24% of the global wheat supply averaging just over 80 M t/yr (**Figure 2**). The United States was the second largest wheat producer during that period, averaging 13% world production share (44 M t/yr). In the 1980s, China gained, and has continued to hold, the greatest share of world wheat production, averaging 112 M t from 2006 to 2010 (**Figure 2**). Other significant increases in production share over

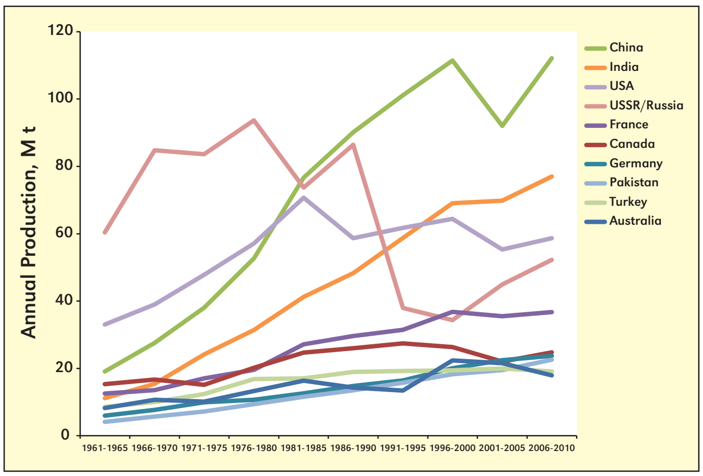


Figure 2. Wheat production trends (1961 to 2010) for the top 10 producing countries. (FAOStat, 2012). Values graphed are the means for each 5-year period.

the last half century occurred in India and Pakistan, while the dissolution of the Soviet Union still left Russia as the largest wheat producer among the former Soviet Union countries. The greatest single-country decreases occurred in North America with the United States and Canada shares dropping 32% and 38%, respectively (**Figure 2**). Out of 123 wheat-producing countries, approximately 70% of world wheat production is currently located in the top 10 countries represented in **Figure 2** and 85% is in the top 20 countries (**Table 1**).

Production Area

The top ten wheat-producing countries also contain nearly 70% of the wheat area (144 M ha) in the world (**Table 1**). This percentage has been consistent since the end of the USSR in the early 1990s. Since 1995, wheat area has increased most in Russia (2.7 M ha), Australia (1.6 M ha), and India (1.2 M ha) although there can be quite large changes in area planted between years due to seasonal and financial conditions. The increase in total wheat area in Russia since 1996 corresponds to an increase in the percentage of total crop area planted to wheat over the same time period, suggesting that this increase is likely a result of wheat substituting for other crops. Australia also shows a slight increase in the percentage of crop area in wheat. Total crop area there increased by 2.2 M ha between 1996 and 2010, mainly as land that was previously either in permanent pasture or in rotation with crops was brought into wheat production, with a consequent significant decline in sheep numbers. The additional 1.2 M ha of wheat in India is also likely a result of new land being cropped, as the percentage of total crop area allocated to wheat has not changed in the past 15 years. Germany added 400,000 ha of wheat over the past 15 years, which is small relative to total wheat area, but represents a 15% increase in wheat area in the country.

The largest decreases in wheat area during the same time period occurred in China (-5.1 M ha), United States (-3.3 M ha), Canada (-1.9 M ha), and Turkey (-1.2 M ha) (**Figure 3**). China, United States, and Canada all had corresponding

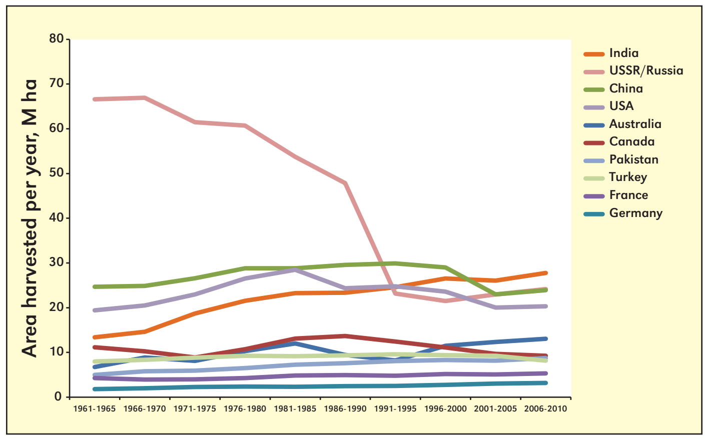


Figure 3. Trends in harvested wheat area (1961 to 2010) for the top 10 producing countries. (FAOStat, 2012). Values graphed are the means for each 5-year period.

drops in wheat area percentages indicating crop shifts, while in Turkey the percentage of total crop area growing wheat did not change, reflecting a reduction in total crop area.

These changes in wheat area can explain, at least in part, the increases observed in overall production in India, Russia, and Germany and the decreases seen in the United States and Canada.

Grain Yield

Changes in total wheat production over time, not related to changes in area, are likely a result of changes in grain yield. Global wheat yield doubled from 1.2 t/ha in 1961 to 2.4 t/ha in 1990 (**Figure 1**). Yield has continued to increase but at a slower rate, moving from 2.4 t/ha in 1990 to 3.0 t/ha in 2010 (**Figure 1**). The progress in wheat yields for the 10 top-producing countries is shown in **Figure 4**. The countries with the highest wheat yields among the top 10 producers have always been Germany and France. However in the last decade, yield gains in Germany have slowed considerably and yield has declined slightly in France. Yields in China have increased at approximately the same rate as those in Europe over the past several decades and have continued to increase over the last 10 years. These large and consistent yield gains explain how Chinese production has continued to increase despite a significant reduction in wheat-producing area over the past 15 years.

The average grain yield in Canada has also increased

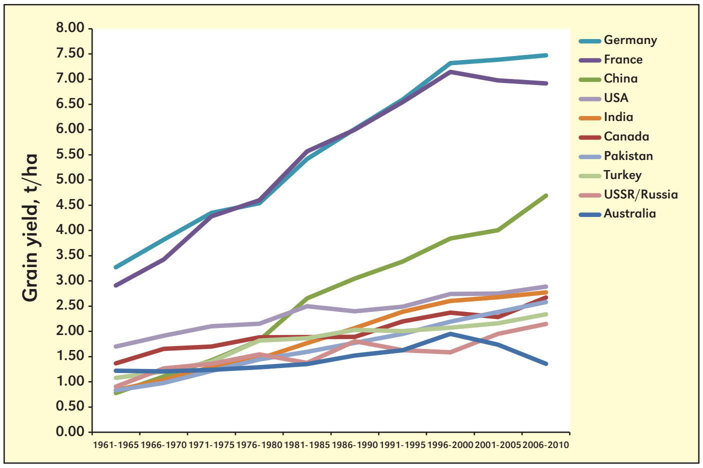


Figure 4. Wheat grain yield trends (1961 to 2010) for the top 10 producing countries. (FAOStat, 2012). Values graphed are the means for each 5-year period.

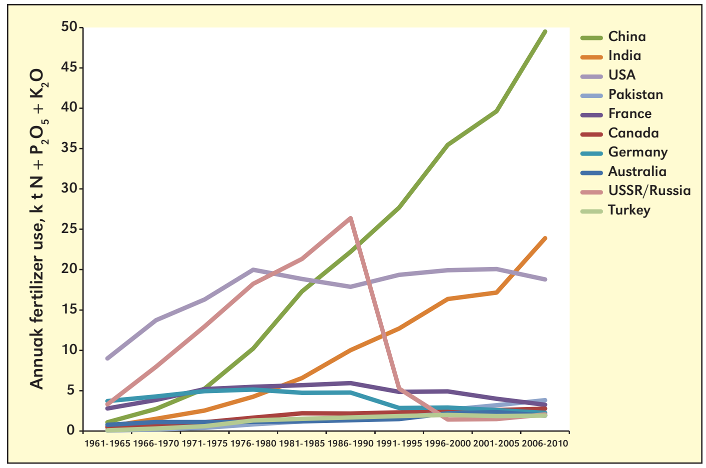


Figure 5. Annual total fertilizer use trends (1961 to 2010) for the top 10 wheat producing countries. (IFADATA, 2012). Values graphed are the means for each 5-year period.

rapidly in the last decade; but of the top 10 wheat producers, only Germany, France, and China have grain yields above the global average (**Table 1**). Grain yields in Pakistan, Russia, and Turkey are rising at or near the global average of 1% annually, but are still at least 0.5 t/ha below the global average. Nonetheless, these yield gains have been enough to contribute to overall production increases in Pakistan and Russia and kept production stable in Turkey despite reductions in the wheat growing area. Yields in India and the United States are near the global average of 3.0 t/ha, but growth rates are well below 1%/yr. Due to a 10-year drought in Australia, yields have fallen at around 2.2%/yr since 1996 to 2000. This fall helps to explain the drop in overall production in Australia despite recent increases in wheat area.

Fertilizer Use in Wheat

The quantity of fertilizer (total N, P_2O_5, K_2O) used in wheat by the top 10 producing countries is approximately 18 M t (**Table 1**). Total annual fertilizer use for all crops has risen from 37 M t of N+P_2O_5+K_2O in 1961-65 to 161 M t in 2005-09 (**Figure 1**). Since 1990 the consumption of fertilizer has risen for all crops and this is also likely to be the case for wheat, although the only data on fertilizer use by crop were released in 2009 (Heffer, 2009). Wheat-growing consumes around 15% of the total nutrients used, and 83% of the fertilizer used on wheat is applied in the top 10 wheat-producing countries.

In the period between 1991 and 1995, France and Germany began reducing fertilizer use and currently apply 34% and 23% less, respectively, than amounts used in the early 1990s (**Figure 5**). Australia has also reduced fertilizer use in wheat by 18% since 2000. The greatest increases in fertilizer use have occurred in India, Pakistan, Russia, and China—all of which have increased use between 40 and 46% in the past 15 years (**Figure 5**). Fertilizer use in Canada and Turkey has been fairly stable for the past several years, and use in the USA has declined by 6% since the period 1996 to 2000. Without knowing use patterns in each crop it is not possible to define which crops have had use rates lowered.

In the cases of China, Pakistan, and Russia, the timing of the yield increases compared with the timing of increases in total fertilizer use coincide, indicating the significant role good nutrition plays in sustaining wheat yields. However, a relationship between increasing fertilizer use and subsequent increases in wheat grain yield is no indication that the current fertilizer management in these countries is at an optimum. Fertilizer rate is only one component of 4R Nutrient Stewardship, which is applying the right nutrient source, at the right rate, at the right time, and in the right place. The 4R's are interdependent and if one is wrong, none of the others can be right.

Conclusion

Increased yields rather than increased area sown has been the main factor behind the increase in wheat production. A range of interventions including the increased use of fertilizers has supported this trend. Increase in fertilizer use mirrors the gains in productivity, although to maintain production it will require continual review of nutrient inputs. The challenge will be to ensure that future growth in food production is met by careful and targeted use of fertilizers. BC

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Improving Soil Fertility and Wheat Crop Management Through the Long-term Study of Cereal Crop Rotations

By Brian Arnall and Fernando García

Long-term fertility trials are established and used across the globe. Unfortunately, for many reasons long-term trials are regularly discontinued. These trials are a wealth of data and information laden with golden nuggets of new and amazing insight. In this article, such nuggets gleaned from long-term wheat trials in Canada, United States, and Argentina are presented.

Northern Great Plains

The Swift Current "Old Crop" rotation is located in southeast Saskatchewan and was established in 1967. Swift Current is located in the driest portion of the Canadian Prairies and is known for its long-cold winters and short growing seasons (Pelton et al. 1967). This report will focus on four of the original 12 treatments implemented in 1967: fallow-wheat-wheat with N and P fertilizer (FNP); fallow-wheat-wheat with P fertilizer only (FP); continuous wheat with N and P fertilizer (CNP), and continuous wheat with P fertilizer only (CP). On average, all cropped treatments designated to receive P received 9 to 10 kg P/ha/yr. The data, figures, and results are derived from Selles et al. (2011).

To evaluate trends over time, the data set was evaluated as three periods identified by water deficit estimations of 1967 to 1979; 1980 to 1993; and 1994 to 2005. The response in Olsen P (0 to 15 cm) soil test values were significantly affected by treatments among the three periods. During the first 12 years, there were no differences among the four treatments. During the second period; treatments began to separate, due to the higher frequency of cropping and therefore fertilization, and as a result the Olsen P of the CW rotations became significantly higher than the FWW. In the third period, FNP had significantly lower Olsen P than the other treatments. Phosphorus balance, calculated as fertilizer added – grain P removal, of the CW rotation was significantly higher than the FWW. During this time period, FWW received 43 kg P/ha less than the CW treatments. In the second period, P balance of the FWW was significantly lower than the first period and again significantly lower than the CW treatments. By the third period, the P balance of the FP and CNP was similar and the CP significantly higher than other treatments. The P balance of the FNP became negative; however, the Olsen P level was still significantly higher than at establishment.

The temporal trend in Olsen P levels was also assessed (**Figure 1**). All treatments showed linear positive trends that persisted for the first 20 years of the experiment. The P only treatments, CP and FP, maintained the increasing trend over the duration of 0.68 and 0.45 kg P/ha/yr, respectively. The rotations receiving both N and P created linear trends of 0.64 and 0.56 for CNP and FNP, respectively, for the first 20 years of the experiment then Olsen P stabilized for the remainder (**Figure 1**).

Many long-term trials have opportunity to incorporate split plots; the Old Crop rotation is one of those. In 1993, the researchers decided to split treatments receiving P fertilizer to provide an area in which P fertilization was discontinued. Withholding fertilizer P had no impact on grain yield in either treatment in the FWW rotation; however, 10% reduction in grain yield was observed in the CW systems (**Table 1**). Selles et al. (2011) noted that the yield reduction in CW was not consistent; however, for both CNP and CP there were 2 years in which yield reduction was more than 35%.

The results demonstrate that residual soil P accumulated during the previous 27 years (1967 to 1993) remained in forms

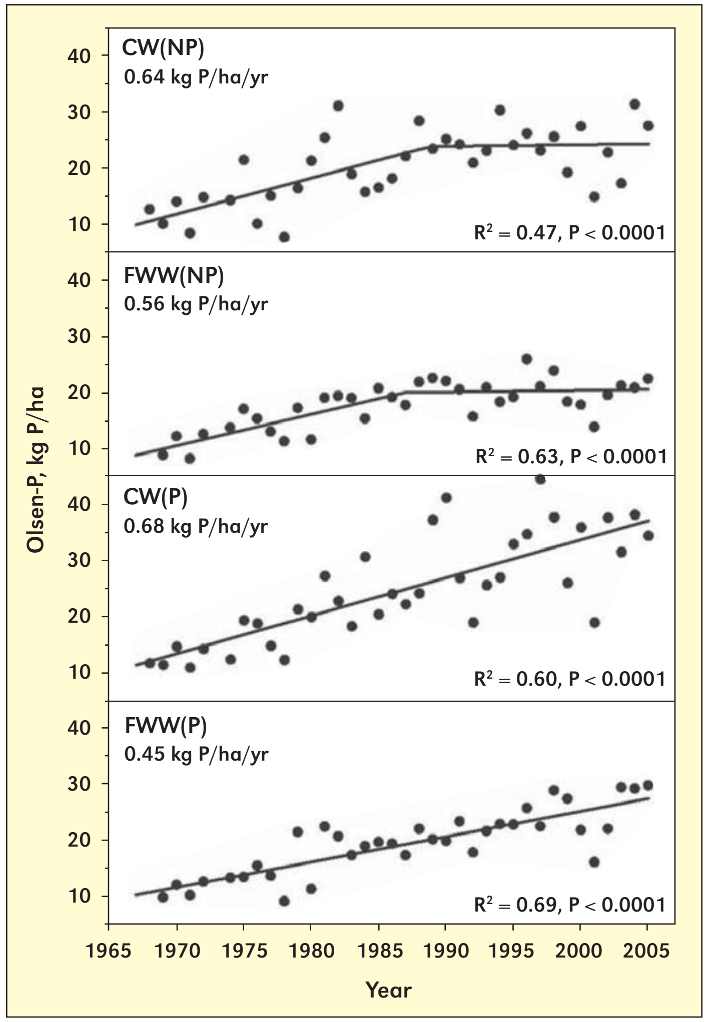

Figure 1. Trends in Olsen P for the original plots, 1967 to 2005. [Trend models given by following expressions: CW(NP) if time ≤22, y = 9.9 + 0.64 x time, otherwise y = 9.9 + 0.64 x time – 0.61 x (time – 22); FWW(NP) if time ≤20 y = 8.9 + 0.56 x time, otherwise y = 8.9 + 0.56 x time – 0.59 x (time – 20); CW(P) y = 11.5 + 0.68 x time; FWW(P) y = 10.4 + 0.45 x time]. From Selles et al. (2011).

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium, Mg = magnesium, B = boron, Cu = copper; Zn = zinc.

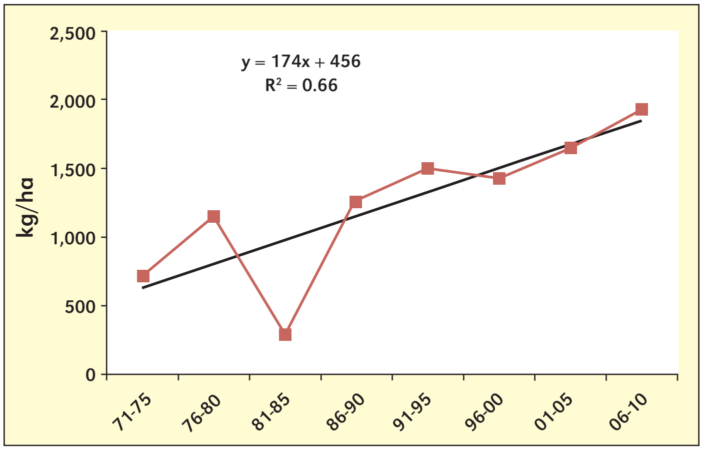

Figure 2. Yield increase due to N over time. Increase calculated as yield of the 112 kg N/ha treatment minus the yield of the 0 N treatment.

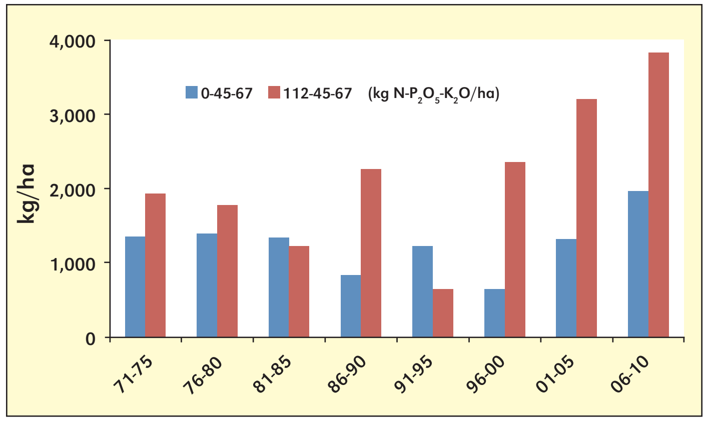

Figure 3. Yield difference between the highest and lowest yielding years within each 5-year grouping.

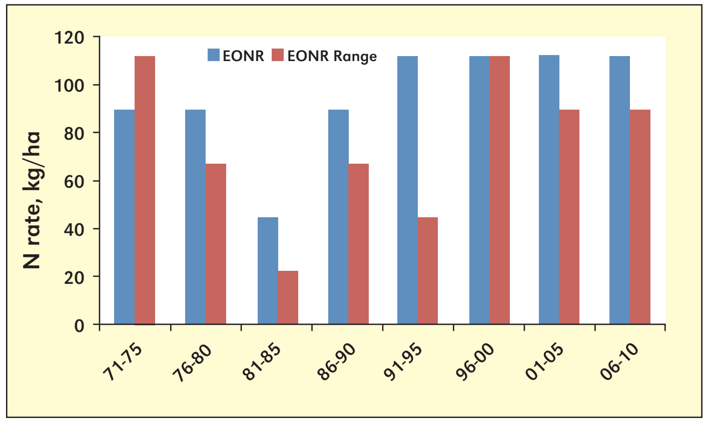

Figure 4. Economical optimum N rate (EONR) for 5-year groupings and the range in EONR value within each grouping.

readily available to the crop, confirming that in soils with high levels of residual P, crops rarely suffer production losses when fertilizer P is not supplied (Selles et al. 2011).

Central Great Plains

Oklahoma is home of several long-term winter wheat trials; including the Magruder Plots, the oldest continuous wheat plot west of the Mississippi River. These data are derived from a continuous winter wheat NPK study established in 1971 in northwestern Oklahoma. This report will focus on data from six treatments over a range of N rates from 0 to 112 kg/ha in 22.4 kg increments. Each treatment receives 20 kg P/ha and 56 kg K/ha annually.

For more than 30 years of production the N check plot recorded yields ranging from 0.75 to 2.84 t/ha, averaging 1.78 t/ha per year. The 112 kg N/ha plot (highest N rate) recorded a low of 1.42 t/ha and high of 5.94 t/ha with a 30-year average of 2.96 t/ha. The standard deviation of the grain yield from the two treatments was 0.55 and 1 t/ha, respectively. To aid in the review of these data, they were grouped into 5-year segments where general tends become visible. One is the increase in yield due to the addition of N fertilizer, calculated by subtracting the yield of the zero from the fertilized. With exception of the early 1980s, yield response has increased over time (**Figure 2**). It is evident the difference between good years and bad years, within each 5-year grouping, is also increasing in the fertilized plot. The last three periods: 1995 to 2000, 2001 to 2005, and 2006 to 2010, resulted in yield differences of 2.36, 3.20, and 3.83 t/ha, respectively (**Figure 3**). This trend identifies that the likelihood of either over or under fertilizing is also increasing as the variability in annual N removal increases. For each year, the economic optimum nitrogen rate (EONR) was calculated. When evaluated in 5-year groupings, EONR has been static at 112 kg N/ha since the early 1990s (**Figure 4**). However, within each 5-year grouping the range of EONR has been 90 kg N/ha or more since the late 1990s (**Figure 4**).

Table 1. Effect of withholding P on total wheat grain production during the period of 1994 to 2005.

Rotation	Grain Production P applied (t/ha)	Grain Production P withheld (t/ha)
CNP	29.1	26.3*
CP	19.8	18.7*
FNP	21.3	21.0
FP	18.0	16.8
Nested LSD	1.8	

Significance between P applied and P withheld at $p < 0.05$.

Typical N management of the region consists of average yield goals calculated from the previous 5 years, plus 20%. This strategy would result in the over application of 1,672 kg N/ha over the period between 1976 and 2011. Use of 5-year EONR reduced over application to 1,187 kg N/ha, 30% less than the strategy based on yield goals plus 20%.

The data not only shows how the yield potential of winter wheat grown on the Great Plains has increased, but also how the response to added fertilizer N is also increasing with time. Much of this increase could be a consequence of improved varieties and better crop management strategies. More importantly, these data indicate the magnitude of the temporal variability in maximum yield and N requirements. This shows the need for in-season measurements that can adjust total N recommendation based upon environment and crop status.

Argentinean Pampas

The youngest of the three studies discussed is located in the Pampas Region of Argentina. Unlike the previous two experiments, this fertility study comprises 11 on-farm experimental locations. Sites belong to the Nutrition Network of CREA Southern Santa Fe, and reside in the three provinces of Santa Fe, Cordoba, and Buenos Aires. CREA (Regional Consortia for Agricultural Experimentation) are farm groups dedicated

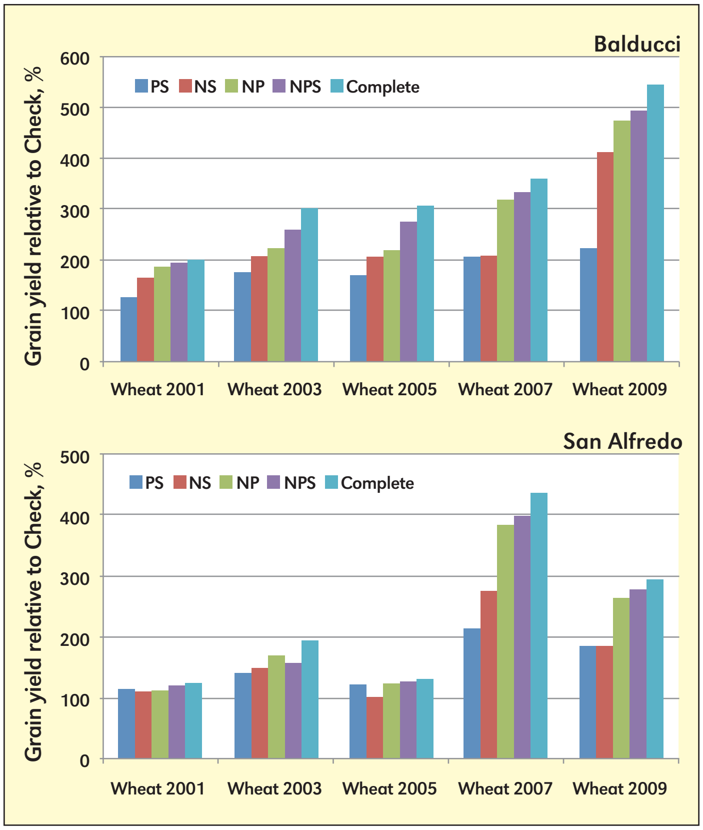

Figure 5. Relative wheat grain yields for different fertilization treatments in the sites of Balducci (C-W/S rotation) and San Alfredo (C-W/S rotation), considering the check yield as 100%.

to develop and share knowledge and information on crop, soil, and farm management.

The 11 locations are separated according to crop rotation into two categories: corn-wheat/soybean (C-W/S) and corn-soybean-wheat/soybean (C-S-W/S). Six treatments are applied at all locations: 1) Check, 2) PS, 3) NS, 4) NP, 5) NPS, and 6) Complete (NPS plus: K, Mg, B, Cu and Zn). Nutrient rates applied to cereal crops were equivalent to grain nutrient removal + 10%, except for N for which rates were decided according to local calibrations of soil nitrate-N test at planting.

A summary of the first 6 years was presented in García et al. (2007), and since establishment in 2000; wheat has been included in 33 site/years: five cropping seasons from the C-W/S locations and three from the C-S-W/S sites. From these trials the correlation between crop response and soil test can be evaluated. Over the 33 site/years, there were significant grain yield increases at 16 site/years for N, 25 site/years for P, 6 site/years for S, 20 site/years for NPS, and 4 site/years for other nutrients (García et al., 2010).

Significant relationships were established between N response and soil nitrate-N availability at planting (0 to 60 cm), and sap nitrate concentration at tillering. Critical soil nitrate-N of 130 to 140 kg N/ha at planting (soil N + fertilizer N) have been established for wheat yields of 4 t/ha. Phosphorus responses were observed in 95% of the sites with soil Bray P levels lower than 15 mg/kg, as reported by Berardo (1994) and Zamuner et al. (2004) for the southern Pampas. A critical range of 15 to 20 mg Bray 1 P/kg has been defined. There was no relationship between S response and sulfate-S availability at planting, as it was observed for other wheat experiments in the Pampas (García, 2004). Conversely, corn yield responses to S were related with sulfate-S at planting (0 to 20 cm).

Yield differences among fertilized treatments and the check increased along years of evaluation, suggesting that changes in soil fertility status, other than Bray P, have occurred. These increased differences are attributed not only to decreasing check yield, but also increased fertilized yields. **Figure 5** demonstrates the increase in response and yield at two C-W/S locations.

Increases of soil Bray P differences between P fertilized and non-fertilized treatments were determined. The 10-year review (2000 to 2011) identified an increase in Bray 1 P of 1.9 to 3.1 ppm per year in those treatments receiving P. In the NS treatments, Bray 1 P decreased by an average rate of 0.50 to 1.0 ppm per year.

Summary

The Old Crop Swift Current trial reveals that in the low rainfall environments of the southwestern Canadian prairies, fertilizer P may remain in a labile form in areas of positive P balance and that producers may be able to take advantage of the past fertilization in years of high P prices. The long-term plots in Oklahoma shed light on the volatility of yield potential and N demands of winter wheat grown in the US Central Great Plains. The On-Farm CREA trials within the Central Pampas of Argentina demonstrate that soil test N and P adequately identify areas in which responses to fertilizer can be expected, while soil test S is providing little estimation of yield response in wheat production. This brief glimpse into the data from these long-term studies carried out across North and South America highlights the importance of such studies to contributing to our understanding of strategies to improve soil fertility and nutrient management for wheat production worldwide. BC

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The Diversity of Nitrogen Use Efficiency for Wheat Varieties and the Potential for Crop Improvement

By Malcolm J. Hawkesford

Nitrogen use efficiency (NUE) is a complex process and must be de-convoluted into tractable and measurable sub-traits, which may be targeted for specific improvement that can be included in new wheat varieties. Current research conducted at Rothamsted Research aims to define the key traits contributing to yield and NUE, and to quantify existing diversity. Evolving from these studies are genetic and molecular analyses aimed at identifying specific markers for breeding and the underlying genes involved.

Global food security requires yield improvements or an expansion of land area used for agriculture. In addition optimum resource use efficiency (RUE) is a prerequisite for sustainability. A major driver for yield, especially in intensive agricultural systems, is N fertilizer. Canopy growth requires N, and it is canopy photosynthesis that ultimately drives yield. The canopy also acts as a reservoir of N and other minerals, which are recycled into grain tissues with potentially high efficiency. Inappropriate use of N fertilizers, particularly excessive or ill-timed application can lead to poor uptake, wasted valuable resource, and potential environmental damage. Well-informed agronomic management has a crucial role in optimum fertilizer use to exploit the full potential of existing germplasm. Additional greater efficiency will require improved germplasm, with more effective capture and biomass conversion.

Definition of Nutrient Use Efficiency

There are many interpretations of nutrient and specifically N use efficiency. Fertilizer use efficiency reflects the recovery of applied fertilizer by the crop, however from the crop perspective, N (or other nutrient) use efficiency is a measure of biomass produced as a function of the N (or other nutrient) available to that crop. Key traits are illustrated in **Figure 1**. NUE in wheat is the grain yield divided by available N (fertilizer N + soil mineralized N); NUE is the product of two definable and independent major sub-traits, N uptake efficiency (NUpE) and N utilization efficiency (NUtE). NUpE is the total N taken up by the crop as a fraction of the total N available; as such it is a measure of the ability of the crop to capture available N and is principally determined by root-associated traits such as root depth proliferation and activity (e.g. transporter efficiency). Total N-uptake may be affected by sink size, in the form of above ground biomass, but also in turn, directly determines the size of this biomass. NUtE reflects the functionality of the aboveground biomass, and for wheat is defined as the grain yield as a function of the total amount of N taken up (grain + straw). Canopy architecture, function and longevity determine the production of carbohydrate for grain filling and hence yield. A complication is the need for N by the grain during grain filling, a requirement fulfilled mainly by remobilization from the senescing (and hence decreasingly functionally active) canopy. Hence the harvest index (HI) and N harvest index (NHI) are important considerations for efficient crop production.

Yield and Nitrogen

NUE and yield are being investigated in the Wheat Genetic Improvement (WGIN) trials (http://www.wgin.org.uk/). The aim is to dissect and assess variability in NUE, NUpE, and NUtE amongst modern wheat germplasm. Multiple elite commercial cultivars (primarily dwarf or short-straw varieties) are being grown, including many released in the UK over the past 25-year period, a selection of continental European varieties, and older, tall varieties. Varieties span the quality spectrum from bread to feed types. Fertilizer inputs are ammonium nitrate at five rates in the range 0 to 350 kg N/ha. A preliminary report of the first 4 years of this 10-year project has been published (Barraclough et al. 2010). Grain yield ranged from 2.1 to 11.8 t/ha (85% DM), grain %N from 1.1 to 2.8% (in DM), total N uptake from 31 to 264 kg N/ha, and grain NUtE from 27 to 77 kg DM/kg N. There were significant varietal differences in total N uptake and grain NUtE both between dwarf and non-dwarf varieties and within dwarf varieties. The best dwarf varieties took up 31 to 38 kg/ha more N than the worst, and grain NUtE was 24 to 42% better, depending on N rate. Up to 77% of the variation in grain NUtE was accounted for by

Common abbreviations and symbols: N = nitrogen; DM = dry matter.

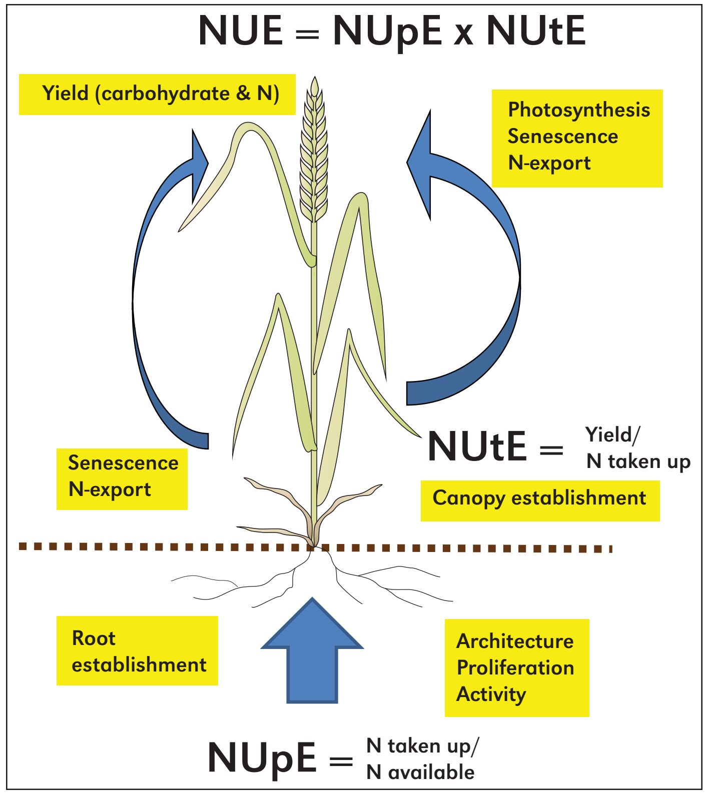

Figure 1. Diagrammatic representation of the key terms used to describe wheat nutrient use efficiency, focussing on N. Underlying physiological processes are indicated.

yield. All interactions between the varieties, year, and N rate were highly significant.

For both yield and grain NUtE, there was an inverse relationship with grain %N; high yield is achieved by high carbohydrate content and a dilution of N (protein) and other minerals; high-quality wheat (high grain %N) can be expected to have a low grain NUtE because of the low yields of these varieties (less carbohydrate) and often the need to use even more N fertilizer to boost grain protein. Improving grain NUtE for fixed total NUp and NHI can only be achieved at the expense of grain %N. To improve grain NUtE and maintain grain %N requires a simultaneous increase in NHI and grain starch yield, which may be difficult to achieve in practice.

The summary performance for four key traits is presented in **Figure 2**. The quartile performance of 39 varieties for each of the traits is indicated. The bread-making varieties (nabim Group 1) have generally low yields but high grain %N; nabim Group 3 and 4 (biscuit and feed wheat) have the converse; uptake and utilization efficiencies reflect these performances. Clearly a goal would be to have upper ranking performances for all traits for an ideal bread wheat, however for high starch end-use wheats, high N-uptake may be a negative trait. For a subset, a detailed analysis of protein composition and the influence on dough functionality and bread-making quality has been investigated for multiple sites and years (data not shown). Grain total protein content and composition of protein have fundamental influences on quality parameters of wheat flour. Genetic variation exists in all of these traits and component traits and improvement strategies need to clearly define the targeted components and identify specific genetic variation in each, as well as environmental interactions.

Variety	nabim group	Years	Yield	%N	Uptake	Utilization
Avalon	1	5	Inter-Q (orange)	Inter-Q (orange)	Upper-Q	Inter-Q (yellow)
Flanders	1	1	Lower-Q	Upper-Q	Inter-Q (yellow)	Lower-Q
Hereward	1	5	Inter-Q (yellow)	Inter-Q (orange)	Upper-Q	Inter-Q (yellow)
Hurley	1	5	Inter-Q (yellow)	Inter-Q (orange)	Inter-Q (orange)	Inter-Q (yellow)
Malacca	1	5	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)	Inter-Q (orange)
Mercia	1	4	Inter-Q (yellow)	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)
Maris Widgeon	1	5	Lower-Q	Upper-Q	Lower-Q	Lower-Q
Shamrock	1	4	Inter-Q (yellow)	Inter-Q (yellow)	Inter-Q (orange)	Inter-Q (orange)
Solstice	1	5	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)	Upper-Q
Spark	1	1	Inter-Q (orange)	Inter-Q (orange)	Inter-Q (orange)	Inter-Q (yellow)
Xi 19	1	5	Upper-Q	Lower-Q	Inter-Q (orange)	Upper-Q
Cadenza	2	5	Inter-Q (yellow)	Inter-Q (orange)	Upper-Q	Inter-Q (orange)
Cordiale	2	3	Upper-Q	Inter-Q (orange)	Upper-Q	Inter-Q (orange)
Einstein	2	1	Inter-Q (yellow)	Lower-Q	Lower-Q	Inter-Q (orange)
Lynx	2	5	Upper-Q	Inter-Q (yellow)	Upper-Q	Inter-Q (orange)
Rialto	2	1	Inter-Q (yellow)	Upper-Q	Inter-Q (yellow)	Lower-Q
Scorpion	2	1	Upper-Q	Lower-Q	Inter-Q (orange)	Upper-Q
Soissons	2	5	Inter-Q (yellow)	Upper-Q	Inter-Q (orange)	Lower-Q
Beaver	3	4	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)	Inter-Q (orange)
Claire	3	4	Upper-Q	Inter-Q (yellow)	Upper-Q	Upper-Q
Riband	3	5	Inter-Q (orange)	Lower-Q	Inter-Q (yellow)	Upper-Q
Robigus	3	4	Upper-Q	Lower-Q	Upper-Q	Upper-Q
Istabraq	4	4	Upper-Q	Lower-Q	Inter-Q (orange)	Upper-Q
Napier	4	3	Upper-Q	Inter-Q (yellow)	Upper-Q	Inter-Q (orange)
Savannah	4	4	Upper-Q	Lower-Q	Inter-Q (orange)	Upper-Q
Paragon (spring)	1	5	Inter-Q (yellow)	Upper-Q	Inter-Q (orange)	Inter-Q (yellow)
Chablis (spring)	2	1	Lower-Q	Lower-Q	Lower-Q	Upper-Q
Arche	F	1	Lower-Q	Inter-Q (yellow)	Lower-Q	Inter-Q (yellow)
Batis	G	5	Inter-Q (orange)	Inter-Q (yellow)	Upper-Q	Inter-Q (yellow)
Caphorn	F	1	Lower-Q	Upper-Q	Lower-Q	Lower-Q
Cappelle Desprez	F	1	Lower-Q	Upper-Q	Lower-Q	Lower-Q
Enorm	G	1	Inter-Q (orange)	Inter-Q (orange)	Upper-Q	Inter-Q (yellow)
Isengrain	F	1	Lower-Q	Upper-Q	Lower-Q	Lower-Q
Monopol	G	5	Lower-Q	Upper-Q	Inter-Q (yellow)	Lower-Q
Opus	G	1	Upper-Q	Lower-Q	Lower-Q	Upper-Q
PBis	G	1	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)	Inter-Q (orange)
Petrus	G	1	Inter-Q (yellow)	Inter-Q (orange)	Inter-Q (yellow)	Inter-Q (yellow)
Sokrates	G	5	Inter-Q (orange)	Inter-Q (orange)	Inter-Q (orange)	Inter-Q (orange)
Zyta	P	1	Lower-Q	Upper-Q	Lower-Q	Lower-Q

Upper-Q | Inter-Q | Inter-Q | Lower-Q

Figure 2. Indicative performance of 39 wheat varieties for four key traits (grain yield, grain % N, total N uptake and NUtE). Varieties are grouped according to the national association of British and Irish millers (nabim) classification system, except for those originating from France (F), Germany (G), and Poland (P). Ranking in quartiles is indicated. Used with permission from Barraclough et al. 2010.

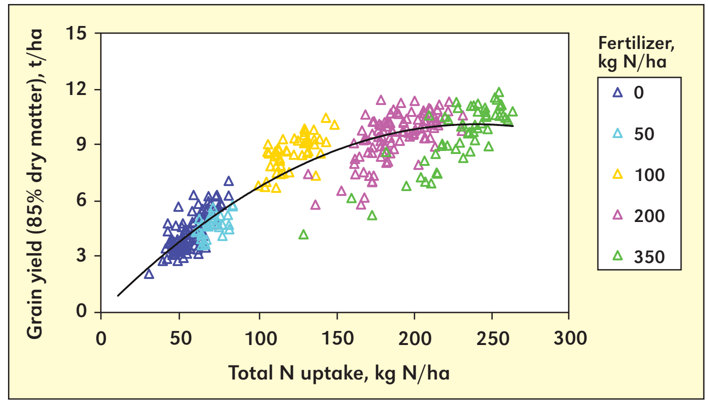

Figure 3. Effect of N fertilizer inputs on grain yield and total N uptake in 39 wheat varieties grown at Rothamsted from 2004 to 2007. A trend line shows the non-linear relationship. Adapted and used with permission from Barraclough et al. 2010.

Importantly, multiple trials facilitate evaluation of trait stability, a desired attribute with huge economic implications. Site and year-to-year seasonal variation had a major influence on trait expression, which was both a useful and valuable experimental parameter as well as a hindrance in terms of the need for replication. Over the 8 years to date, yield stability at 200 kg N/ha varied greatly, with Cadenza being the most stable variety (range: 8.3 to 10.2 t/ha) and Soissons the least (range: 5.8 to 15.5 t/ha). The year-to-year variability was mostly due to rainfall patterns and consequent influences on the duration of the grain filling period.

Limits to Yield

The relationships between N uptake and the conversion into grain yield for the WGIN dataset (2004 to 2007) are shown in **Figure 3**. Increased N application generally resulted in both increased yield and total N uptake, particularly below 200 kg N/ha; between 200 and 350 kg N/ha there was no trend for increased yield, however the total amount of N taken up increased and this was reflected in higher grain %N; generally NHI was little affected by N input (Barraclough et al. 2010). The fitted trend line shows this plateau of yield increase. This leads to a decreased NUE (for grain) but higher protein content and quality. However it is evident that factors other than N uptake are limiting yield. Whilst increasing fertilizer applications above 200 kg N/ha have little impact on yield, the benefits in

Aerial view of the N use efficiency experiments at Rothamsted.
Photograph contributed by M. Hawkesford.

terms of grain protein (increased N) positively influence flour quality and dough properties (Godfrey et al. 2010). This quality improvement comes at the cost of a decreased overall NUE at the high N inputs, and additionally, and significantly, there is greater N runoff from the crop. In the UK, wheat yields have continued to rise over the past 20 years at around 0.1 t per year due to husbandry and genetic improvements, whilst N fertilizer use has remained static at 190 kg/ha, largely as a result of legislative control (limiting N inputs in Nitrogen Vulnerable Zones in the UK); this data indicates that this would be at the cost of grain N and furthermore that raising N inputs would not impact directly on yield with current germplasm.

Prospects

The key target traits for improved NUE are focused on improved capture and consist of enhancing root depth and proliferation and possibly root functioning. Increasing yield is focused on canopy longevity with early flowering or late maturation offering benefits but with high risk of crop failure. Screening has focused on the analysis of a relatively restricted set of germplasm and mapping populations where there is limited diversity. Evolving strategies such as the Wheat Strategic Improvement Programme (WISP) (http://www.wheatisp.org/), and others, are examining older and more diverse germplasm or are generating novel germplasm by the production of synthetic hexaploids or through chromosome segment introgression using wheat relatives. Linking screening programmes to transcriptome analyses and high-density genotyping has the potential to identify the specific genes and alleles involved which will speed plant breeding, including genes for high yield and efficient nutrient scavenging.

Summary

Is striving for efficient fertilizer use at odds with the need for increased crop production and food security? The two objectives are bound together: an important and essential component of crop production is efficient use of N fertilizer. In spite of the costs, both economic and environmental, worldwide efficiency has been estimated at only 30% of that applied to that recovered as harvested grain. As such NUE is a key target for crop improvement, both in terms of agronomy management and germplasm selection. BC

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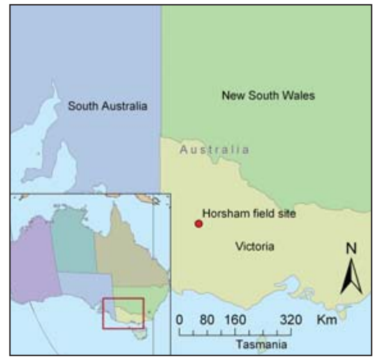
Notes on Describing Nutrient Use Efficiency

There are many ways to assess nutrient use efficiency depending on the purpose to which the data will be put. In this article, nitrogen use efficiency is assessed using two measures. The Table below summarizes the terms used in this article compared to other commonly used nutrient efficiency terms.

Term	Calculation
Nutrient Uptake Efficiency	NUpE = (kg nutrient taken up)/(kg nutrient available) = U/(F+S)
Nutrient Utilization Efficiency (Internal Utilization Efficiency)	NUtE = (kg grain produced)/(kg nutrient taken up) = Y/U
Apparent Recovery Efficiency	RE = (kg increase in uptake)/(kg fertilizer applied) = $(U - U_0)/F$ (whole plant) = $(Ug-U_0g)/F$ (grain only)
Physiological Efficiency	PE = (kg yield increase)/(kg fertilizer nutrient uptake) = $(Y-Y_0)/(U-U_0)$
Agronomic Efficiency	AE = (kg yield increase)/(kg nutrient applied) = $(Y-Y_0)/F$ = RE x PE
Partial Nutrient Balance (Nutrient Removal Ratio)	PNB = (kg nutrient removed)/(kg applied) = Ug/F
Partial Factor Productivity	PFP = (kg yield)/(kg nutrient applied) = Y/F = (Y_0/F)

Y = crop yield with applied nutrient; Y_0 = crop yield with no applied nutrient; F = fertilizer applied; S = nutrient in the soil; U = plant nutrient uptake of above ground biomass at maturity; U_0 = plant uptake with zero fertilizer; Ug = grain nutrient content with applied nutrient; U_0g = grain nutrient content with no applied nutrient.

How Will Climate Change Affect Wheat Nutrition in Australian Cropping Systems?



By Shu-kee Lam, Deli Chen, Roger Armstrong, and Rob Norton

Understanding N dynamics is crucial to crop sustainability under rising atmospheric CO_2 concentration. Field and glasshouse trials were conducted to investigate the effect of elevated CO_2 on N dynamics in Australian cropping systems, with specific focuses on fertilizer N recovery by wheat, symbiotic N_2 fixation by legumes, and N_2O emission. Our results indicate that grain N removal will be higher in a carbon-rich world, and that current N management practice will need to be revised. However, because of the positive relationship between CO_2 elevation and N_2O emissions, global warming may be higher than current estimates.

Atmospheric [CO_2] has been rising since the industrial revolution and has increased at a much greater rate since 1950. If CO_2 emissions continue at their present rate the atmospheric [CO_2] is estimated to reach about 550 ppm by 2050 and 700 ppm by the end of this century (Houghton et al., 2001; IPCC, 2007). When grown under elevated [CO_2], C_3 crops generally produce more biomass and grain yield, and demand more N (Kimball et al., 2002). This increase in N demand would be expected to gradually reduce soil N reserves unless replenished. So in order to secure future crop yields, this increased demand must be met with a combination of fertilizer and biological N fixed by legumes.

Another consequence of the "fertilizer effect" of elevated [CO_2] is the likely increase in the amount of root growth. These roots then provide more C substrate that are available to denitrifying soil microbes, so that N_2O production may be stimulated under elevated [CO_2] (Baggs et al., 2003).

Common abbreviations and notes: N = nitrogen; P = phosphorus; C = carbon; CO_2 = carbon dioxide; [CO_2] = carbon dioxide concentration; N_2O = nitrous oxide; NO_3^- = nitrate.

Even though there is general understanding, the effects of elevated [CO_2] on fertilizer N recovery by cereals, symbiotic N_2 fixation by legumes, and soil N_2O emission in Australian cropping systems have not been studied for rainfed wheat production systems. To investigate the implications of these various processes on soil fertility we conducted outdoor (Australian Grains Free-air CO_2 enrichment; AGFACE) and indoor (glasshouse chamber) experiments at Horsham, Victoria, Australia.

AGFACE Study Site

Field experiments were conducted on a Vertisol from early June to mid December in 2008 and 2009 at Horsham (36°45'S, 142°07'E), Victoria. This area has a temperate climate with a long-term average rainfall and maximum temperature of 316 mm and 17.5°C during the wheat-growing season. Elevation of atmospheric [CO_2] was achieved using a FACE system, consisting of sixteen 12 m diameter (expanded to 16 m in 2009) experimental areas, eight ambient and eight elevated (**Figure 1**). The experimental areas were sown with wheat at 60 kg/ha seed and 23 kg P_2O_5/ha. The two target CO_2 concentrations were 390 (ambient) and 550 ppm (elevated). Seasonal rainfall

Figure 1. One of the eight FACE rings in Horsham, Victoria.

Table 1. The effect of elevated [CO_2] and supplementary irrigation on fertilizer ^{15}N recovery in wheat and in soil.

	Fertilizer N recovery, %					
	Plant	Soil	Plant	Soil	Plant	Soil
	2008NS †		*2008LS*		*2009NS*	
Rainfed						
Ambient [CO_2]	43	29	4	82	39	31
Elevated [CO_2]	49	27	4	78	42	27
Irrigated						
Ambient [CO_2]	49	27	25	61	48	23
Elevated [CO_2]	46	24	32	54	44	26
[CO_2] (C)	ns	ns	ns	ns	ns	ns
Irrigation regime (I)	ns	ns	***	***	ns	*
C × I	ns	ns	ns	ns	ns	*

Values are means of the four replicates for each treatment.
† *2008NS* = 2008 normal sowing; *2008LS* = 2008 late sowing; and *2009NS* = 2009 normal sowing.
Significant effects for main effects and interactions are indicated as *$p < 0.05$ and ***$p < 0.001$. ns = not significant.

Table 2. Effect of elevated [CO_2] and P application on the proportion of N derived from the atmosphere (%Ndfa) and the amount of N fixed by chickpea, field pea, and barrel medic.

	%Ndfa		Amount Ndfa, mg N/pot	
Soil P status	–P	+P	–P	+P
	Chickpea			
Ambient [CO_2]	34	30	17	17
Elevated [CO_2]	26	36	18	27
	Field pea			
Ambient [CO_2]	46	48	23	35
Elevated [CO_2]	39	44	28	42
	Barrel medic			
Ambient [CO_2]	30	43	11	26
Elevated [CO_2]	57	51	30	49
[CO_2] (C)	ns		**	
P	ns		**	
Species (Spp)	*		*	
C × P	ns		ns	
C × Spp	ns		ns	
P × Spp	ns		ns	
C × P × Spp	ns		ns	

Values are means of the four replicates for each treatment. Significant effects for main effects and interactions are indicated as *$p < 0.05$ and **$p < 0.01$. ns = not significant.

and temperature scenarios were simulated by supplementary irrigation and delayed sowing. The fertilizer N recovery experiment was conducted over three experimental periods [2008 normal sowing (2008NS), 2008 late sowing (2008LS) and 2009 normal sowing (2009NS)], while N_2O flux measurements were made on the 2009NS treatment.

Application of ^{15}N-labeled Fertilizer

In each treatment area, a micro-plot was established by enclosing part of a wheat row with a PVC cylinder (0.24 m diameter, 0.25 m deep) inserted to 0.20 m depth. At the start of tillering, ^{15}N-enriched (10.22 atom%) granular urea was surface broadcast onto the micro-plot at the same rate (50 kg N/ha) and at the same time as non-labeled granular urea was applied to the remainder of the plot. Plants were harvested ten days after physiological maturity. Samples of dried plant (grain, shoot, and root) and soil (0 to 0.10 m, 0.10 to 0.20 m, and 0.20 to 0.40 m depths) were weighed, finely ground to ~100 µm, and analyzed for total N and ^{15}N enrichment by isotope ratio mass spectrometry (IRMS).

N_2O Flux Measurement

Gas samples for N_2O analysis were taken from closed static chambers (0.24 m diameter, 0.25 m deep) between 1200 and 1500 h at stem elongation, booting, anthesis, dough development, and ripening of wheat, respectively. One day before each sampling event, two chambers were inserted to a soil depth of 50 mm at random locations on each treatment area. On each sampling day, gas samples (30 mL) were collected at 0, 30, and 60 minutes after chamber closure using a gas-tight syringe, transferred into vacutainers and analyzed by gas chromatography.

Symbiotic N_2 Fixation

The interaction of [CO_2] and P availability on symbiotic N_2 fixation by chickpea, field pea, and barrel medic was examined under controlled environment conditions. These legumes were grown on pots (0.14 m diameter, 0.15 m deep) with addition of either 0 or 46 kg P_2O_5/ha in either ambient (390 ppm) or elevated [CO_2] (700 ppm) glasshouse chambers. Plants were harvested at flowering stage, and the dried plant samples (legume and wheat as a reference plant) were finely ground to ~100 µm and analyzed for total N and ^{15}N enrichment by IRMS. The proportion of shoot N derived from the atmosphere was assessed using ^{15}N natural abundance technique.

Results

Depending on treatment and year, the total N removed in grain was between 75 to 118 kg N/ha under elevated [CO_2] compared to 63 to 101 kg N/ha under ambient [CO_2]. This increase in grain N removal was not apparent in rainfed plots at 2008LS, which was equivalent to severe drought conditions. Regardless of [CO_2] the recovery of fertilizer N in the wheat parts followed the order grain > shoot > root, and the recovery from the soil decreased with soil depth. The recovery in the whole plant ranged from 43 to 49%, 4 to 32%, and 39 to 48% for 2008NS, 2008LS, and 2009NS, respectively (**Table 1**). Elevated [CO_2] had no significant effect on the recovery of fertilizer N in the whole wheat plant or in any plant parts for any experimental periods. The [CO_2]-induced increase in plant N uptake (18 to 44%) was satisfied mostly by increased uptake of indigenous N (20 to 50%), probably because the proportion of applied fertilizer N in soil mineral N pool was small. Irrespective of [CO_2], the recovery of fertilizer N in wheat grown under supplementary irrigated plots was higher than that in rainfed counterparts in 2008LS (hot and dry period). Elevated [CO_2] generally did not affect the total recovery of fertilizer N in these systems (**Table 1**), so nutrient recovery from fertilizer is not expected to be any higher.

The proportion of shoot N derived from the atmosphere (%Ndfa) of the chickpea, field pea, and barrel medic was not affected by elevated [CO_2] regardless of soil P supply. However, because the legumes responded well to the higher P supply, the total amount of shoot N fixed by these legumes was increased by elevated [CO_2] (chickpea: 34%; field pea: 21%; barrel medic: 118%) and P fertilization (chickpea: 26%; field pea: 52%; barrel medic: 84%) (**Table 2**). In a similar experiment, we found the amount of N removed in grain from these legume crops also increased under elevated [CO_2] for chickpea (31%) and field pea (26%). As a result, the increased N fixation was mostly exported in grain that resulted in a negative N contribution by the legumes to the whole system.

Elevated [CO_2] increased the overall N_2O emission by 108%, with changes being greater during the wheat vegetative stage than during either dough development and ripening stages (**Figure 2**). This is possibly because N uptake by plant and N loss during the vegetative growth stage of wheat resulted in lower availability of NO_3^- at those later growth stages. Moreover, later in crop growth, wheat root activity and N uptake declined, which reduced the difference in C and N dynamics between [CO_2] treatments. The supplementary irrigation reduced N_2O emission by 36% when averaged across [CO_2] treatments (**Figure 2**), suggesting that N_2O was reduced to N_2 in the denitrification process.

The results of the present study have several implications. First, grain N removal will be higher under elevated [CO_2], and extra N will need to be added to the systems to maintain soil N availability and sustain grain yield. Second, higher rates of fertilizer N application and greater use of pasture legume intercropping rather than grain legumes will be able to rectify the negative N balance due to grain N removal. The contribution of N by the legumes to the overall N economy of these mixed cropping systems will be contingent on adequate P supply. Finally, the extent of the stimulation of N_2O emission by elevated [CO_2] will be lower if water supply is sufficient to facilitate the reduction of N_2O to N_2, or if the vegetative stage of crop growth is shortened (e.g. by future warmer and drier climates).

This research has identified that fertilizer N and P strategies will need review as the impact of climate change and elevated [CO_2] become more evident. Changing patterns of growth and therefore nutrient demand mean that research will need to consider new combinations of the right source at the right rate, right time, and right place for nutrient best management practices. BC

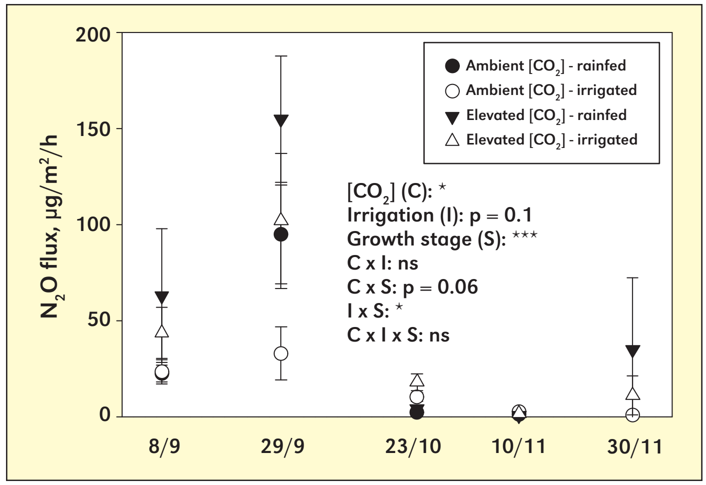


Figure 2. Effect of elevated [CO_2] and supplementary irrigation on N_2O flux at various key growth stages of wheat (stem elongation on 8/9/09; booting on 29/9/09; anthesis on 23/10/09; dough development on 10/11/09 and ripening on 30/11/09). Values are the means of four replicates for each treatment. Vertical bars indicate standard errors. Significant effects for main effects and interactions are indicated as $^*p < 0.05$ and $^{***}p < 0.001$. ns = not significant.

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Nutrient Management for Wheat in a Variable Climate

By Rob Norton

Profitable use of N and P to meet crop requirements in a variable climate such as the grain belt of southeastern Australia means adopting strategies that minimize risk. Using yield potentials, N and P demands can be estimated, but research shows there is no particular penalty if N is provided as the yield develops during the season. As yet there are no strategies for in-crop P application although research is pointing the way.

Nineteenth century poet Dorothea Mackellar described Australia as a land "of drought and flooding rains" and this phrase still resonates today. The southeastern wheat belt of Australia has been through an extended drought from the late 1990's until the floods of 2010 and 2011. **Figure 1** shows the annual rainfall for Horsham in the Victorian grain belt, indicating the large annual variation in rainfall, driven by conditions in the Pacific, Southern, and Indian Oceans.

This rainfall variation is an important driver of yield variation, where soil water at sowing plus in-crop rainfall can account for 61% of yield variation (Hochman et al. 2009). **Figure 1** also gives the wheat yields from a farm in the Horsham

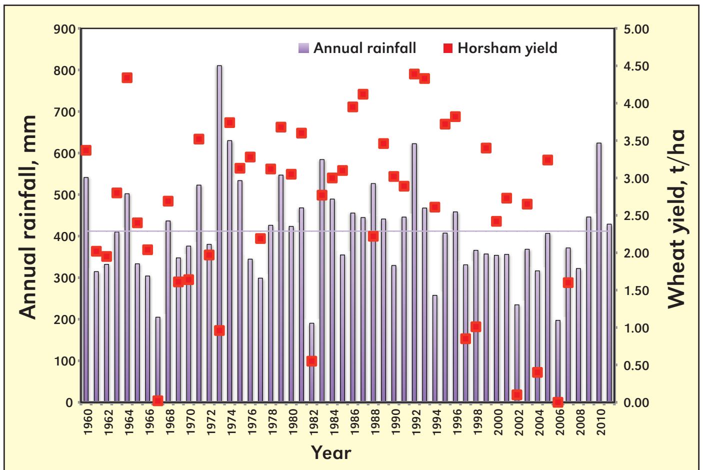

Figure 1. Annual rainfall and wheat grain yield from a farm near Horsham in the Victorian grain belt.

district, showing how yields generally follow rainfall. Wheat yields reflect the large differences in rainfall and simple and more complex models based on rainfall allow growers to estimate yield potential at or near sowing, and therefore nutrient demand. Over application of N and P is a waste of money and resources, and too much N in particular in dry seasons can result in small grain size and a large price penalty. Under application means that yield potentials are not met.

Selecting the Right Rate for N and P

To estimate fertilizer rate, an achievable or target yield needs to be predicted. This water limited yield potential can be based on a water use efficiency of 20 kg/ha/mm of seasonal water supply (French and Schultz, 1983). The water supply includes measured or estimated plant available stored soil water plus an estimate of future rainfall. From this is it possible to then develop a nutrient budget based on the predicted yield of the crop (**Box 1**).

Based on the example in **Box 1**, it would be estimated that the crop would need 116 kg N/ha to achieve this target

Common abbreviations and notes: N = nitrogen; P = phosphorus.

Box 1: Yield Estimate
Available Soil Water – 100 mm
Expected seasonal water – 250 mm
Total Water Supply = 350 mm
Water Use Efficiency (WUE) – 20 kg/ha/mm
Non-Productive soil water – 110 mm
Yield Potential = WUE x (Available Water – Non-productive water)
= 20 x (350 – 110)
= 4,800 kg/ha (4.8 t/ha)

yield. There are several assumptions within this estimate including that the rooting depth of the crop is not restricted, the efficiency of soil and fertilizer N to grain N is 50%, and the mineralization rate of these soils will follow the model in **Box 2**. More significantly, it makes an assumption that there

Box 2: Nitrogen Balance Estimate
Yield Potential = 4.8 t/ha
N demand = 45 kg N/t of grain = 216 kg N/ha
Mineral N at sowing = 50 kg N/ha (measured)
% Organic C (%OC) = 1.2%
In-crop mineralization estimate = %OC x (seasonal rainfall)/6
= 1.2 x (250)/6 = 50 kg N/ha
Soil N supply = N at sowing + Mineralization
= 50 kg N/ha + 50 kg N/ha = 100 kg N/ha
Fertilizer N to meet yield potential = (216 – 100) = 116 kg N/ha

will be 250 mm of seasonal rainfall and the distribution of this rainfall is appropriate to achieve that yield.

A similar approach can be taken for P demand, using a water-limited yield potential and therefore an expected P removal. Typical grain P contents are around 3 kg/t of grain mean a target yield of 4.8 t/ha would need to be balanced with around 15 kg P/ha. This base rate would need to be adjusted for the P buffering capacity of the soil, any demands for P to raise soil P test, and account taken of any P lost through transport off the paddock. Because grain P can vary from 2.0 to 4.0 kg P/t (Jensen and Norton, 2012), growers may improve the precision of this budget by measuring actual grain P and derive actual removal.

Managing Risk Around the Right Rate for N

Given the uncertainty of future rainfall once the crop has been sown, applying the full dose of N at sowing is when least is known about the seasonal conditions. From fieldwork in the Victorian grain belt, Norton et al. (2009) compared timing strategies where N was deferred either in part or full to tillering or even later (**Table 1**). The delayed application of all N until tillering produced significantly higher yields at three sites and did not reduce yields at any site when compared to an at-sowing application. Splitting 50:50 the applications did give benefits in three sites and no yield reduction at any site.

Based on these results, there would seem to be little yield

Table 1. Comparison of a range of various timings for N strategies on grain yield (t/ha) for eight site-years tested in the Victorian grain belt.

Post Sowing	2005 Sealake	2006 Hopetoun	2007 Walpeup	2005 Marnoo	2007 Kalkee	2005 Inverleigh	2006 Inverleigh	2007 Inverleigh
Urea deep banded	4.35	0.95	1.44	3.95	2.35	3.48	2.20	5.20
Urea deep banded + 50% @ Zadoks 31	4.11	0.98	1.40	3.98	2.83	3.40	2.54	5.69
Urea deep banded + 33% @ Zadoks 31 + 33% @ Zadoks 41	4.29	-	1.39	4.17	2.77	3.91	-	5.59
Urea topdressed @ Zadoks 31	4.44	0.93	1.61	4.27	2.72	3.43	2.25	5.24
LSD (p=0.05)	0.27	0.22	0.23	0.30	0.28	0.54	0.23	0.40

penalty by delaying part or the entire N until later in the season, even on relatively high yielding sites. The caution here is that all those sites had at least 40 kg N at sowing in the profile, and this soil N supply was likely to be adequate to carry the crop through to tillering with little N stress.

If the season does not provide good rains in the late winter or spring, yield potentials can be adjusted down. Because part of the N has been withheld, there would be no penalty due to haying off, or a financial loss with low fertilizer efficiency. Growers now tend to apply maybe 20 to 30% of the N at sowing, and then apply added N (or not) as the seasonal conditions roll out.

Most wheat growers would now use some sort of tool to estimate yield potential and then match N supply to meet that potential. The rules of thumb used in the examples in **Box 1** and **Box 2** have been integrated with sophisticated crop simulation models and tools – such as Yield Prophet® (http://www.yieldprophet.com.au/yp/wfLogin.aspx), which enables an ongoing view of the yield and the potential response to N (Hunt et al. 2010).

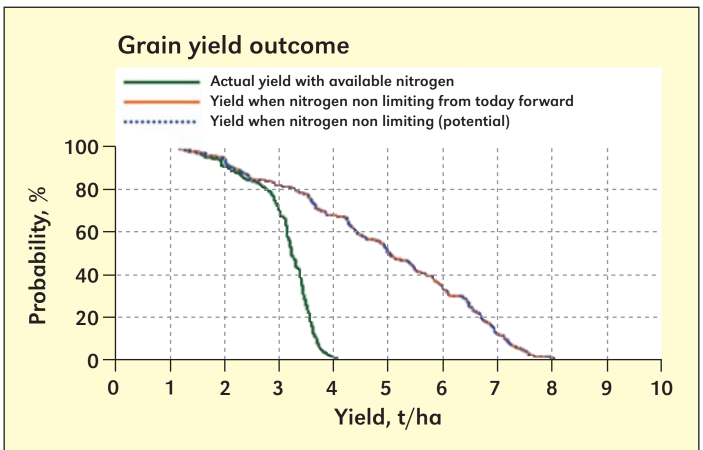

Figure 2. Probability of exceedance for a range of seasonal conditions using weather conditions to June 22, measured soil N and other agronomic inputs for a wheat paddock in the Wimmera region of Victoria.

Figure 2 shows part of a screenshot from the Yield Prophet® website showing the probability of exceedance of grain yield at a site in the Wimmera of Victoria. The outcome in the graph is based on yields from 100 years of rainfall records from the date of the report until crop maturity. This shows that if no added N is used, the median (50% probability) yield would be around 3.3 t/ha, while the conditions suggest yields would not exceed 4 t/ha. This outcome is based on the current N status of the paddock (101 kg N/ha).

The second line on the graph shows the yield in response to added N modeled over 100 years. This shows there is adequate water to take the median yield to 5 t/ha if N was not limiting, and the yield response ranges from 0 to 4 t/ha. This provides growers with the magnitude of the typical response, plus the range of responses likely given the variable climate.

Managing Risk Around the Right Rate for P

Phosphorus is usually applied at seeding in the drill row as this has long been seen as the most efficient delivery strategy. Rates are usually based on average removal, but this tends to over apply P in poor years and under apply it in better years. Topdressing of P in-crop does not supply the P near the roots because it is relatively immobile and will not leach into the root zone. Provided the important early crop demands are met with an at-sowing P source, and if products are developed that do not damage the crop canopy at appropriate use rates, P application could become tactical (Noack et al. 2010), similar to common N management strategies. Research into the right source, rate, time, and place for tactical P for wheat is currently under investigation (Noack et al. 2010).

Conclusion

In a variable climate, matching nutrient demand to supply relies on a good estimate of the yield potential. Nutrient budgets for N can be tailored around these variable yields to provide adequate N to prevent N stress early in the crop's life with little or no yield penalty. As the seasonal conditions unfold, additional N can be added (or not) to meet the rising (or falling) yield potential and nutrient demand. A similar approach to tactical application of P is an attractive option and current research is investigating appropriate products and their deployment to make this a viable strategy. BC

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Optical Sensor-based Nitrogen Management for Irrigated Wheat in the Indo-Gangetic Plains

By Bijay-Singh, R.K. Sharma, Jaspreet-Kaur, M.L. Jat, K.L. Martin, Yadvinder-Singh, Varinderpal-Singh, H.S. Thind, H.S. Khurana, M. Vashistha, W.R. Raun, and R. Gupta

Robust relationships were observed between in-season GreenSeeker™ optical sensor-based estimates of yield at Feekes 5-6 and 7-8 growth stages and actual wheat yields. Sensor-guided fertilizer N applications resulted in high yield levels and high N use efficiency. Application of 90 kg N/ha at planting, or in two equal doses at planting and crown root initiation stage, were appropriate prescriptive fertilizer N management options before applying a corrective GreenSeeker™ guided fertilizer N dose for the Indo-Gangetic Plains (IGP) in northwest India.

In the IGP in northwestern India, wheat is generally grown under assured irrigation conditions and with a standard fertilizer recommendation (120 kg N/ha in the state of Punjab and 150 kg N/ha in Haryana and Uttar Pradesh) applied in two equal split rates at planting and at crown root initiation stages. The second application coincides with a first irrigation event around 21 days after planting. To achieve high fertilizer use efficiency, prescriptive N applications at planting and crown root initiation stage (or first irrigation) can be moderately reduced provided the N needs of the crop are considered for the entire season. This can be done by considering field-to-field and temporal variability using a suitable criterion to apply a corrective fertilizer dose. These subsequent applications usually coincide with a second or third irrigation event. Therefore, the major objective of the present study was to evaluate optical sensor-based N management in irrigated wheat compared to the standard fertilizer N recommendations in the IGP. Different combinations of prescriptive and corrective N management scenarios were evaluated to compare a more objective basis for N management in wheat.

Demonstration of GreenSeeker™ optical sensor technology on-farm with lead author on the left.

Materials and Methods

Field experiments were conducted in three wheat seasons (2004 to 2005 and 2006 to 2007) at Ludhiana (30°56'N, 75°52'E), Karnal (29°42'N, 77°02'E), and Modipurm (29°40'N, 77°46'E). The three sites have subtropical climates. Soils were mildly alkaline loamy sands (Typic Ustipsamment) at the Punjab Agricultural University farm, Ludhiana; mildly alkaline sandy loam (Typic Ustochrept) at the Directorate of Wheat Research farm, Karnal; and alkaline sandy loams (Typic Ustochrept) at the farms of Project Directorate for Cropping Systems Research, Modipuram.

The treatments consisted either of application of fertilizer N as urea at 60, 120, 180, and 240 kg N/ha during planting, or 60, 120, and 180 kg N/ha applied in two equal split doses, one at planting and one at crown root initiation stage, which occured around 21 days after planting and coincided with the first irrigation. A zero N control plot was also included. During the 2004 to 2005 wheat season, two on-going field experiments at Ludhiana and one on-going experiment at Karnal were used to generate data to develop relationships for in-season estimation of wheat yields. In these experiments, two equal doses of urea, varying from 0 to 90 kg N/ha, were applied at planting and crown root initiation. During 2006 to 2007 at Ludhiana, two experiments were conducted under zero-till; one with rice straw mulch and the other without mulch. All field experiments were laid out in a randomized complete block design with three or four replications.

Common abbreviations and notes: N = nitrogen; GDD = growing degree days; YP_0 = yield potential with no added fertilization; YP_N = yield potential with additional fertilizer N; NDVI = normalized difference vegetation index; RI = response index.

Spectral reflectance, expressed as NDVI, was measured using a handheld GreenSeeker™ optical sensor unit (NTech Industries Incorporation, Ukiah, CA, USA). In-season estimated yield proposed by Raun et al. (2002) was calculated by dividing NDVI data by the number of growing degree days (GDD) > 0. The yield potential with no additional fertilization (YP_0) was calculated using an empirically-derived function relating in-season estimated yield to yield potential. In all experiments, an N-rich strip was established by applying 200 kg N/ha in split applications to ensure that N was not limiting. The NDVI measurements from the N-rich strip ($NDVI_{NRICH}$) and the test plots ($NDVI_{TEST}$) were used to calculate the response index (RI) to fertilizer N (Johnson and Raun, 2003) and then the appropriate fertilizer N application.

Grain and straw subsamples were collected for analysis of total N. The data generated from the calibration experiments were used to fit relationships between in-season estimated yield and YP_0.

Predicting Yield Potential of Wheat from In-season Optical Sensor Measurements

The relationship between grain yield and in-season estimated yield was plotted from data generated from Karnal, Ludhiana, and Modipurum for both the Feekes 5 to 6 and Feekes 7 to 8 growth stages (**Figure 1**). With wheat planting dates ranging from the 2nd to 23rd of November, and sensing dates ranging from the 2nd to 23rd of January, a value of R^2 as high as 0.61 suggest that wheat yields can be predicted fairly accurately as early as the Feekes 5 to 6 growth stagewhen the first node appears on the wheat plant and the second irrigation becomes due. This relationship was even more robust (R^2 = 0.76) at Feekes 7 to 8 when more data became available from the field trials. At Feekes 7 to 8, the wheat crop requires irrigation once again and an application of fertilizer can also be applied along with this water.

Differences from yield prediction equations formulated using the data collected for the three wheat-growing seasons were not substantial.

Estimating Fertilizer N Application Using an Optical Sensor for Correcting In-season N Deficiency

Using YP_N and YP_0, the amount of additional N fertilizer required was determined by taking the difference in estimated N uptake between YP_N and YP_0 and an efficiency factor (Raun et al., 2002). Prescriptive N management in the form of applying different amounts of fertilizer N at planting and the crown root initiation stage of wheat, and whether optical sensor-based N management was practiced at either Feekes 5 to 6 or Feekes 7 to 8 greatly influenced the amount of fertilizer N to be applied following the N fertilizer optimization algorithm (**Table 1**).

In general, the amount of sensor-guided N to be applied at Feekes 5 to 6 was less than that determined for Feekes 7 to 8. For similar prescriptive applications of fertilizer N at planting and the crown root initiation stage, higher optical sensor-guided fertilizer N rates at Feekes 7 to 8 were due to higher RI values recorded at this stage. Also, when only 60 or 80 kg N/ha was applied at planting, and no N was applied at crown root initiation stage, optical sensor-guided recommendations were underestimated. Thus total fertilizer N applications in these treatments were less than in treatments with 100 kg N/ha or more, applied either all at planting or in two split amounts. This was possibly because at low prescriptive N levels, YP_0 is low and the associated RI value is not proportionately high. Since the fertilizer N rate is calculated from the difference of YP_N and YP_0, the total fertilizer recommendation (prescriptive + optical sensor-based) remained low relative to a treatment receiving an adequate prescriptive rate of fertilizer N.

Evaluation of GreenSeeker™ Guided N Management Versus Blanket Recommendations

Increased fertilizer N use efficiency at optimum yield levels was observed due to lower rates of total N application compared with blanket recommendations when appropriate prescriptive fertilizer N applications strategies were combined with a GreenSeeker™ optical sensor-guided fertilizer N application (**Table 1**). However, this reduction in total N application cannot be used as a clue for formulating another blanket recommendation consisting of moderate amounts of N at planting, the first irrigation stages, and a small dose of N during the Feekes 5 to 8 growth stages.

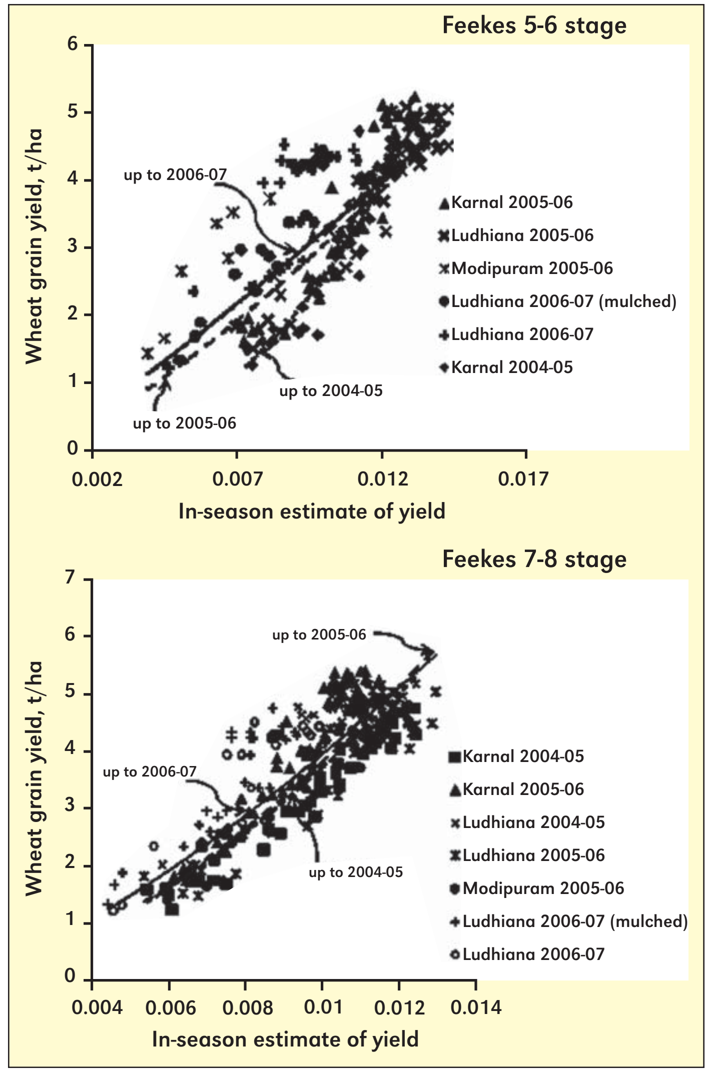

Figure 1. Relationship between in-season estimate of yield and potential grain yield of irrigated wheat at Feekes 5 to 6 and 7 to 8 stages. For Feekes 5 to 6 stage, R^2=0.90 (up to 2004 to 2005), 0.66 (up to 2005 to 2006), and 0.61 (up to 2006 to 2007). Relationship between in-season estimated yield (x) and potential yield (y) up to 2006 to 2007: $y=602.47x^{1.1348}$. For Feekes 7 to 8 stage, R^2=0.84 (up to 2004 to 2005), 0.83 (up to 2005 to 2006), and 0.76 (up to 2006 to 2007). Relationship between in-season estimated yield (x) and potential yield (y) up to 2006 to 2007: $y=2581x^{1.4072}$

Corrective N application determined by use of the GreenSeeker™ optical sensor and grain yield revealed that for different variants of moderate prescriptive N application, the corrective N application to obtain high yield levels was influenced by the timing of the prescriptive N amounts as well as the timing of the corrective N amounts. Thus, a combination of moderate prescriptive fertilizer N consisting of either 90 kg N/ha at planting, or 45 to 50 kg N/ha both at planting and at the crown root initiation stages, and a corrective GreenSeeker™-guided fertilizer N application at the 2nd or 3rd irrigation events can lead to improved fertilizer N use efficiency with no reduction

Table 1. Evaluation of GreenSeeker™-based N management in wheat (cultivar PBW 343) at Ludhiana, India during 2005-06.

Treatment	Fertilizer N application, kg N/ha: Basal sowing	CRI¥ 1st irrigation	Feekes 5 to 6 2nd irrigation	Feekes 7 to 8 3rd irrigation	Total	YP_0‡, t/ha	RI§	Grain yield, t/ha	Total N uptake, kg/ha	AE†	RE¶	PE#
1	0	0	-	-	0			1.52	31.9	-	-	-
2	60	60	-	-	120			4.35	103.2	23.6	59.2	39.9
3	75	75	-	-	150			4.41	110.3	19.3	52.3	37.1
4	60	0	17 *	-	77	3.25	1.16	3.66	73.1	27.8	53.2	52.2
5	80	0	12 *	-	92	3.52	1.11	3.80	87.8	24.8	60.9	40.7
6	100	0	10 *	-	110	3.61	1.09	4.20	95.2	24.4	57.3	42.5
7	40	40	3 *	-	83	4.02	1.02	3.81	88.5	27.6	68.1	40.6
8	50	50	0 *	-	100	4.30	0.98	4.32	98.8	28.0	67.0	41.8
9	60	60	0 *	-	120	4.20	0.99	4.39	105.4	23.9	61.3	39.3
10	60	0	-	29 *	89	2.98	1.30	3.99	94.2	27.8	69.7	39.4
11	80	0	-	24 *	104	3.24	1.24	4.13	97.6	25.1	63.5	40.5
12	100	0	-	21 *	121	3.43	1.19	4.29	102.4	22.9	58.3	39.2
13	40	40	-	18 *	98	3.62	1.15	4.27	100.5	28.1	70.0	39.9
14	50	50	-	12 *	112	3.84	1.10	4.35	108.5	25.3	68.4	36.8
15	60	60	-	15 *	135	3.77	1.12	4.40	115.2	21.3	61.5	34.7
LSD ($p = 0.05$)								0.37	11.04	3.03	9.52	4.41

*GreenSeeker™ guided N application; ¥Crown root initiation stage; †AE: Agronomic efficiency of applied N (kg grain/kg N applied); ¶RE: Recovery efficiency of applied N (%); #PE: Physiological efficiency (kg grain/kg N uptake); ‡YP_0: Yield potential with no additional fertilizer N applied; §RI: Response index, RI_{NDVI}.

in yield. This strategy saved total fertilizer N application if compared with the prevalent blanket recommendations.

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Symposium on Modeling the Economics of Fertilizer Applications ASA/CSSA/SSSA International Annual Meetings - Monday 22 October 2012, 8:00 am - 12:00 pm.

Sponsored by: SSSA Divisions S4 (Soil Fertility and Plant Nutrition) and S8 (Nutrient Management and Soil & Plant Analysis).

Nutrient recommendations are being called upon to meet many objectives, such as increased efficiency, increased production, and lower environmental losses; however, farmers, who are the ones making the final fertilization decisions, are most concerned about profitability. This symposium examines various methodologies for incorporating economic variables into fertilizer recommendations. Approaches range from short-term considerations for one nutrient to long-term optimizations that consider multiple factors simultaneously. Presentations will span this range of complexity to assess how far science has come and where it must go in the future to improve the economic decision-making of farmers.

We invite all participants of the ASA/CSSA/SSSA International Meetings in Cincinnati to attend this symposium. More details can be found by following the link: http://scisoc.confex.com/scisoc/2012am/webprogram/Session9944.html

Topdressing Nitrogen in Modern Winter Wheat Varieties in Central Russia

By B.I. Sandukhadze and E.V. Zhuravleva

This research found that split N topdressing is not always more efficient than single topdressing on winter wheat in Russia. Modern wheat varieties generally have both the highest yield potential and response to N fertilizers.

Winter wheat is the most important food crop occupying a considerable portion of sowing area in the Non-Chernozem zone of Russia. The Central part of the Non-Chernozem zone has a total cropped area of about 5 M ha and is characterized by variation in climatic conditions. The frost-free period ranges from 112 to 148 days and climate needs to be considered by agricultural producers when selecting both crop management technologies and variety. Winter wheat has the highest potential biological productivity among other cereal crops cultivated in the region.

Even though winter wheat was grown on individual estates as far back as the beginning of 20th century (Sandukhadze et al., 2003), it is a relatively new crop for the central Non-Chernozem region of Russia. In less than a century, breeders have developed wheat varieties that are well adapted to the conditions in this region, and planted areas have increased dramatically. Currently, the area planted in Russia to only one winter wheat variety, Moskovskaya 39, developed in the Laboratory of Winter Wheat Breeding, Moscow Research Institute of Agriculture "Nemchinovka", is more than 3 M ha. This and other new varieties such as Galina, Nemchinovskaya 24, and Moskovskaya 56 allow more efficient crop management including the response to fertilizers. It is generally accepted that crop agronomy contributes half of the realized yield response and variety gives the other half, and only the combination of these two components, expressed in developing modern varieties, allows the full impact of both to be seen as increased good quality grain.

Nitrogen fertilizers have a large effect on grain yield and quality on almost all soil types. Nitrogen regulates growth, increases grain protein and gluten content, and has a positive effect on yield (Mineev and Pavlov, 1981). The requirement for N is especially high in the Central area of the Non-Chernozem zone. These soils often have organic matter contents less than 1.7 to 2.1% and total N and mineral N are also low. The application of N fertilizers is now considered the most effective and efficient strategy to increase yield and improve grain quality. It is also important, at the same time, to maintain an adequate supply of other nutrients to the crop.

Summarized data indicate that winter wheat requires 30 to 35 kg N, 13 to 16 kg P_2O_5, and 23 to 26 kg K_2O per tonne of grain with the corresponding amount of straw. In general applied N gives a 30 to 60% yield response. Nitrogen uptake is relatively low after planting in the fall and active uptake occurs as growth resumes in spring and continues through to the beginning of heading. By then, plants take up two-thirds of the total N requirement. Demand increases again after grain formation and filling and during this period the crop takes up the remaining 25 to 30% of N requirements. For winter wheat, the prolonged cold weather and soil compaction in spring can reduce N mineralization so that nitrate content in the arable layer may be 6 to 7 times lower than is required for normal development of plants (Sozinov and Zhemela, 1983). Spring N topdressing is an important strategy for high quality and high yielding winter wheat crops. The timing of spring topdressed N, the rate to use and the number of splits depend on weather conditions, status of the crop stand, soil N supply, and wheat variety. Plant response to fertilizer is closely related to genetically fixed characteristics specific to a genotype (variety) (Sandukhadze et al., 2003).

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; KCl = potassium chloride; HCl = hydrochloric acid; M = million.

Winter wheat breeding programs in Central Russia have generated many successful, high yielding varieties—a key to the region's annual increases in planted area.

Experiments on the efficiency of topdressed N fertilizer were conducted at the Laboratory of Winter Wheat Breeding during 1998 to 2007. Fourteen winter wheat varieties that represented different stages in the development of the breeding program (Zhuravleva, 2011) were selected for study. Soil properties were measured each year over the course of the study. Soil pH_{KCl} varied from acid to close to neutral reaction and soil P (extracted with 0.2 M HCl) ranged from 237 to 497 ppm P_2O_5. Hydrolytic acidity, varying from 2.09 to 3.59 $cmol_+$/kg of soil, changed correspondingly to the exchangeable acidity. Soil K extracted with 0.2 M HCl ranged from 124 to 196 ppm K_2O, soil organic matter content was 1.10 to 1.53%, or 1.27% on average.

Experiments were laid out in winter wheat fields preceded by tilled fallow with good weed control. The soil was a soddy-podzol (Albeluvisol) with an arable layer depth of 25 cm. Win-

Table 1. Effect of single and split topdressing N applications on the grain yield (t/ha) of four varieties of winter wheat and mean agronomic efficiency.

No	Topdressed N rates, kg/ha	Year 2005	2006	2007	Mean	Agronomic efficiency of N, kg of grain/kg N
			Pamyati Fedina			
1	0	3.93	7.35	5.78	5.68	-
2	60	5.62	7.55	6.49	6.55	14.5
3	30 + 30	6.11	8.15	7.05	7.10	23.7
4	120	7.10	7.84	6.66	7.20	12.7
5	60 + 60	7.84	7.81	6.41	7.35	13.9
6	40 + 40 + 40	7.42	7.93	6.80	7.38	14.2
	$LSD_{0.05}$	0.18	0.14	0.15	0.21	
			Moskovskaya 39			
1	0	3.67	6.14	4.73	4.84	-
2	60	5.99	7.02	5.56	6.19	22.5
3	30 + 30	5.38	7.48	5.58	6.15	21.8
4	120	6.49	7.60	5.77	6.62	14.8
5	60 + 60	7.23	7.31	6.11	6.88	17.0
6	40 + 40 + 40	6.78	7.54	6.37	6.90	17.2
	$LSD_{0.05}$	0.16	0.24	0.07	0.21	
			Galina			
1	0	3.56	7.12	5.83	5.50	-
2	60	6.10	8.42	6.97	7.16	27.7
3	30 + 30	5.66	8.57	6.41	6.88	23.0
4	120	7.92	8.66	7.24	7.94	20.3
5	60 + 60	7.73	9.23	6.58	7.85	19.6
6	40 + 40 + 40	7.58	8.64	7.13	7.78	19.0
	$LSD_{0.05}$	0.14	0.22	0.14	0.19	
			Nemchinovskaya 24			
1	0	4.00	7.87	4.94	5.60	-
2	60	6.63	9.88	6.71	7.74	35.7
3	30 + 30	6.45	10.79	6.59	7.94	39.0
4	120	7.04	10.56	7.02	8.21	21.8
5	60 + 60	7.60	10.32	6.85	8.26	22.2
6	40 + 40 + 40	7.53	10.69	7.71	8.64	25.3
	$LSD_{0.05}$	0.13	0.29	0.19	0.24	

ter wheat management was standard for the zone with P and K fertilizers broadcast before cultivation at 60 kg/ha for both P_2O_5 and K_2O. Fungicide and insecticide treatments were applied as required along with appropriate herbicide applications.

Spring application of N was done either as a single topdressing [0, 60 (medium rate), and 120 kg N/ha (high rate)] in early spring just after snowmelt, or as split topdressings providing 30+30 and 60+60 kg N/ha (in spring just after snowmelt and during the stem elongation stage) or 40+40+40 kg N/ha (in spring just after snowmelt, during the stem elongation stage, and before flowering). Nitrogen was applied as ammonium nitrate. In this summary, N responses for two cultivars from the current breeding program and two from an earlier program are compared.

Results and Discussion

Seasonal weather conditions were unfavorable for 3 years of the study as 1999, 2002, and 2007 had low growing season rainfall. Both temperature and moisture regime interact with variety as well as impact leaching and gaseous losses of N from the soil. These varying conditions can be summarized by a hydrothermal coefficient (HTC = $\Sigma P/(0.1\Sigma t)$, which combines precipitation (mm) in the given period (P), with the average daily air temperature (t) above 10ºC (Selyaninov, 1937). Coefficient values < 1.0 indicate dry weather and values < 0.5 indicate a period of significant drought. There was no significant correlation between HTC and grain yield for the control treatments in the 14 varieties studied, but use of grain yield data from the topdressed N treatments improved this relationship. The correlation coefficient (r) was equal to 0.45 in modern varieties and 0.95 in varieties from the earliest breeding periods. Therefore, the application of N has allowed the varieties to respond to meet their genotypic yield potential in all conditions. Importantly, the application of N increased drought resistance of varieties as shown by of the higher relative yield increase due to N application in dry years.

Of interest are the responses to topdressed N of four modern winter wheat varieties, Pamyati Fedina and Moskovskaya 39 from an earlier breeding program, and Galina and Nemchinovskaya 24 from the current program. Our results show that plant height increased with higher N rates with the single N application for all four varieties (**Figure 1**). Varieties had achieved their maximum height with a single application of 120 kg N/ha. Among four studied varieties, the Moskovskaya 39 variety was the tallest and the Nemchinovskaya 24 the shortest. Where N was split, plants appeared to be not as tall if compared with a single N application; however, this decrease was not significant and had no effect on lodging resistance. It should be noted that all four varieties are short-stem varieties, and are generally considered resistant to lodging with increasing N rates.

Some researchers recommend splitting topdressed applications of N fertilizer to better match supply and demand because N can be lost to the environment if applied early in crop growth when uptake is slow. However, our research has shown that splitting N application is not always an efficient measure to increase the yield of winter wheat (**Table 1**). As is the case for a single topdressing of N, the influence of weather conditions is also large for split N applications, but the effect is often expressed to a lesser extent. The three-factor analysis of variance showed that when N is split-applied "year" accounted for 46% of the variation, while "variety" and "fertilizer" shared the remainder.

Thus, the weather in each year should be considered when assessing N use efficiency, including the effect of fertilizer timing and splitting. For example, the highest yield of Moskovskaya 39, Pamyati Fedina, and Nemchinovskaya 24,

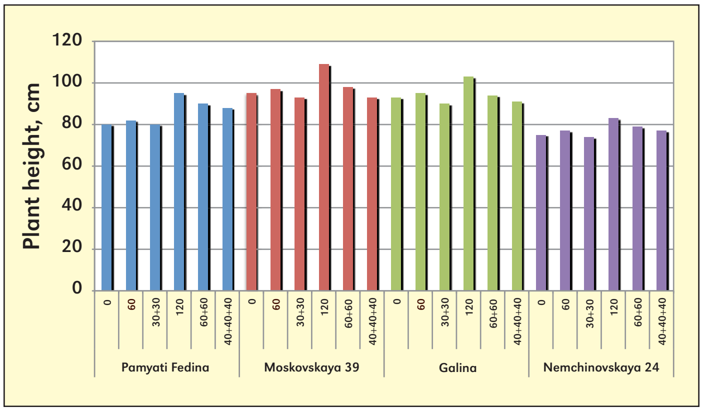

Figure 1. The effect of N topdressing rate and timing on the height of four winter wheat varieties (average data, 2005 to 2007).

was in the very wet year of 2005, and this was obtained when N was topdressed as two splits applied as 60+60 kg/ha. On the other hand, Galina gave the highest yield with a single N application at 120 kg N/ha. The highest yield of Moskovskaya 39 and Pamyati Fedina varieties in conditions of sporadic rainfall in 2006 was from a single application of 120 kg N/ha, while Galina and Nemchinovskaya 24 gave the highest yield from the treatment with two splits of 60+60 and 30+30 kg N/ha, respectively.

Agronomic efficiency of N (AEN, Dobermann, 2007) was calculated from these experiments and it varied from 12.7 to 39.0 kg of grain/kg N over 3 years for the single and split topdressing N rates (**Table 1**). The AEN for Pamyati Fedina increased from 14.5 to 23.7 kg grain/kg N when N was applied in two splits (30+30 kg N/ha) rather than a single topdressing of 60 kg N/ha. This response was seen in each year during our 3-year study. In general, the highest benefit from topdressed N was found in the newer varieties—Galina and Nemchinovskaya 24.

Our research indicates that wheat varieties from the modern period (Nemchinovskaya 24 and Galina) have the highest yield and are more responsive to N fertilizer than the other varieties studied. Our analysis of yield components revealed that N application increases the number of kernels per wheat spike and this increase can be explained by the reallocation of assimilates to wheat spikes during stem elongation and, hence, the spikes formed with more kernels per spike. For example, under the unstable weather conditions in 2006, the highest yields for Pamyati Fedina were with two splits (30+30 kg N/ha) and three splits (40+40+40 kg N/ha). This response was a consequence of higher kernel weight in the case of two splits, but was due to more fertile tillers under three splits. The highest yield for Moskovskaya 39 was from a single topdressing at 120 kg N/ha, but this variety produced considerably more fertile tillers with 30+30 kg N/ha, while 40+40+40 kg N/ha increased both kernel number and kernel weight. Nemchinovskaya 24, like Moskovskaya 39, produced high yields in three splits. In this case, maximum yield was obtained with 30+30 kg N/ha due to more fertile tillers and higher kernel weights, while a high response to 40+40+40 kg N/ha generated a significant increase in fertile tiller number, and the single N application at 120 kg N/ha increased both kernel weight and number per spike. The maximum yield of Galina was attained with two splits of 60+60 kg N/ha and this increase was a consequence of considerable improvement of all yields components.

Dr. Sandukhadze (left) and Dr. Zhuravleva visiting the winter wheat field site at the Moscow Research Institute of Agriculture "Nemchinovka".

Our research results indicate a high efficiency of topdressed N in winter wheat although these data also show that split applications are not always more efficient than a single topdressing. The efficiency of either single or split applications of N fertilizer is strongly dependent on weather conditions. According to data obtained in our experiments, modern Russian wheat varieties such as Nemchinovskaya 24 and Galina have both the highest yield and the largest response to N fertilizer. BC

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Wheat Grain Nutrient Concentrations: Wide-scale Average Values May Not Be Adequate for Field Nutrient Budgets

By Tom Jensen and Rob Norton

Large variability is observed in grain nutrient concentrations, which results in a degree of uncertainty in developing detailed nutrient budgets on a sub-region or individual field basis. This paper examines the interaction between individual grain nutrient values and the geographic scale in which they are collected and discusses the appropriate use of grain nutrient concentrations in developing nutrient budgets.

A nutrient budget for a wheat crop is similar in concept to a bank account. A balanced bank account is maintained by having deposits equal withdrawals. For a wheat crop nutrient budget, removals in the harvested grain of the crop need to equal nutrient inputs made available to the crop. Some mineral nutrients need to be supplemented in amounts close to removals, while other nutrients can be supplied by a combination of what is mineralized annually from the soil supplemented by fertilizer inputs, and yet other nutrients can be supplied sustainably from the soil for many years.

A working group within IPNI developed a decision support system (DSS) for farmers to decide what rate of supplemental fertilizer nutrients to apply to a wheat crop (see article on Nutrient Expert Wheat in this issue). This type of DSS is needed in areas where soil testing services are not commonly available. Since yields are often recorded, or at least quite accurately estimated, an understanding of the nutrient concentrations of grain is important in developing budgets for plant nutrients. One challenge is deciding what grain nutrient concentrations should be used to calculate the amount in nutrient removed. For a specific nutrient the amount removed in the grain is a product of nutrient concentration and crop yield.

IPNI has conducted three projects to assess the variability of grain nutrient concentrations in some of the important wheat-growing areas of the world. In 2009, a selection of wheat samples from India, China, Russia, USA, and Canada were tested for nutrient concentration. At the same time, the grain nutrient contents were assessed from two varieties of wheat from 70 sites in the southeast region of Australia. These sites were part of the Australian National Variety Testing (NVT) program conducted during the years 2008 and 2009. The third project was a sub-regional study in 2010 conducted in western Canada where grain samples from ten wheat varieties at six trial sites were analyzed for their nutrient content.

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; S = sulfur; Ca = calcium; Mg = magnesium; B = boron; Cl- = chloride; Cu = copper; Mn = manganese; Zn = zinc.

There have been several studies undertaken on grain nutrient densities in Australia (Schultz and French, 1978) and much of that information has been collated and published in "Plant Analysis – An Interpretation Manual" (Reuter et al., 1997). Those values are now used as benchmarks in developing regional nutrient budgets. However, the variability observed in regional, cultivar, and annual changes in grain nutrient concentrations results in a degree of uncertainty to develop detailed nutrient budgets on a sub-region or individual field basis. In this article, the spread of the values measured is reported as the coefficient of variation or CV. This is a measure of the "normal" range of values; in fact it is the range that covers the middle 67% of measurements made. **Table 1** compares the means and CVs for selected macro and micronutrient grain concentrations from the three IPNI studies with the mean and proposed critical values in Reuter et al. (1997).

The data from the three studies show that the variability around a mean value, as shown by the CV, decreases for most nutrient concentrations as you move from an international data set, down to a region, and then down to a sub-region level. For example the CV values for S went from 22 to 13, then to 11. Some of the nutrient grain concentrations were more variable compared to others, for example B with respective CVs of 69 to 58 and then 38 with data originating from the global through sub-regional level. This can be explained using knowledge of the soils in southeast Australia, ranging from acidic soils to soils containing free carbonate. Their formation has meant that topsoil and subsoil B levels are highly variable. Nitrogen

Table 1. Wheat grain nutrient concentration means and coefficient of variations (CV) for multiple country, regions within a country, and sub-region studies, and Australian benchmark values.

		Macronutrient†						Micronutrient†				
Study	Statistic	N	P	K	S	Ca	Mg	B	Cl-	Cu	Mn	Zn
International - 2009	Mean	2.5	3,600	4,000	1,700	890	730	2.9	330	5.7	43	31
	CV, %	16	33	20	22	61	55	69	47	61	37	42
Regional – 2008 to 2009 Southeast Australia	Mean	2.6	3,300	4,600	1,700	420	1,300	2.2	-	4.8	44	23
	CV, %	18	20	14	13	21	10	58	-	24	32	32
Sub-regional - 2010 Western Canada	Mean	2.5	3,600	3,600	1,600	340	1,500	1.6	560	4.9	52	33
	CV, %	16	14	15	11	26	16	38	14	18	27	19
Reuter et al. 1997	Mean	-	2,900	4,000	1,600	430	1,400	-	-	-	-	-
Proposed Critical Values		-	2,700	-	1,200	-	-	<2.0	1.0 to 2.5	-	20	5 to 15

†N reported as %, all other nutrients as mg/kg.

Table 2. Field site P removal in IPNI studies (2010) compared to removals estimated using a regional nutrient removal guide value (kg P/ha).

Site Name	Actual site P removal, kg P/ha	Calculated P removal using 1998 guide, kg P/ha	Over estimation using regional 1998 value, kg P/ha
Watrous, SK	19.1	19.6	0.5
Regina, SK	11.1	11.5	0.3
Moose Jaw, SK	15.7	17.8	2.1
Vulcan, AB	13.1	16.3	3.3
Delia, AB	10.7	13.8	3.1
Three Hills, AB	16.3	24.1	7.8

on the other hand appears to be closely regulated physiologically within wheat plants, as N mean values for wheat at all three levels of study were quite close, and the corresponding CV values were low compared to most of the other nutrients analyzed.

Of the three macronutrients commonly applied as fertilizers, (N, P, and K), it appears that P concentrations in wheat grains are more variable at the multi-country and regional-scale, and use of large area general values may not be appropriate for developing nutrient budgets on an individual field basis. For example an average P removal value for wheat in a regional nutrient removal guide used in western Canada (CFI, 1998) shows that a 40 bu/A crop removes about 23.5 lb P_2O_5/A (11.5 kg P in a 2,720 kg/ha crop). Using these numbers, the wheat grain P concentration would be 4,300 mg P per kg of grain. The grain P concentrations of the six sites used in the 2010 IPNI western Canada study ranged from 2,900 to 4,100 mg P per kg of grain. **Table 2** shows the actual P removal for each site compared to the amount that would be calculated if the nutrient removal guide value was used. For two of the six field sites the regional grain P concentration value gave a close estimate of actual P removal, but if used for the rest of the sites there would be an overestimation and result in P fertilizer recommendations that could be greater than needed.

In many world locations N content values are often known for wheat crops as this is measured as protein content at local grain delivery facilities, and use of grain N concentrations using these values may be accurate for calculating N nutrient budgets. Of the remaining macro and micronutrients, grain nutrient concentrations are not available unless grain samples are analyzed. Of the remaining macronutrients, Ca is more variable than Mg, which seems to be more stable, similar to N and K.

It is also important to consider the type of wheat grown in an area if improved nutrients budgets are to be developed. In the sub-regional 2012 western Canada project three different types of wheat were assessed: hard red spring or bread-type wheat; durum or pasta wheat; and Canadian Prairie Spring Red wheat or higher yielding/lower protein wheat used for animal feed or bio-fuel production. For many of the nutrients measured, grain concentrations and total nutrient removed in harvested grain were significantly different across wheat types. For example, the durum types had higher K concentrations and harvested K removals compared to the bread wheat types. The average grain K concentrations were 4,100 mg/kg for durum types compared to 3,300 mg/kg for bread wheat types, and similarly, average K removal was 16 lb/A (18 kg/ha) and 11 lb K/A (12 kg K/ha) for the respective wheat types. This variation highlights a benefit from separating these measurements according to wheat type if more accurate nutrient budgets are desired.

All of the micronutrients are quite variable and nutrient budgets for these should probably be developed at a local sub-region or field basis. Generally low amounts of micronutrient fertilizers are used compared to N, P, and K worldwide. It is advised that use of micronutrients be based on a combination of soil and plant testing or at least visual diagnosis at a field level, rather than developing nutrient budgets based on yields and general grain nutrient concentrations. BC

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Yield Responses and Potassium Use Efficiency for Winter Wheat in Northcentral China

By Ping He, Jiyun Jin, Hongting Wang, Rongzong Cui, and Chunjie Li

Field experiments were conducted to study yield responses and K use efficiency parameters for wheat in three provinces across three years in northcentral China. Potassium application increased grain yield and profit for wheat in most cases. Determination of K use efficiency parameters demonstrated that there is potential to optimize K use efficiency further with best nutrient management practices.

Wheat (Triticum aestivum L.) is one of the most important cereal crops in China, and K fertilizer applications have played a major role in increasing wheat yield. However, wheat production sometimes is limited because farmers give little attention to K application. Due to the limited potash resources in China and increasing fertilizer cost, efficient application of K is very important. Understanding the yield responses, profitability and K use efficiency parameters of K application is essential for the further improvement of K use efficiency for high yielding wheat production systems.

To evaluate K responses on winter wheat in northcentral China, field experiments were carried out for nine sites/years in farmer fields in Hebei, Shandong, and Shanxi provinces from 2006 to 2009. The trial soils were fluvo-aquic, brown, and calcic cinnamon soils for Hebei, Shandong, and Shanxi respectively. Prior to sowing, soil samples (0 to 20 cm) were collected and analyzed for nutrient status. Soil nutrients were determined with procedures applied by the National Laboratory of Soil Testing and Fertilizer Recommendation using the method described by Portch and Hunter (2002). Winter wheat was sown at the beginning of October and harvested in mid-June of the next year. Each experiment was designed in a randomized complete block with three replications of two treatments: with K application, and without K. Urea, SSP, and KCl were selected as fertilizer sources. All other limiting nutrients in addition to K were applied using a rate suited to eliminate limitations on yield (**Table 1**).

About one half to one third of N, and all the P and K fertilizer, were applied basally before sowing and the remaining N was topdressed in early spring before the tillering stage of winter wheat. Irrigation, insect-control, inter-row tillage and other management activities were conducted according to farmers' practice. At harvest time, aboveground biomass including straw and grain yield were recorded. Seed and straw samples were randomly collected for determination of dry matter weight, and analyzed for total K.

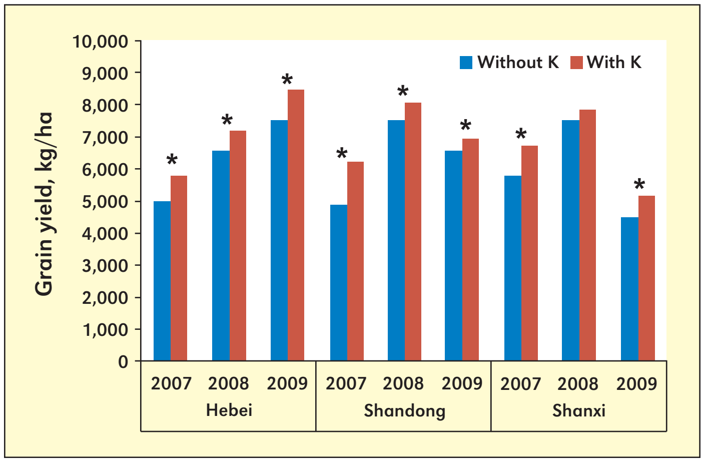


Figure 1. Grain yield of wheat in different sites-years as influenced by K application (wheat was harvested in June of 2007, 2008 and 2009; the symbol * indicates significance at $p<0.05$ between treatments without K and with K).

Yield Responses to K Application

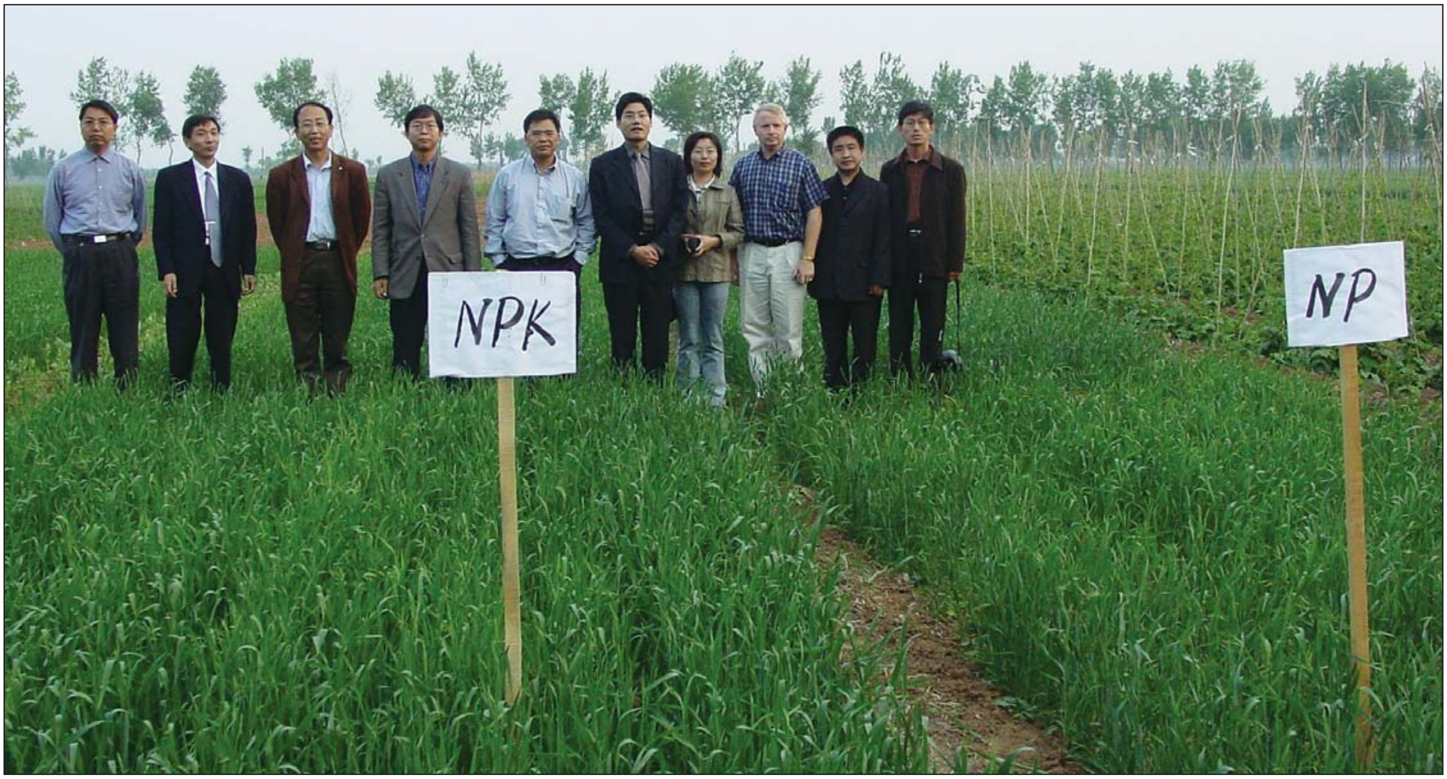
Potassium application increased grain yields of wheat sig-

Common Abbreviations and Notes: N = nitrogen; P = phosphorus; K = potassium; NO_3^- = nitrate; NH_4^+ = ammonia; KCl = potassium chloride; SSP = single superphosphate; RE = recovery efficiency; AE = agronomic efficiency; PFP = partial factor productivity; USD = United States dollar; RMB = Chinese Yuan.

Table 1. Fertilizer application rates and agro-chemical properties of tested soils.

Province	Location	Year	N	P_2O_5	K_2O	pH	OM	NO_3^--N	NH_4^+-N	P	K
			---------- kg/ha ----------				%	-------------- mg/L --------------			
Hebei	Xinji	2007	180	100	75	8.4	0.70	ND[1]	4.9	22	78
	Xinji	2008	180	75	120	8.4	0.53	23.4	23.4	43	72
	Xinji	2009	180	60	90	8.3	0.49	23.9	10.6	18	50
Shandong	Haiyang	2007	240	30	120	7.9	1.17	3.5	8.9	59	45
	Qingzhou	2008	210	75	60	8.2	1.01	17.6	5.4	25	83
	Qingzhou	2009	240	75	90	7.7	0.80	20.6	12.2	28	75
Shanxi	Linfen	2007	195	90	150	8.1	0.35	3.1	20.5	21	72
	Linfen	2008	180	150	120	8.3	0.65	ND	0	29	266
	Linfen	2009	210	105	90	8.3	1.03	12.0	9.7	32	79

[1]ND = no data



Field experiments comparing the effects of K application in wheat production in Hebei. Dr. Terry Roberts (the third from right), Dr. Ping He (the fourth from right) and Dr. Shutian Li (the fourth from left) along with project cooperators.

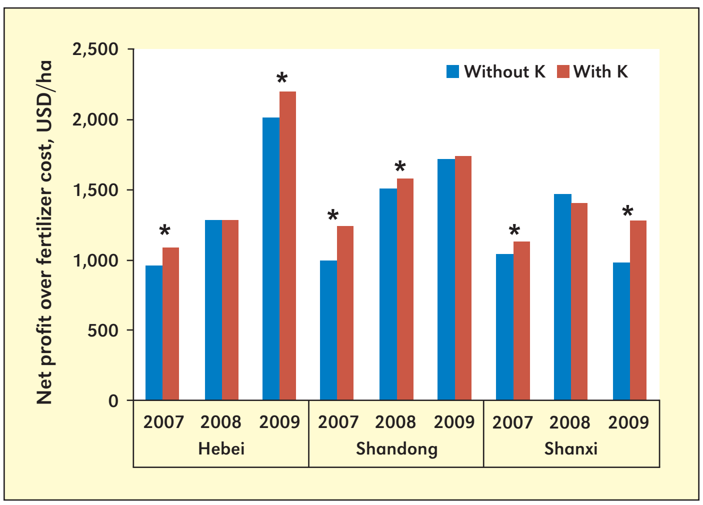


Figure 2. Net profit over fertilizer cost for wheat in different sites/years as influenced by K application (the symbol * indicates significance at $p<0.05$ between treatments without K and with K).

nificantly in all sites except Shanxi in 2008. Yield responses to K application in 2007, 2008, and 2009 were: 13, 10, and 11% in Hebei; 21, 7, and 5% in Shandong; and 13, 5, and 13% in Shanxi, respectively (**Figure 1**). The low yield response to K application for Shanxi in 2008 was at the site with a very high soil K level, and the largest yield response to K application in Shandong in 2007 was related to a very low soil test K level (**Table 1**). Therefore, to some extent, yield response was inversely related to soil fertility, in that yield response was low when soil test was high, and vice versa. These results have also been used to develop a fertilizer recommendation method based on yield response for use under conditions when soil testing is not available (Pampolino et al., 2011; He et al., 2012).

Table 2. Fertilizer and crop prices used in profit analysis shown in Figure 2.

Province	Year	Wheat	N	P_2O_5	K_2O
		- - - - - - - - - - - - - RMB/kg - - - - - - - - - - - - -			
Hebei	2007	1.56	3.91	4.38	4.33
	2008	1.60	5.65	8.13	8.67
	2009	2.00	4.35	6.25	7.33
Shandong	2007	1.60	3.40	4.50	3.40
	2008	1.60	4.80	7.60	6.70
	2009	2.00	3.90	4.17	6.70
Shanxi	2007	1.44	3.90	5.20	3.70
	2008	1.65	5.70	7.60	9.00
	2009	2.00	3.70	7.30	7.00

1 USD=6.9 RMB

Profitability from K Application

Generally, the net profitability over fertilizer cost from K application followed similar trends to grain yields (**Figure 2**). In most cases (six out of nine), K application significantly increased net profitability by 12% in 2007 and 8% in 2009 in Hebei, 20% in 2007 and 5% in 2008 in Shandong, and 9% in 2007 and 23% in 2009 in Shanxi. Some variability existed across years and sites due to the changes in crop price and fertilizer cost. Comparatively, good profitability was observed in 2009 with good crop prices and moderate fertilizer cost, while low profitability in 2008 in Hebei and Shanxi was related to low crop prices and high fertilizer cost (**Table 2**). In the latter case, farmers can decide on how much K fertilizer to apply to

Table 3. Potassium use efficiency parameters for wheat in different sites/years.

Province	RE, %			AE, kg/kg K_2O			PFP, kg/kg K_2O		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
Hebei	47	35	47	10.2	5.5	9.9	77	60	94
Shandong	42	38	52	11.0	9.4	4.2	52	134	77
Shanxi	41	35	27	5.7	3.2	11.1	45	66	61

make K application profitable.

K Use Efficiency

Nutrient use efficiency can be expressed by crop RE, AE, and PFP (Fixen, 2007). AE refers to the crop yield increase per unit nutrient applied, RE refers to the increase in plant nutrient uptake per unit nutrient applied, and PFP refers to the crop yield per unit nutrient applied. Measurements of RE, AE, and PFP for applied K resulted in large location-to-location variability. Mean RE values across three years were 47, 44, and 34% for Hebei, Shandong and Shanxi, respectively. Mean AE values were 8.5, 8.2, and 6.7 kg/kg, while mean PFP values were 77, 88, and 57 kg/kg for Hebei, Shandong and Shanxi, respectively. The different values for K nutrient use efficiency were related to how much fertilizer was used and how much grain yield or yield increase was obtained by K application. For example, the very high PFP value of 134 kg/kg in 2008 in Shandong was due to the relatively low K application rate (60 kg K_2O/ha) and very high grain yield (**Figure 1**).

In summary, K application increased wheat grain yield, and net profitability in most cases in northcentral China. The average yield response to K application was less than 1 t/ha, and K use efficiency parameters of RE, AE, and PFP were relatively low. Therefore, further best management practices, through 4R Nutrient Stewardship (right source at the right rate, right time and right place) should be integrated into common practices to improve fertilizer use efficiency for wheat. BC

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2012 IPNI Crop Nutrient Deficiency Photo Contest Announced

Once again we welcome all those with a keen eye and ready access to agricultural production, at either the field or research plot scale, to seek out and gather their best examples of crop nutrient deficiency for entry into the 2012 edition of our photo contest.

The competition continues to foster awareness about, and focus attention on, identifying the common traits of nutrient deficiency for a wide range of crops. We are proud of how this contest has grown into an international challenge to field researchers, farmers, students, and other interested in crop production.

The competition continues with its four nutrient categories: Nitrogen (N), Phosphorus (P), Potassium (K), and Other (Secondary and Micronutrients). Entrants are limited to one entry per category (i.e., one individual could have an entry in each of the four categories). The winner in each category will receive a cash prize of USD 150 while second place receives USD 75. Selection of winners will be determined by a committee of IPNI scientific staff.

Photos and supporting information can be submitted until December 11, 2012 (5 pm EDT). Winners be notified and the results will be announced at our website and in this publication in January of 2013. Entries should only be submitted as original, digital files. Please see the contest site www.ipni.net/photocontest for all details. BC

Development and Evaluation of Nutrient Expert for Wheat in South Asia

By Mirasol Pampolino, Kaushik Majumdar, M.L. Jat, T. Satyanarayana, Anil Kumar, V.B. Shahi, Naveen Gupta, and Vinay Singh

Nutrient Expert (NE) for Wheat, a new nutrient decision support tool, is based on the principles of site-specific nutrient management (SSNM) and recommends balanced application of nutrients based on crop requirement. The tool was a joint development of wheat stakeholders in India including representatives from national research and extension system, private industries, International Maize and Wheat Improvement Center (CIMMYT), and International Plant Nutrition Institute (IPNI). It enables crop advisers to rapidly develop field-specific fertilizer recommendations for wheat using existing site information. Field evaluation showed that the location-specific nutrient recommendations from the tool increased yield and economic benefits of wheat farmers as compared to the existing practices.

Wheat is the second most important cereal crop next to rice in Asia. Wheat is grown on about 29 M ha in India with an annual production of 81 M t in 2009-10 and an average yield of 2.8 t/ha (FAI, 2011). Recent statistics show that there are considerable yield gaps between the major wheat-growing states in the country with highest yield recorded in Punjab (4.3 t/ha) and lowest in Bihar (2.1 t/ha). In addition, considerable yield gaps exist between researcher-managed optimum NPK plots and farmers' fertilizer practices (FFP, Ladha et al., 2003), indicating a great opportunity for increasing wheat yield and productivity through improved nutrient management practices.

Site-specific nutrient management is a set of nutrient management principles that aims to supply a crop's nutrient requirements tailored to a specific field or growing environment. Its purpose, to (a) account for indigenous nutrient sources, including crop residues and manures; and (b) apply fertilizer at optimal rates and at critical growth stages to meet the deficit between the nutrient needs of a high-yielding crop and the indigenous nutrient supply.

Nutrient Expert is a new, computer-based decision support tool that helps crop advisers formulate fertilizer guidelines based on SSNM principles. NE considers the most important factors affecting nutrient management recommendations in a particular location and enables crop advisers to provide farmers with fertilizer guidelines that are suited to their farming conditions. The tool uses a systematic approach of capturing site information that is important for developing a location-specific recommendation. Yet, NE does not require a lot of data nor very detailed information as in the case of many sophisticated nutrient decision support tools, which could overwhelm the user. It allows users to draw the required information from their own experience, the farmers' knowledge of the local region, and the farmers' practices. NE can use experimental data, but it can also estimate the required SSNM parameters using existing site information. Currently, NE has been applied to hybrid maize for different geographies in Asia and Africa and wheat for South Asia and China.

The objectives of this paper are: 1) to provide a brief description of the conceptual background of the NE nutrient decision support tool, and 2) to demonstrate the performance of NE as applied to wheat by presenting results from on-farm evaluation trials conducted in India.

Common abbreviations and notes: N = nitrogen; P = phosphorus; K = potassium; M = million; USD = United States dollar; INR = Indian rupee.

Conceptual Background

NE is based on the principles of SSNM as developed for rice (Dobermann and Witt, 2004) and later adapted to maize and wheat. The fertilizer requirement for a field or location is estimated from the expected yield response to each fertilizer nutrient, which is the difference between the attainable yield and the nutrient-limited yield. Nutrient-limited yields are determined from nutrient omission trials in farmers' fields, while attainable yield is the yield in a typical year at a location using best management practices without nutrient limitation. The amount of nutrients taken up by a crop is directly related to its yield (Janssen et al., 1990) so that the attainable yield indicates the total nutrient requirement and the nutrient-limited yield is the yield supported only by the indigenous supply of the concerned nutrient without any external application (Dobermann et al., 2003). The yield response, which is the yield difference between an ample nutrient plot yield and the nutrient omission plot yield, is used as an indirect estimate of the nutrient deficit in soil that must be supplied by fertilizers. NE follows the SSNM guidelines for fertilizer application and split dressings to consider the crop's nutrient demand at critical growth stages. In the absence of trial data for a specific location, NE estimates the attainable yield and yield response to fertilizer from site information using decision rules developed from on-farm trial data.

Information Requirement

NE only requires information that can be easily provided by a farmer or a local expert. The set of information includes:

- Farmers' current yield
- Characteristics of the growing environment or estimate of the attainable yield (if known)
- Soil fertility indicators (e.g. soil texture and color, his torical use of organic inputs) or estimates of yield re sponses to fertilizer N, P, and K (if known)
- Crop sequence in the farmer's cropping pattern
- Crop residue management and fertilizer and organic manure inputs

Nutrient Expert for Wheat (NE Wheat): Database, Design, and Development Approach

We developed SSNM strategies for N, P, and K for wheat using data from 33 locations (with multiple field replicates) in five countries in Asia (IPNI unpublished data). These strategies comprise the algorithm for calculating fertilizer N, P, and

K requirements based on known attainable yield and yield responses. The dataset was also used as the basis for developing the decision rules for estimating SSNM parameters. It provided a range of attainable yields and yield responses to fertilizer N, P, and K across diverse environments characterized by variations in amount and distribution of rainfall, varieties, soils, and cropping systems.

We collaborated with target users and local stakeholders from the early stage of NE development through a participatory approach to ensure that the tool meets the users' needs and preferences, which could increase the likelihood of its adoption. Crop advisers from the public sector and private sector (e.g. fertilizer companies) as well as scientists and extension specialists played an important role in the development of NE Wheat.

NE Wheat has four modules: (1) Current Farmer Fertilization Practice and Yield, (2) SSNM Rates, (3) Sources and Splitting, and (4) Profit Analysis. Each module asks two or more questions and the user selects from a list of options or enters a number in a box. The first two modules include questions that are used to determine the attainable yield and yield responses to fertilizer; and the N, P, and K requirements for the selected attainable yield based on the site information are calculated in the SSNM Rates module. NE Wheat specifies the amount and timing of fertilizer to apply, including split applications in the Sources and Splitting module. It allows users to select a fertilizer source from a list of options and helps to choose sources whose nutrient contents match the requirement for optimal split dressings. And finally it provides a simple ex-ante profit analysis between the existing practice and the improved nutrient management guideline provided by the tool for a particular location.

Table 1. Sites for the field evaluation of Nutrient Expert for wheat under conventional tillage and conservation agriculture practice in India, 2010-2011.

Site no.	State	Cropping system	Field replicate (n)
Conventional tillage			
1	Bihar	Rice – Wheat	11
2	Haryana	Rice – Wheat	15
3	Karnataka	Maize – Wheat	10
4	Punjab	Cotton – Wheat	4
5	Punjab	Rice – Wheat	6
6	Uttar Pradesh	Pearl millet – Wheat	16
Conservation agriculture			
1	Haryana	Rice – Wheat	15
2	Punjab	Cotton – Wheat	4
3	Punjab	Rice – Wheat	8

Table 2. Agronomic and economic performance of Nutrient Expert for wheat (NE) as compared with farmers' fertilizer practice (FFP) and state recommendation (SR) across all sites under conventional tillage in India, 2010-2011.

		Comparison with FFP (n = 46)				Comparison with SR (n = 62)			
Parameter	Unit	FFP	NE	(NE – FFP)†		SR	NE	(NE – SR)†	
Grain yield	t/ha	3.5	4.4	+0.9	***	4.3	4.6	+0.3	***
Fertilizer N	kg/ha	134	141	+6	**	124	141	+16	***
Fertilizer P_2O_5	kg/ha	57	54	–2	ns	64	58	–6	**
Fertilizer K_2O	kg/ha	13	76	+63	***	44	77	+33	***
Fertilizer cost	USD/ha	54	65	+11	***	59	66	+7	***
GRF‡	USD/ha	818	1,039	+221	***	1,023	1,090	+68	***

***, **Significant at 0.001 and 0.01 level, respectively; ns = not significant

† Statistical analysis was performed with JMP version 8 (SAS Institute, 2009) using Mixed Procedure with sites as random effects.

‡GRF refers to the gross return above fertilizer costs; estimated using actual local prices of fertilizer and grain at USD 1 = INR 45.

Performance of NE Wheat in Conventional Tillage Areas

In 2010-2011, field evaluation of a beta version of NE Wheat was conducted at six sites under conventional tillage (CT) in the Indo-Gangetic Plains (IGP) representing five states with different cropping systems (**Table 1**). At each site, nutrient management recommendations from NE Wheat were tested against farmers' fertilizer practice (FFP) and the state recommendation (SR) with 4 to 16 field replicates per site and plot sizes of ≥100 m^2. Across all sites, NE Wheat increased yield and economic benefit (i.e. gross return above fertilizer costs or GRF) over FFP and SR (**Table 2**). Compared with FFP, it increased yield by 0.9 t/ha and GRF by 221 USD/ha with slight increase in fertilizer N (+6 kg N/ha) but with large increase in fertilizer K (+63 kg K_2O/ha). Recommendations from NE Wheat also increased yield (by 0.3 t/ha) and GRF (by 68 USD/ha) over SR with moderate increase in fertilizer N (+16 kg N/ha) and substantial increase in fertilizer K (+33 kg K_2O/ha).

Performance of NE Wheat in Conservation Agriculture Areas

NE Wheat recommendations were also tested against FFP and SR at three sites (4 to 15 field replicates per site) practicing conservation agriculture (CA) in 2010-11 (**Table 3**). In India, CA in wheat refers to the practice of zero tillage with or without retention of crop residue from previous crop. Across three sites (n = 27), grain yield and GRF were significantly higher with NE than SR and FFP (**Table 3**). NE Wheat increased grain yield by 0.8 t/ha over FFP and by 0.5 t/ha over SR; and it increased GRF by 180 and 112 USD/ha over FFP and SR, respectively. Average fertilizer N rate was highest with NE and lowest with SR, while average fertilizer K rate was highest with NE (84 kg K_2O/ha) and lowest with FFP (1 kg K_2O) (**Table 3**).

Discussion

Wheat yield improvements with NE Wheat could be attributed to a balanced application of nutrients that is based on nutrient uptake requirement and nutrient supply for a growing environment. Compared with FFP and SR for both CT and CA

Table 3. Agronomic and economic performance of farmers' fertilizer practice (FFP), state recommendation (SR), and Nutrient Expert for wheat (NE) across all sites (n = 27) under conservation agriculture practice in India, 2010-2011.

Parameter	Unit	FFP	SR	NE	P>F[†]
Grain yield	kg/ha	4.4 b[‡]	4.7b	5.2a	<.001
Fertilizer N	kg/ha	157b	139c	165a	<.001
Fertilizer P_2O_5	kg/ha	56a	61a	57a	0.387
Fertilizer K_2O	kg/ha	1c	47b	84a	<.001
Fertilizer cost	USD/ha	57	62	73	-
GRF[#]	USD/ha	1,034b	1,102b	1,214a	<.001

[†]Statistical analysis was performed with JMP version 8 (SAS Institute, 2009) using Mixed Procedure with sites as random effects.
[‡]Within rows, means followed by the same letter are not significantly different according to Tukey (0.05)
[#]GRF refers to the gross return above fertilizer costs; estimated using actual local prices of fertilizer and grain at USD 1 = INR 45.

sites, NE largely increased K, slightly increased N, and did not change P (**Tables 2 and 3**). This suggests that the yield increase was primarily due to the increased application of fertilizer K. Many farmers did not apply K at all (52% of those who participated in CT and 96% of those in CA). The farmers who used fertilizer K, applied it at 19 to 65 kg K_2O/ha, which was less than the average fertilizer K recommended by NE Wheat (76 and 84 kg K_2O/ha for CT and CA, respectively). Fertilizer K application with SR was 30 to 60 kg K_2O/ha depending on the state. The yield increase with NE Wheat over SR seems to indicate that the K recommendations of SR were not sufficient for most of the field locations. The higher GRF in NE than in SR justifies the substantial increase in fertilizer K application.

More importantly, an average increase of 0.3 t/ha would mean an increase of 8.7 M t grain for a total wheat area of 29 M ha, which is a significant contribution to the food supply in the country. NE Wheat provides nutrient recommendations that are tailored to location-specific conditions. In contrast to SR, which gives one recommendation per state (e.g. 120 kg N, 60 kg P_2O_5, and 40 kg K_2O per ha), NE recommends a range of N, P, and K application rates within a site depending on attainable yield and expected responses to fertilizer. The NPK requirement of wheat for a specific field or location is affected by factors in the growing environment such as soil type and farmer's crop management practices. **Table 4** shows that within one site (i.e. Punjab rice-wheat area), fertilizer N, P, and K requirements determined by NE varied among fields or locations.

Table 4. Variation in wheat grain yield and fertilizer N, P, and K rates among field replicates at Punjab rice-wheat site. Values in parentheses show the standard deviation of the mean.

		Conventional tillage (n = 6)						Conservation agriculture (n = 8)					
Parameter	Unit	FFP[†]		SR		NE		FFP		SR		NE	
Grain yield	t/ha	4.0	(0.7)	4.2	(0.8)	4.9	(0.9)	4.2	(0.9)	4.4	(0.7)	5.1	(1.0)
Fertilizer N	kg/ha	147	(6)	125	(0)	155	(16)	149	(6)	125	(0)	159	(16)
Fertilizer P_2O_5	kg/ha	52	(6)	62	(0)	83	(19)	53	(5)	62	(0)	83	(16)
Fertilizer K_2O	kg/ha	5	(12)	30	(0)	91	(11)	4	(11)	30	(0)	89	(10)

[†]FFP = farmer's fertilization practices; SR = state recommendations; NE = nutrient expert.

Summary

Nutrient Expert for Wheat is a nutrient decision support tool that is based on the principles of SSNM. It was developed in collaboration with local stakeholders including scientists, extension agents, and crop advisers from both government and private organizations. NE recommendation takes into account variations in the growing environment that is affected by climate, soil type, cropping system, and crop management practices. NE Wheat provides crop advisers with a simple and rapid tool to apply SSNM principles in individual farmer's wheat field through the use of existing site information. In India, NE Wheat increased yield and economic benefits through balanced application of nutrients that is based on crop requirement. The tool was able to capture the inherent differences between conventional and conservation practices of crop management and site specific nutrient recommendations from NE Wheat performed better than FFP and SR for wheat. Besides providing location specific nutrient recommendations rapidly, the tool has options to tailor advices based on resource availability to the farmers. We expect that the user friendliness of NE Wheat and it's robust estimation of site specific nutrient recommendation will be attractive to extension specialists working with millions of farmers in the intensively cultivated wheat areas in South Asia. BC

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Wheat – The Staff of Life

The origins of wheat stretch back to the "Fertile Crescent" in the Middle East. The chance combination of two wild grasses over 9,500 years ago produced a new grass with plump grains and a set of chromosomes from both parents. Around 3,000 years later, probably on the edge of a field of this tetraploid wheat, another cross occurred to produce our modern wheat—Triticum aestivum. This new species most importantly carried genes for the elastic protein (gluten) that allowed baked products to rise when set with yeasts, and then retain that light and airy shape when baked.

To provide this bounty, wheat gave up a brittle rachis with the result that its seed was retained on the stalk, rather than being dispersed. This was a successful strategy for the plant as each year wheat now produces around 20 thousand, million million seeds (2.0 x 10^{16}) or 650 million tonnes. A good deal for its survival as well as ours.

The archeological evidence suggests that civilization and wheat-growing co-evolved, although it seems uncertain if growing wheat led to settlements or that settlements grew up around culturally important sites such as Göbekli Tepe in southeastern Anatolia. At that site it is thought that wheat was brought into these settlements as the area became hunted out. Whatever the start, the extraordinary spread of wheat to Greece and India 8,000 years ago, Germany and Spain a thousand years later, and then to England 5,000 years ago and China 4,000 years ago, now sees wheat grown on more land than any other commercial crop.

Rightly so that bread—made from wheat—is called the "staff of life." As a staff or walking stick, wheat provides support to our human family and contributes mightily to food security. But in turn, the wheat plant also needs support, and a balanced supply of nutrients is vital to ensure that the grain is wholesome and nutritious. The balance between nitrogen and sulfur is vital for baking quality, phosphorus and calcium for strong teeth and bones, and zinc derived from grain is particularly important for healthy children. The good nutrition growers practice on their wheat crops flows through to produce a healthy community.

So whether it is as chapatti, a steamed bun, a baguette, some noodles or a slice of bread, good nutrition from the staff of life is supported by good crop nutrition in the field.

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