**Table 1.** Total P added and P balance 1986-1991; Olsen P, mg/kg, in 1986 and 1991.

| P added, kg/ha | P balance[1], kg/ha | Olsen P, mg/kg | |
|---|---|---|---|
| | | 1986 r. | 1991 r. |
| 786 | 700 | 7 | 48 |
| 522 | 437 | 8 | 38 |
| 264 | 182 | 7 | 18 |

[1]P applied in excess of removal by crops.

**Table 2.** Relationship between Olsen P, maximum yield of winter wheat grain, total P removed in grain plus straw, P applied annually, and percent recovery of applied P, estimated by the balance method.

| | | | | |
|---|---|---|---|---|
| Olsen P, mg/kg, in 2004 | 9 | 14 | 23 | 31 |
| Winter wheat grain, t/ha | 7.1 | 7.8 | 7.9 | 7.9 |
| P removed in grain plus straw, kg/ha | 14 | 27 | 19 | 19 |
| P applied annually, kg/ha | 20 | 20 | 20 | 20 |
| Percent recovery of applied P estimated by the balance method | 70 | 85 | 95 | 95 |

P was added between 1993 and 1999. By 1999, Olsen P ranged from 2 to 31 mg/kg so that the yield response to Olsen P could be measured. From 2002 to 2006 when winter wheat was grown, 20 kg P/ha was applied each year to replace the maximum offtake in grain plus straw on plots that had received P from 1986 to 1991. These additions maintained the 1999 Olsen P levels.

The data from this experiment show that maximum grain yield was with a soil at the critical level of plant available P (Olsen P) and when this level was maintained by replacing the P removed in the harvested crop, then P use efficiency of the annual application exceeded 90% (**Table 2**).

**Table 2** shows that the maximum yield was 7.9 t/ha at 23 mg/kg Olsen P and yield was not further increased at 31 mg/kg. On soil with less than 14 mg/kg Olsen P, yield was decreased, which would result in a financial loss to the farmer. Maintaining the Olsen P at the critical level by replacing the P removed in the harvested crop resulted in more than 95% efficiency of the annual application. Similarly, in the experiment described by McCollum (1991), replacing the P removed in the harvested crop maintained the critical level of Mehlich-1 P.

## Summary

A recent review of the behavior of soil and fertilizer P envisages soil P as existing in four pools according to the availability of the P for uptake by roots and extractability of the P by reagents used for routine soil analysis, and that these two measures are closely correlated.

This concept has practical implications for the efficient use of P fertilizer. Namely, for most soils the amount of P in the readily plant-available pool of soil P should be raised to a critical level such that yield is not limited by lack of P and the benefits of all other inputs, especially N, required to achieve optimum yield are used as effectively as possible. For most soils that can be maintained at about the critical level of P, replacing the P removed each year in the harvested crop will typically result in P efficiency exceeding 90% when measured by the balance method. A project to develop an experimental protocol is being formulated, and sponsors sought, to extend the critical P concept to a wider range of cropping systems, soil types, and climates.

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# Role of Crop Nutrition in Narrowing the Yield Gap for Spring Wheat in Siberia

By G. Gamzikov and V. Nosov

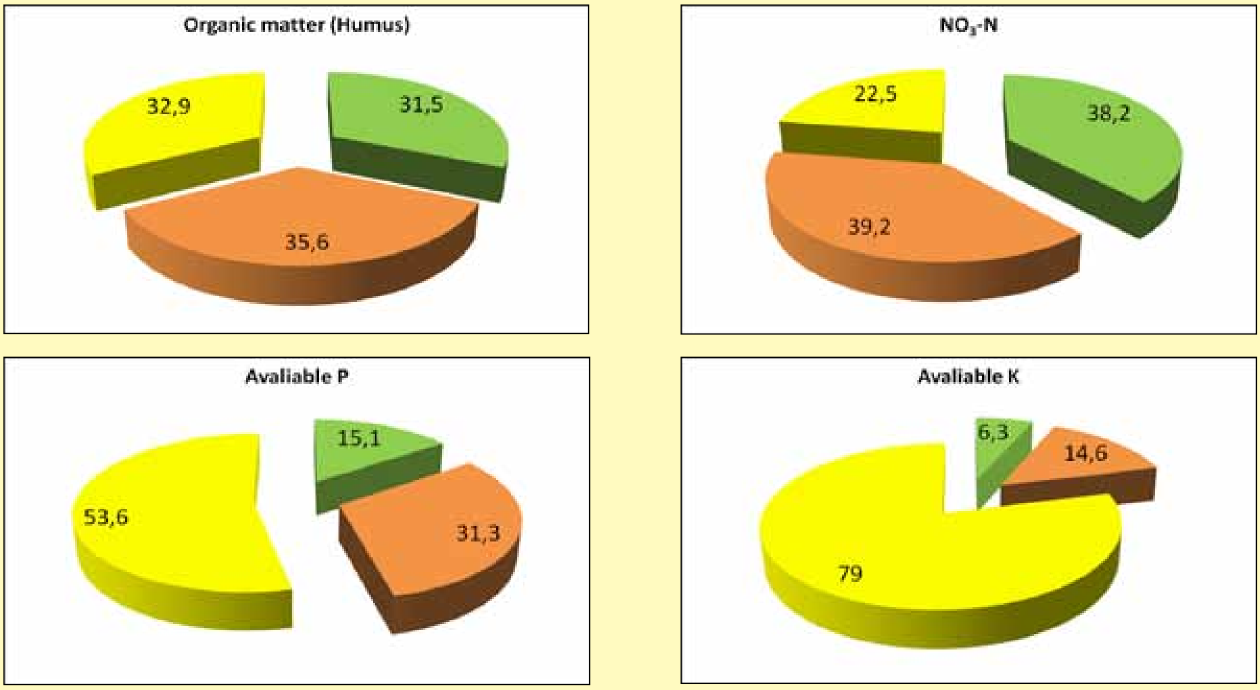
*Mineral fertilizers and other agro-inputs are important for achieving high and stable yields of spring wheat, the principle field crop in Siberia. This article reviews the at-tainable yield of spring wheat by the major soil-climatic zones through the region. The authors characterize the present status of fertilizer consumption in Siberia and, based on minimum nutrient requirements of crops, give a short-term estimate of fertilizer consumption in the region.*

Siberia is located in the Asian part of Russia, occupying an area of about 10 million square kilometers (M km2). Arable farming and animal husbandry are concentrated in the southern part of Siberia, with more than 56 M ha of agricultural lands. Siberia has about 23.5 M ha of arable land, representing about one-fifth of the total arable land area in Russia. Spring cereals such as wheat, barley, oats, and millet, as well as buckwheat, pulses, sunflower, potato, and vegetables are traditional crops in Siberia. Winter cereals include rye and triticale. Spring rapeseed, soybean, and sugar beet are promising crops giving high yields in this region. Cereals are grown on 70% of cropped area. Spring wheat dominates the cereal acreage (75 to 80%). However, the average grain yield of spring wheat in Siberia over the 5-year period of 2004 to 2008 was only about 1.3 t/ha.

The grain belt of Siberia, comprising several soil-climatic zones, is characterized by diversity in annual rainfall (230 to 550 mm), the sum of active temperatures above 10 °C (1,400 to 2,800 growing degree days), and length of vegetation or frost-free period…100 to 140 days. In the forest zone, arable soils are represented by soddy-podzolic and grey forest soils occupying 17% of land in Siberia. Podzolized, leached, and common chernozems, and also meadow chernozem soils (63%) are spread throughout the forest-steppe zone. Southern cher-nozems and chestnut soils (14%) are dominant in the steppe zone. Soil fertility parameters affect crop production potential in the various soil zones of Siberia. A recent agrochemical soil survey indicated that organic matter (humus) content in Sibe-rian soils can be very low to low (<4.0%), medium to high (4.1 to 8.0%), and high to very high (>8.1%), with about one-third of the monitored arable area under each group (**Figure 1**). Acid arable soils, which need liming for optimal yield, occupy about 2 M ha in the region.

Nitrate-N (NO3-N), is the major source of soil N for plant nutrition (Gamzikov, 1981). Siberian soils have a high po-tential to accumulate NO3-N during the fallow season, after late summer tillage following perennial grasses, pulses, and annual grasses. Spring wheat grown after fallow and the above-mentioned crops has no requirement for additional ap-plication of N fertilizer. Two-thirds of the area sowed to field crops, following other preceding crops, has low soil N status and requires annual application of N fertilizer. According to routine soil analyses, slightly more than half of Siberian arable soils have high and very high content of available P, about one-third of soils test medium to high, and only 15% of soils are low to very low in available P (**Figure 1**). The lowest content of P (low and very low classes) is observed in soddy-podzolic soils (57%), and in southern chernozems and chestnut soils (40%). Most soils (79%) have high to very high contents of available K (**Figure 1**). Taking into consideration the status of soil nutrients in Siberian soils, annual recommendations for cultivated crops include N on 16 M ha, P fertilizer on more than 10 M ha, and K fertilizer on 5 M ha.

Soil-climatic conditions in three natural zones of Siberia are favorable for obtaining high yields of spring wheat when recom-mended crop management practices are followed (**Table 1**). The role mineral fertilizers play in crop production is most impor-tant in the forest zone.




| | | High and very high | Medium to high | Very low and low |
|---|---|---|---|---|
| Organic matter (Humus), % | | ≥ 8.1 | 4.1 - 8.0 | ≤4.0 |
| $NO_3$-N, ppm (0-40 cm soil layer) | | ≥ 15.1 | 10.1 - 15.0 | ≤10.0 |
| Available P, ppm $P_2O_5$ | 0.2 M HCl[1] | ≥ 151 | 51 - 150 | ≤50 |
| | 0.5 M $CH_3COOH$[2] | ≥ 151 | 51 - 150 | ≤50 |
| | 1% $(NH_4)_2CO_3$[3] | ≥ 46 | 16 - 45 | ≤15 |
| Available K, ppm $K_2O$ | 0.2 M HCl[1] | ≥ 171 | 81 - 170 | ≤80 |
| | 0.5 M $CH_3COOH$[2] | ≥ 121 | 41 - 120 | ≤40 |
| | 1% $(NH_4)_2CO_3$[3] | ≥ 401 | 201 - 400 | ≤200 |

*[1]soddy-podzolic soils [2]grey forest soils and noncarbonated chernozems [3]carbonated chernozems and chestnut soils*

**Figure 1.** Distribution (%) of arable soils in Siberia in fertility classes according to status of soil organic matter, $NO_3$-N, and available P and K. (Source: Russian Res. Inst. of Agrochemistry, 2005.)

**Table 1.** Possible grain yields (t/ha) of spring wheat depending on soil-climatic conditions and systems of agriculture in Siberia (Gamzikov et al., 2008).

| Natural zone | Climatic and soil limitations[1] | | | System of agriculture[5] | | |
|---|---|---|---|---|---|---|
| | Solar radiation[2] | Rainfall[3] | Soil fertility[4] | Extensive | Ordinary | Intensive |
| Forest | 4.0-5.8 | 3.8-5.0 | 0.6-1.5 | 0.5-1.0 | 0.7-1.6 | 2.6-4.5 |
| Forest-steppe | 5.0-7.2 | 1.7-4.0 | 1.2-2.4 | 0.8-1.5 | 1.0-1.8 | 2.2-4.0 |
| Steppe | 6.0-8.6 | 0.8-2.2 | 1.0-1.6 | 0.4-1.0 | 0.8-1.6 | 1.5-2.2 |
| Distribution of agricultural enterprises, % | | | | 35-40 | 50-60 | 10-15 |

*[1]Possible yields when climate and soil factors are not limiting.*
*[2]Possible yield range with application of fertilizer (and lime if required) plus optimal rainfall.*
*[3]Possible yield range with application of fertilizer (and lime if required).*
*[4]Possible yield range without fertilizer or lime.*
*[5]Extensive: without fertilizers and plant protection. Ordinary: 10 to 20 kg/ha N+$P_2O_5$+$K_2O$ in seed row and plant protection in selected fields.Intensive system: recommended crop management technologies; use of all agro-inputs.*

**Table 2.** Long-term average effect of mineral fertilizer use on grain yield of spring wheat on Siberian soils (Gamzikov et al., 2008)..

| Soil | Yield without fertilizers, t/ha | Yield increase with fertilizers1, t/ha | | | |
|---|---|---|---|---|---|
| | | N | P | NP | NPK |
| Soddy-podzolic soil | 1.06 | 0.46 | 0.32 | 0.57 | 0.79 |
| Grey forest soil | 1.57 | 0.41 | 0.30 | 0.60 | 0.67 |
| Chernozem | 1.68 | 0.33 | 0.22 | 0.49 | 0.52 |
| Chestnut soil | 1.14 | 0.16 | 1.18 | 0.31 | 0.31 |

Without plant protection and application of mineral fertilizer, spring wheat grain yields fail to exceed 1.0 t/ha. But intensive agro-technologies can produce 2.6 to 4.5 t/ha. Unstable rainfall, low soil NO3-N, and low available P in some soil provinces limit yield formation on dark grey forest soils, podzolized, leached and common chernozems, and meadow chernozem soils in the forest-steppe zone. Here, the average grain yield for spring wheat does not exceed 1.5 t/ha under extensive systems of crop production, and only 2.0 t/ha in years with especially favorable hydrothermal condi-tions. Attainable grain yields with recommended, intensive agro-technologies range be-tween 2.2 and 4.0 t/ha. In the steppe zone (in view of the considerable moisture deficit in these southern chernozems and chestnut soils, and their low capacity to mobilize N), the average grain yield for spring wheat under an exten-sive system of crop produc-tion is usually under 1.0 t/ha. Nevertheless, it is possible to improve yield to 1.5 to 2.2 t/ha in this zone if all recommended agro-technologies are applied.

The application of min-eral and organic fertilizers in combination with other agro-inputs and recommended agro-technologies allows grow-ers to realize the existing yield potential in every soil-climatic zone while eliminating, or at least alleviating, the negative impact of common natural and anthropogenic factors. **Table 2** summarizes the average grain yield increase for spring wheat due to application of combina-tions of fertilizer nutrients in Siberia. The highest effect of fertilizers on grain yield can be observed on soddy-podzolic and grey forest soils – the agronomic efficiency of applied fertilizer nutrients is generally in a range of 4 to 9 kg high quality grain per kg of nutrients (N+P2O5+K2O).

The appropriate tillage method in combination with

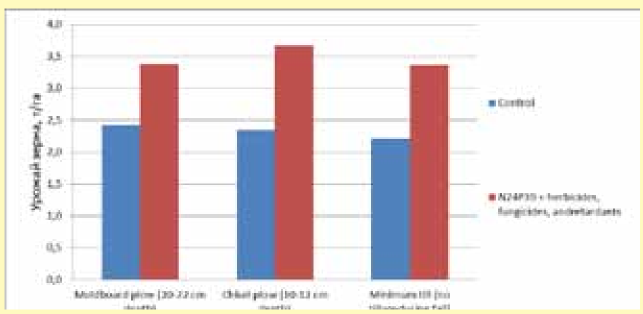



**Figure 2.** Effect of fall tillage method on grain yield of spring wheat grown after fallow in fallow-wheat-maize-wheat-barley crop rotation on leached chernozem; mean 1988-2000 (Kholmov and Yushkevich, 2006).

*Available P and K content (0.5 M $CH_3COOH$) – 80 to 95 ppm $P_2O_5$ and 400 to 500 ppm $K_2O$. Fertilizer rates: 24 kg/ha N and 39 kg/ha $P_2O_5$*

the recommended use of fertilizers and other agro-inputs allows growers to better realize their yield potential (**Figure 2**). Accumulated research data and growers' practice indicate that conservation tillage technologies coupled with recommended applica-tion of all agro-inputs, including mineral fertilizers, generates the highest grain yields (1.5 times higher), decreases the cost of grain production (by 17%), and thus increases profits (by 25%).

Despite this, mineral fertilizer use in Siberian agriculture has declined by more than 10 times over the last 20 years (**Table 3**). Nutrient balance calcula-tions for Siberia clearly indicate a negative balance for all three nutrients (**Table 4**). In fact, total fertilizer inputs account for only 11% of crop nutrient removal in recent years. The short-term forecast (up to 2015) for increased mineral fertilizer consumption gives hope for a gradual alleviation of nutrient deficiencies and a considerable gain in spring wheat yields. Currently, Siberian agriculture has to rely

**Table 3.** Average annual fertilizer consumption (N+P2O5+K2O) in Siberian agriculture, '000 ton.

| Region | 1986-1990 | 2001-2005 | 2006-2009 | 2015-2020 (outlook) |
|---|---|---|---|---|
| Western Siberia | 832 | 53.7 | 70.9 | 260 |
| Eastern Siberia | 470 | 45.3 | 46.9 | 135 |
| Siberia Total | 1302 | 99.0 | 117.8 | 395 |

**Table 4.** Average nutrient balance (kg/ha/year) in Siberian agriculture (2006-2009).

| Nutrient | Crop removal | Fertilizer input | | | Balance | Input/ Removal, % |
|---|---|---|---|---|---|---|
| | | Mineral | Organic | Total | | |
| N | 30.7 | 2.5 | 1.2 | 3.7 | -27.0 | 12 |
| $P_2O_5$ | 10.1 | 0.9 | 0.6 | 1.5 | -8.6 | 15 |
| $K_2O$ | 24.4 | 0.3 | 1.7 | 2.0 | -22.4 | 8 |
| Total | 65.2 | 3.7 | 3.5 | 7.2 | -58.0 | 11 |

**Spring wheat** is grown on millions of hectares of land in Siberia, but yields in recent years have averaged only about 1.3 t/ha.

on crop management systems that exploit indigenous soil fertility because of its limited use of mineral fertilizers and other inputs. Including fallow (the best predecessor for wheat in all natural zones of Siberia) in the rotation is the most commonly used practice. The fallow season in 3 to 4 year rotations allows for high ac-cumulation of moisture reserves (160 to 220 mm within a 100 cm soil depth) and NO3-N (100 to 120 kg/ha within a 40 cm soil depth). Fallow also decreases the number of weed seeds per square meter (to 30 to 35).

Specific soil-climatic conditions in Siberia (i.e., deep and prolonged soil freezing during the winter season, uneven distri-bution of rainfall through the vegetative period, and periodical droughts) increase the role of crop variety and its interaction with the crop management system. Spring wheat breeding in Siberia is done by 11 research institutions and agrarian uni-versities. The State Register of Russia was expanded over the last 30 years (1977 to 2007) to include 63 new soft and 9 new durum varieties of spring wheat (Ruts and Kashevarov, 2008). It is noteworthy that Siberian varieties at present occupy 95% of the total area under spring wheat in the region. Breeding for higher yields of soft and durum spring wheat has progressed by 50% and 35%, respectively.

**Dr. Gamzikov**, left, and **Dr. Nosov**

Grain quality parameters have improved by 14 to 25% and 9 to 20%, respectively, during these last 30 years (Gamzikov, 1997; Ruts and Kashevarov, 2008). Modern spring wheat varieties have high yield potential (3.5 to 7.0 t/ha) and high grain quality (1,000 grain weight of 40 to 50 g, test weight of 780 to 820 g/l, protein content of 15 to 18%, gluten content of 32 to 40%). Most varieties registered for production over the last 8 years have complex immunity to pathogens and resistance to leaf rust, powdery mildew, and loose smut. Siberian research on the genetics of mineral nutrition of spring wheat has resulted in fundamentally new information about the genetic control of uptake and utilization of macronutrients and micronutrients in plants (Gamzikova, 2008). Specific genomes, chromosomes, genes, and cytoplasms controlling uptake and utilization of nutrients in wheat plants have been identified. Concepts and methodologies have been designed for breeding nutrient-efficient genotypes that are more adept at using soil and applied nutrients compared to modern varieties.

In the near-term, spring wheat will continue to be the dominant crop in Siberian agriculture. High and stable yields of spring wheat and also high grain quality in growers' fields will depend on adoption of best management practices rec-ommended by researchers. This may be achieved with the corresponding development of grain export capabilities from Siberia and attractive grain prices at the grower's gate.

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