Soybean

Nutrient Management Guide

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The production of high-yielding, quality soybeans requires sound management, good soil, balanced nutrients, adequate moisture and heat, and a carefully selected variety. Although this publication focuses on nutrient management for maximum soybean production, the importance of other yield-determining factors must not be overlooked.

Soybean

MACRONUTRIENTS	
Nitrogen	N
Phosphorus	P
Potassium	K
Sulfur	S
Magnesium	Mg
Calcium	Ca

The soybean, *Glycine max* (L.), is thought to have originated in the north and central regions of China 4,000 to 5,000 years ago. It was considered by the Chinese to be one of the "Wu Ku," or five grains essential for the existence of civilization. The "Wu Ku" included rice, wheat, barley, millet, and soybeans. Many Asian nations, including China, Japan, Korea, and Southeast Asia, have been using this legume as a source of dietary protein and oil for many centuries.

Although the soybean has a long history in Asian cultures, Europeans did not employ it until relatively recently. A German botanist named Engelbert Kaempfer introduced soybeans to Europe in the early 1700s. A Swedish botanist, Carl von Linne, is credited with giving the soybean its scientific name, *Glycine max* (L.). Glycine is derived from the Greek word glykys meaning "sweet." The word max means "large," referring to the large nodules associated with soybean plants.

The first mention of soybeans in the U.S. is in the 1769 minutes of the American Philosophical Society for the Promotion of Useful Knowledge. The reference is to "Chinese vetches and six bottles of soy." The use of the phrase "Chinese vetches" was traced to Samuel Bowen. Bowen had lived in China for several years and brought soybean samples to Savannah, Georgia, in 1764 when he immigrated to the U.S. Seeds were planted on a local plantation the next year. In a letter written in 1770, Benjamin Franklin mentioned sending soybeans home from England.

MICRONUTRIENTS	
Boron	B
Chloride	Cl
Copper	Cu
Iron	Fe
Manganese	Mn
Molybdenum	Mo
Zinc	Zn

The early use of soybeans in the U.S. was primarily as a forage crop. It was used for hay and silage production. Soybeans were also used as green manure and were frequently grown with corn to supply nitrogen (N) and enhance silage quality. Soldiers used soybeans during the Civil War to brew coffee when real coffee was in short supply.

Soybean production in the U.S. increased dramatically after 1900. The successful utilization of soybeans as an oilseed in Europe from about 1900 to 1910 prompted the increased interest in the U.S. Soybean oil and meal were first produced in the U.S. from imported soybeans by a plant in Seattle, Washington. Cottonseed oil mills in North Carolina processed the first domestically grown soybeans for oil in 1915. The use of combines to harvest soybeans began in 1920, and the first U.S. processing plant opened in 1922. By the end of the 1920s large scale production of soybeans had begun in the U.S. and thousands of new varieties had been introduced. Most were brought from China by William Morse, who later became the first president of the American Soybean Association.

From 1929 to 1939, production increased more than 10-fold, from 9 million to 91 million bushels. China led the world in soybean production until 1954 when the U.S. took the lead. Today the U.S. produces over 2 billion bushels of soybeans annually, representing approximately 50 percent of the world's production.

Uses of Soybeans

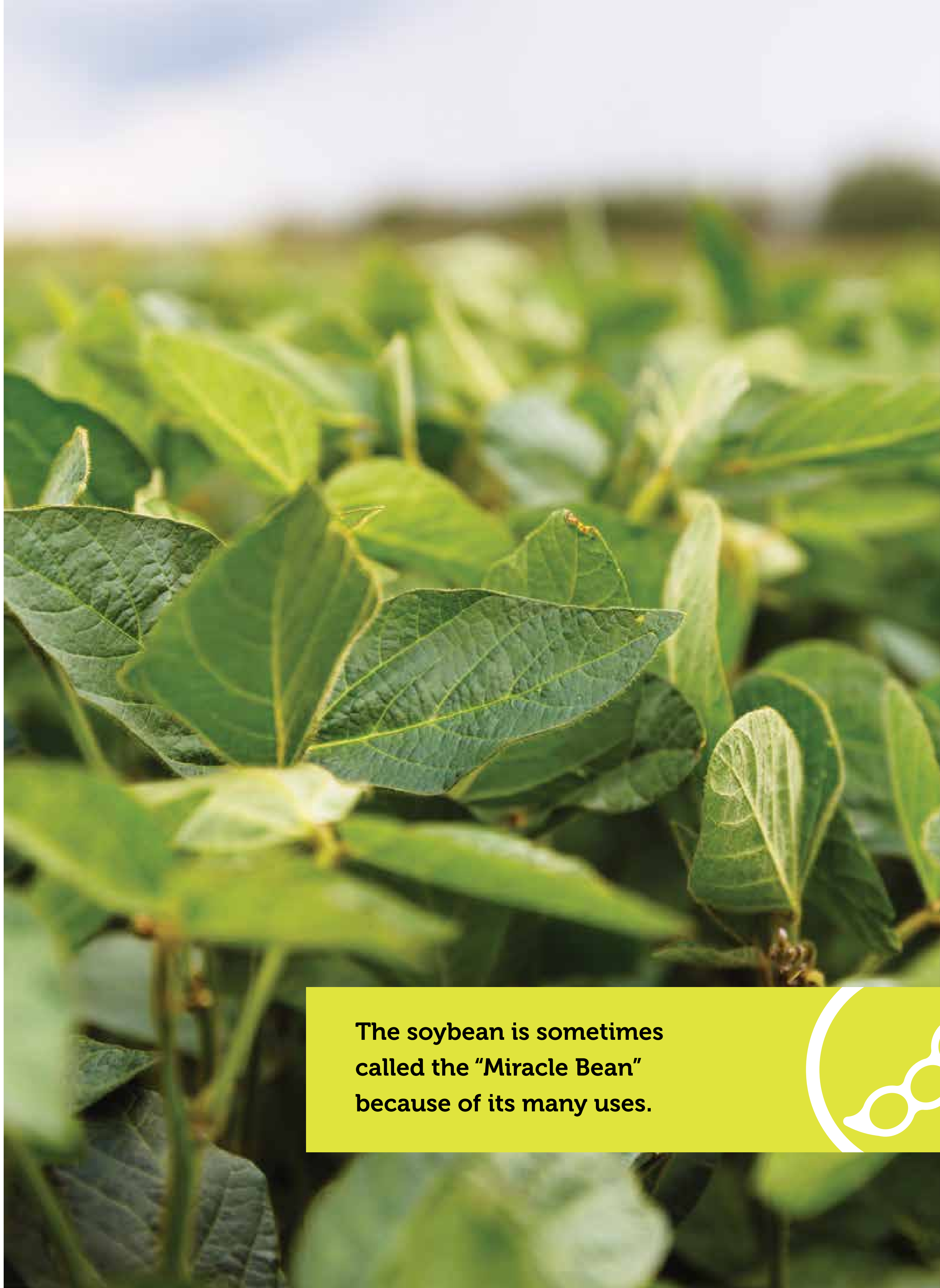
Soybeans are grown for a variety of food, feed, and industrial uses. Nearly all are processed commercially, divided into components of meal and oil. They normally contain about 18 to 20 percent soy oil and 38 to 40 percent soy protein. These two components are used in hundreds of different foods eaten throughout the world. Protein-rich soybean meal essential amino acid content is close to ideal for feeding animals, which makes it extremely valuable as an ingredient in livestock and poultry feed. In fact, almost 80 percent of the soybeans grown in the U.S. are used in some way for feeding animals.

Food products from soybean oil and industrial products from soybeans are also important markets for the soybean crop. Research has shown soybean-derived products to be superior to petroleum-based products for many uses.

Soybean oil is the most frequently consumed vegetable oil in the U.S. Soybean protein can be found in animal feed and food products and has hundreds of industrial uses. The hulls, or outer shell, are used in dairy feed and water purification research. The soybean is sometimes called the "Miracle Bean" because of its many uses. Its high protein content makes it a healthy choice for both humans and other animals. It is the only bean with complete protein. In addition, soybeans or soy products are used in a broad range of products – from roasted soy nuts and salad dressings to lubricants and many products we use every day:

- the protective coating on CDs
- 90 percent of the nation's daily newspapers are printed with color soy ink
- an ingredient in some crayons
- lecithin, a main ingredient in cooking spray – also helps to keep chocolate smooth and creamy
- biodiesel fuel, utilized in truck and bus fleets, boats, and lawn equipment
- vegetable oil used in many homes and fast food restaurants
- building materials used for counter tops and flooring
- an ingredient in infant formula
- ingredients in sunscreen, lip balm, hand lotion, and other makeup products

In processing, soybeans are cleaned, cracked, dehulled, and rolled into flakes. This ruptures the oil cells for efficient extraction. After removal of the soybean oil, the remaining flakes are processed into various edible and industrial soy protein products or used to produce protein meal for animal feed. The soybean's protein and oil find their way into many edible as well as industrial products.



The soybean is sometimes called the "Miracle Bean" because of its many uses.

Distribution

Soybeans are grown
throughout much
of the world.

Soybean Geographic Distribution

Table 1 lists the production for major soybean growing countries. The U.S. produces approximately 33 percent of the total world supply. Figure 1 shows the 2016-2020 distribution of soybean average in the world and the change from the previous year.

TABLE 1. SOYBEAN PRODUCTION IN MAJOR GROWING COUNTRIES

Source: Oilseeds – World Markets and Trade, a USDA Publication

Country	Year				
	2016	2017	2018	2019	2020
	Million Metric Tons				
Brazil	96.500	114.600	122.000	117.000	123.000
Argentina	58.800	55.000	37.800	55.300	53.000
China	12.367	13.596	15.283	15.900	17.100
India	6.929	10.992	8.350	10.930	9.000
Paraguay	9.217	10.336	10.300	8.850	10.200
Canada	6.456	6.597	7.717	7.267	6.000
Mexico	0.341	0.521	0.433	0.335	0.220
European Union	2.320	2.410	2.540	2.664	2.600
Other	16.773	19.551	17.120	19.448	18.828
Subtotal	**209.703**	**233.603**	**221.543**	**237.694**	**239.948**
United States	106.869	116.931	120.065	120.515	96.615
Total World	**316.572**	**350.534**	**341.608**	**358.209**	**336.563**

2020 U.S. SOYBEAN ACRES PLANTED (IN THOUSANDS) AND PERCENT CHANGE FROM THE PREVIOUS YEAR. NUMBERS ARE IN 1,000 ACRES PLANTED

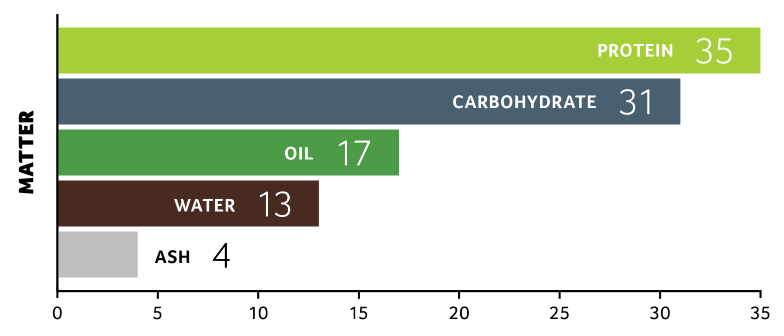
Source: USDA-NASS

State	2019 acres planted	2020 acres planted	% change
Alabama	265	310	17.0
Arkansas	2,650	2,950	11.3
Delaware	155	150	-3.2
Georgia	100	90	-10.0
Illinois	9,950	10,400	4.5
Indiana	5,400	5,700	5.6
Iowa	9,200	9,400	2.2
Kansas	4,550	5,300	16.5
Kentucky	1,700	1,850	8.8
Louisiana	890	1,100	23.6
Maryland	480	420	-12.5
Michigan	1,760	2,300	30.7
Minnesota	6,850	7,400	8.0
Mississippi	1,660	2,000	20.5
Missouri	5,100	5,600	9.8
Nebraska	4,900	5,000	2.0
New Jersey	95	80	-15.8
New York	235	290	23.4
North Carolina	1,540	1,600	3.9
North Dakota	5,600	6,000	7.1
Ohio	4,300	4,800	11.6
Oklahoma	465	550	18.3
Pennsylvania	620	610	-1.6
South Carolina	335	370	10.4
South Dakota	3,500	5,200	48.6
Tennessee	1,400	1,600	14.3
Texas	80	135	68.8
Virginia	570	570	0.0
Wisconsin	1,750	2,050	17.1
United States	**76,100**	**83,825**	**10.2**

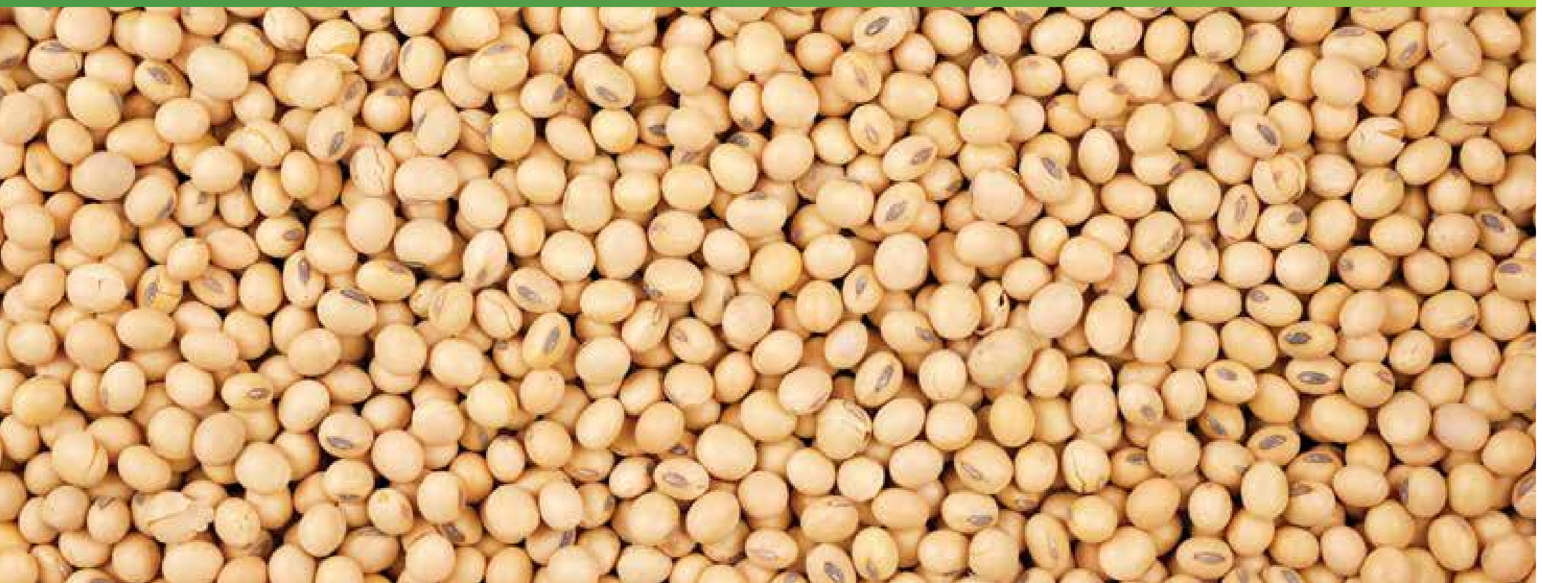
The U.S. produces approximately 33 percent of the total world supply.

Nutrition

The soybean has the highest protein content of all legume and cereal crops.



APPROXIMATE COMPOSITION OF STORED MATURE SOYBEANS



Nutrient Content

Soybeans have approximately 40 percent protein on a dry matter basis compared to 20 to 30 percent in most other legumes. Cereal crops usually range from 8 to 15 percent protein. Soybeans rank second in oil content among the legumes. Peanuts have approximately 48 percent oil on a dry matter basis while soybeans have about 20 percent. Other food legume species consist of 1 to 5 percent oil. The actual composition of stored soybeans depends on variety, location, stress, and overall growing conditions.

In the West, most soybeans are crushed into oil and defatted meal. The oil is used primarily for human consumption and the meal makes up the major protein component in animal feed. In the far East, soybeans are used mainly for human consumption in products such as tofu, tempeh, miso, soy sauce, soymilk, soy sprouts, and natto. Because of the different uses two different types of soybeans have emerged: food beans and oil beans. Most of the commonly produced soybeans are oil beans. Food beans, developed for human consumption, are specialty beans that tend to be higher in protein, lower in oil, have a lighter seed coat, and lower yield potential.

Soy protein, like other protein, provides essential amino acids, nitrogen, and calories. The nutritional quality of protein depends on several factors, including amino acid composition and digestibility. The value of protein also depends on the requirements of the animal being fed. Soy protein contains all of the amino acids essential for animal and human nutrition. In addition, it provides many health benefits for humans. The intake of soy protein has been linked with decreased serum cholesterol and risk for coronary heart disease, and reduced risk of breast cancer and osteoporosis in women.

Carbohydrates are the second most abundant component of soybeans. Both soluble and insoluble carbohydrates are found in the crop. Soybean oil is widely used in food products such as cooking and salad oil, margarine, shortening, and mayonnaise. Like other oils, it provides essential fatty acids, fat-soluble vitamins, and calories. Most of the fatty acids in soybean oil are unsaturated. Soybean oil is healthy oil, high in essential fatty acids, that compares favorably with other highly unsaturated oils like canola.

In addition to the major components, soybeans contain several minor components. The primary constituents of the mineral fraction of soybeans are potassium (K), phosphorus (P), magnesium (Mg), sulfur (S), calcium (Ca), chloride (Cl), and sodium (Na). Most of the phosphorus occurs as phytate. Trace minerals such as silicon (Si), iron (Fe), zinc (Zn), manganese (Mn), and copper (Cu) are also present. The majority of mineral constituents follow the meal or protein portion rather than the oil during processing. Vitamins occurring in soybeans include thiamin, riboflavin, niacin, pantothenic and folic acids, and vitamins A and E. Soy proteins are rich sources of isoflavones that have been shown to have antifungal, antioxidant, and anticarcinogenic activity. The quantity of these minor components is largely dependent on variety and growing conditions.

Growth

Soybeans are grown
in rotation with other crops,
most often corn.

Growth and Development of Soybeans

In the Midwest U.S., soybeans are planted in early- to mid-May if weather permits, usually after the corn crop is planted. There is also a substantial acreage of soybeans planted following small grains in a double-crop system.

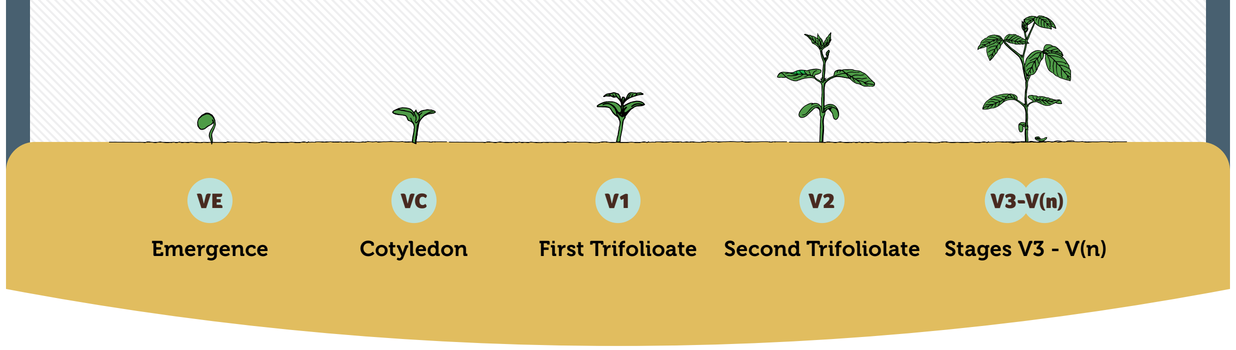
To improve communications on production and pest management practice recommendations, a standardized staging system has been developed. Table 2 provides the general definitions of these growth stages.

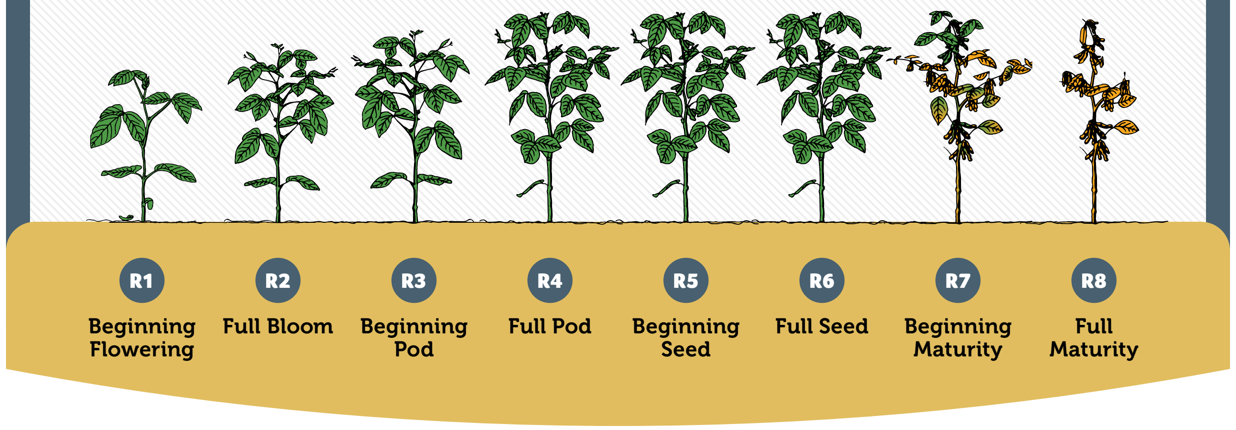
TABLE 2. VEGETATIVE AND REPRODUCTIVE STAGES OF A SOYBEAN PLANT*

Vegetative Stages	Reproductive Stages
VE Emergence	R1 Beginning bloom
VC Cotyledon	R2 Full bloom
V1 First-node	R3 Beginning pod
V2 Second-node	R4 Full pod
V3 Third-node	R5 Beginning seed
*	R6 Full seed
*	R7 Beginning maturity
V(n) nth-node	R8 Full maturity

*This system accurately identifies the stages of a soybean plant. However, all plants in a given field will not be in the same stage at the same time. When staging a field of soybeans, each specific V or R stage is defined only when 50 percent or more of the plants in the field are in or beyond that stage.

Soybean Development and Growth Staging





VEGETATIVE

VE Emergence

Emergence occurs when the cotyledons appear above the ground. The primary and lateral roots begin to develop. Root hairs form shortly after planting. Scouting for emergence is suggested. Planting depth is critical for this stage – too deep can delay emergence and too shallow can create a weak plant.

VC Cotyledon

During the first leaf stage, unifoliolate leaves expand. For the following seven to 10 days, the cotyledons are the main nutrient reservoir for the young plants. Scout for proper emergence and look out for weeds.

V1 First Trifolioate

The first trifoliolate leaf unrolls. Unifoliate leaves are fully developed. At this stage the plant is becoming self-sustaining as new leaves carry out photosynthesis. New nodes will appear every three to five days until the V5 stage.

V2 Second Trifoliolate

Two trifoliolates unroll (fully developed trifoliate leaves at nodes above the unifoliate node). At this stage, nodules have been initiated on the roots. Nitrogen fixation continues until late reproductive stages. Effective nodulation produces higher yields and more seed protein than a non-nodulated soybean plant. Scouting is suggested at this stage for early-season weeds, insects and diseases. Application of herbicides is suggested if needed. If nodes have been established, then nitrogen fertilization is not recommended.

V3-V(n) Stages V3 – V(n)

Vegetative stage designations V3 through V(n) represent the number of nodes on the main stem (n) above the unifoliate node with fully developed leaves. If there is damage to the plant, axillary buds permit the plants to compensate for yield or loss. The root system continues to expand. The number of root nodules and nitrogen fixation increase throughout the vegetative stages. Flowering follows about one week after V5. At V6, new vegetative stages are unfolding about every two to three days. The plant is readying to switch over to reproductive stages. Determinate soybean plants complete most of their vegetative growth when flowering begins. Indeterminate plants produce trifoliolates until the beginning of the seed formation.

REPRODUCTIVE

R1 Beginning Flowering

During this stage, flowering begins at any node on the main stem on the plant. Indeterminate plants start flowering at the low- or mid-canopy and flower upward. Determinate plants start flowering at one of the top four nodes, and then flowering proceeds up and down the stem. Scout for insects and diseases and, if needed, you can spray foliar insecticide or fungicide.

R2 Full Bloom

At this stage, the plant has one open flower on the highest up nodes on the main stem with a fully developed leaf. Continue scouting for insects or diseases at this stage.

R3 Beginning Pod

Pods are beginning to form on the higher up nodes of the plant with fully developed leaves. During this stage, scouting for insects and diseases is suggested. Spray insecticide or fungicide if needed. Water stress can affect pod formation, and irrigation is effective at this stage.

R4 Full Pod

Pods are 3/4 of an inch long near the top of the plant along the main stem. Seasonal nitrogen uptake relative to the final amount attained at maturity is at this stage. R4 marks the beginning of the most critical period of plant development. Late season diseases can impact yields. Irrigation may be needed at this stage, if available.

R5 Beginning Seed

At this stage, seeds are almost 1/8 of an inch long in four of the highest nodes on the main stem. Primary roots are growing until R5. The deeper roots are expanding till R6.5. Scout for late season diseases; they could damage yield.

R6 Full Seed

At full seed, pods contain green seeds that fill up the cavity. Most nutrients have been taken up at this stage. Scouting is suggested for insects and diseases, and spray if needed.

R7 Beginning Maturity

One pod on the main stem has reached maturity. Watch for green stem syndrome, which is when the stem remains green while seeds mature.

R8 Full Maturity

This stage is about five to 10 days before harvest. Pods should have reached full maturity, and 95 percent of pods are mature colored. Scout for green stem syndrome; if present, harvest slow and make sure harvesting equipment is in good condition.

Figure 4 shows dry matter accumulation in various parts of the soybean palnt during the growing season, while Figure 5 illustrates a timeline for growth of the different plant parts.

FIGURE 4. DRY MATTER ACCUMULATION IN VARIOUS PARTS OF THE SOYBEAN PLANT DURING THE GROWING SEASON

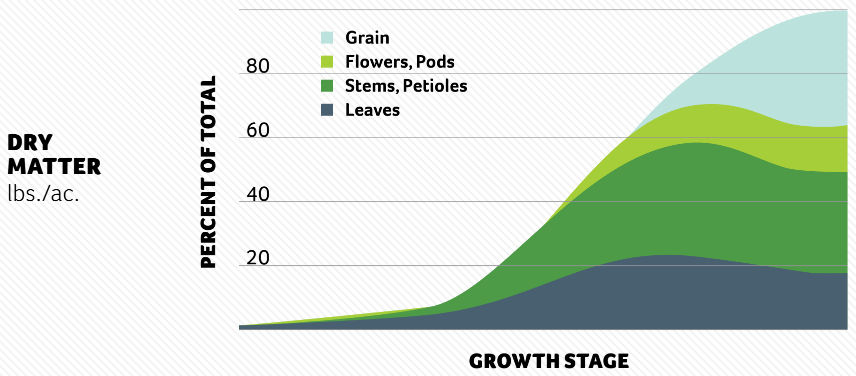
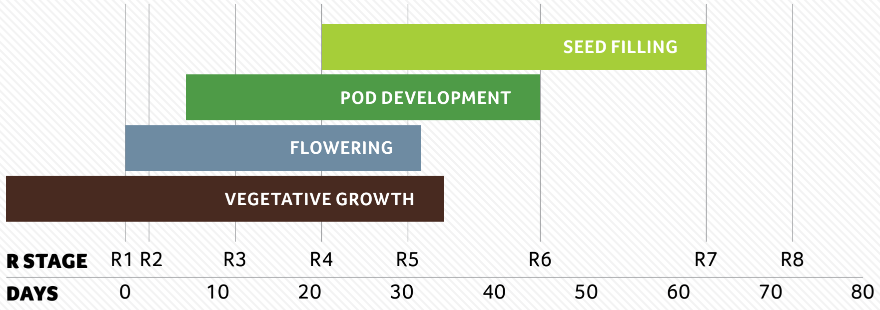


FIGURE 5. TIMELINE FOR GROWTH OF DIFFERENT PARTS OF THE SOYBEAN PLANT. THIS CHART IS FOR THE INDETERMINATE VARIETIES GROWN IN THE MIDWEST.



Management

Soybeans grow best
under a high fertility system.

Nutrient Management

General Concepts

Soybeans grow best under a high fertility system that is generally supportive of other crops in the rotation. Historically, soybeans have often been dependent upon leftover nutrients from the previous corn crop, but modern producers understand that the soybean crop will respond to direct application of nutrients. As management improves and yields increase, nutrient management specific for the soybean crop becomes more important.

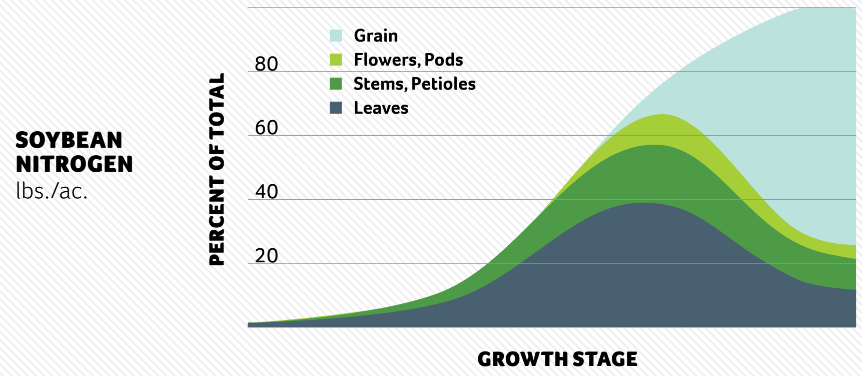
Nutrient Requirements and Uptake by Plants

Most nutrients are absorbed from the soil. However, part of the nitrogen is obtained from bacterial fixation in the nodules and some sulfur is absorbed (primarily as SO_2 and H_2S) from the air. Soil nutrients are absorbed into the plant roots with water and move up into the plant to the leaves and other vegetative plant parts.

The amounts of nutrients available vary with soil type, soil test, depth of soil, and tillage practices, and are influenced by soil temperature and moisture conditions. Roots will not grow into dry soil, and moisture must be present for roots to absorb nutrients from the soil. However, excess moisture in the soil limits aeration (oxygen) required by the roots.

The seasonal patterns of accumulation of nitrogen and potassium in the different parts of soybean plants are illustrated in Figures 6 and 7. The amounts of nutrients taken up by the plants early in the season are relatively small because the plants are small. However, the nutrient concentrations in individual leaves of well-nourished plants are as high during this period as individual leaves later in the season. Uptake and accumulation of some nutrients in the leaves continues throughout the season until maturity; uptake of others is completed by stage R6 (full seed).

FIGURE 6. NITROGEN ACCUMULATION AND REDISTRIBUTION IN SOYBEANS DURING THE GROWING SEASON



Redistribution from older plant parts to newer growing parts is a primary source for some nutrients. Some nutrient elements are very mobile in the plants and are readily translocated from older to newer plant parts. Redistribution of nitrogen, phosphorus, and sulfur is a primary source of these nutrients for growth of the plant and can result in severe depletion of these nutrients in the leaves, petioles, stems, and pods during the late seed-filling period. However, nutrients such as calcium are very immobile in the plant, and there is little redistribution from older to new plant parts. Late-season redistribution of mobile materials that have accumulated in leaves and other plant parts without redistribution of calcium results in increased calcium concentration in the leaves late in the season.

Soil Sampling and Testing

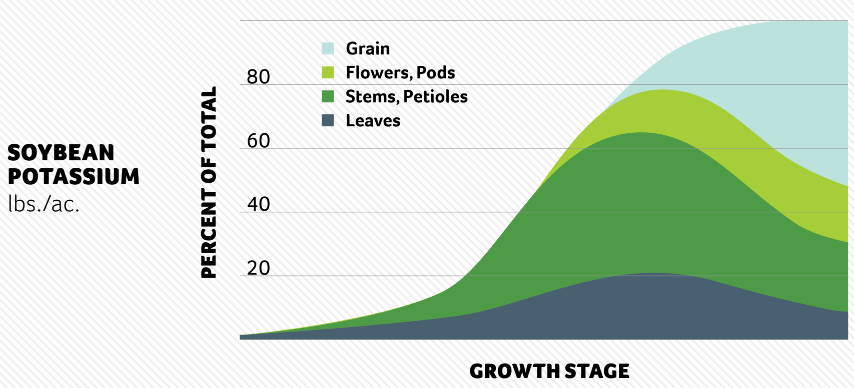
Nutrient management for any crop should be based on a sound soil testing program. Historically, soybeans have been produced as a second or third crop in a rotation (most often following corn in the Midwest or cotton in the South) and have depended on carryover nutrients for their needs. During the 1980s and 1990s, soybean acreage increased to the point that many farmers plant at least 50 percent of their acreage to soybeans. This means that nutrient management for soybeans becomes a more important part of the overall management plan. Soybeans remove large amounts of nitrogen and potassium, so increasing the frequency of soybeans in the rotation usually means increased application of potassium, and in some cases the need for nitrogen fertilizer application.

Establish a soil sampling scheme that will best represent the field. Some people prefer to set sample sites based on soil types. Others prefer a uniform grid sampling pattern. There are good arguments supporting either approach. The important point is to be sure to collect enough samples to adequately represent the variability in the field. Any known sources of variability such as old building sites, previous field boundaries, and topography differences should be taken into account in setting sampling patterns.

In most cases a basic soil test will be adequate, but if there are indications of sulfur and micronutrient deficiencies, a more detailed analysis may be helpful. In general, laboratory procedures for sulfur and most micronutrient soil tests are not very reliable. If sulfur or micronutrient deficiencies are suspected, plant tissue analysis provides a more reliable diagnostic tool.

Care should be taken to be sure soil samples are collected at a uniform depth (usually specified by the laboratory). Each sample should be a composite of several cores collected following locally developed guidelines.

FIGURE 7. POTASSIUM ACCUMULATION AND REDISTRIBUTION IN SOYBEANS DURING THE GROWING SEASON



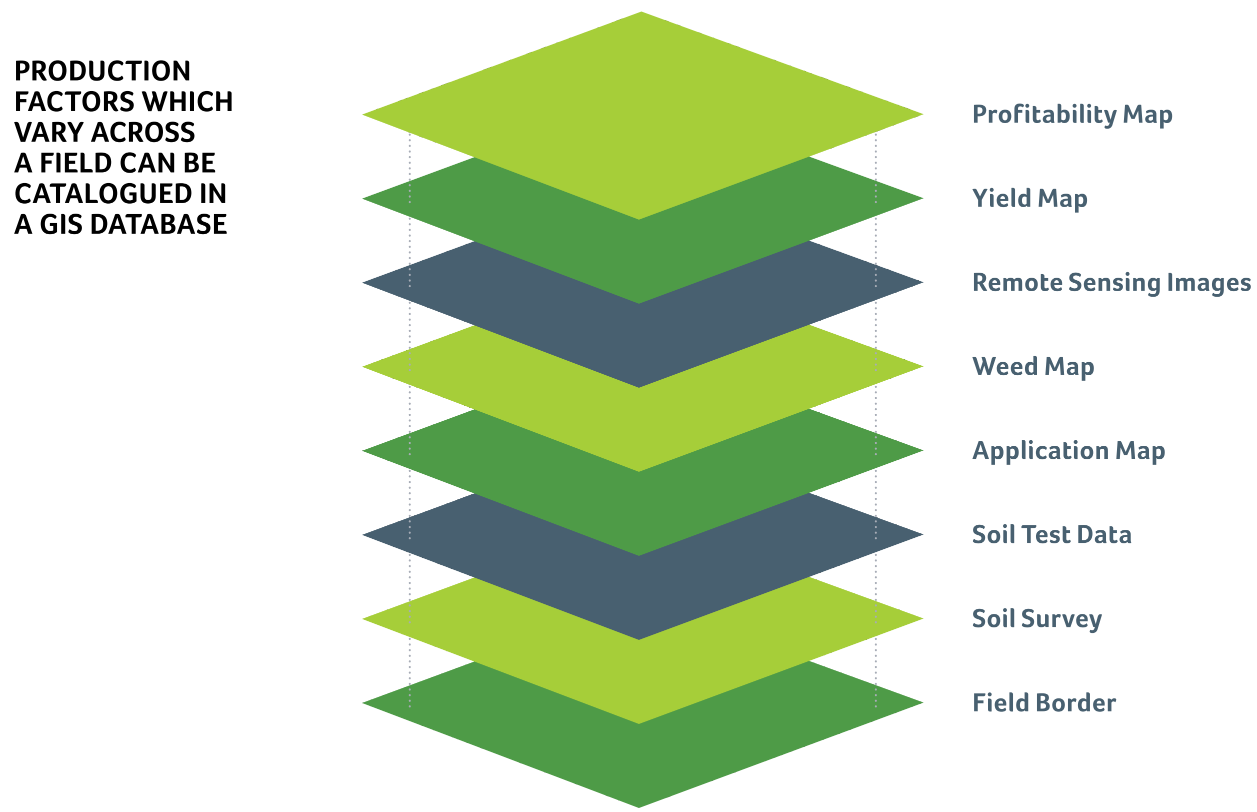
Site-Specific Systems

The development of technology for site-specific management systems offers some new opportunities to improve production efficiency and yield for soybean producers. Yield monitors provide a means of measuring and documenting the variability of yield within individual fields. Linking yield maps to other observations or databases from the field can help identify the sources of yield variability and lead to clues for improving management and profitability.

Site-specific management is really nothing new. We just have new tools to make it easier to implement. Farmers have recognized variability in their fields, but until on-the-go yield monitors were available, it was difficult to determine the impact of that variability on yields or profits. Now the data can be reviewed and exact dollar impact determined. This knowledge has renewed interest in agronomic information and interpretation of yield results. Farmers and their advisers can see the financial impact of problems in the field and make better informed decisions on action to correct those problems.

Incorporating yield data and other information into a geographic information system (GIS) provides a means of relating the different data sets to yield. Any production factor that varies across the field can be cataloged in the GIS database and related to the yield map. Geographically referenced soil survey maps provide a good starting point. Many production factors, including water availability, nutrient supplying power, organic matter, slope, and texture, are tied to soil characteristics. The graph below illustrates several layers of geo-referenced data.

GIS Geographic Information System



Each year's yield maps provide another layer of information that can be related to the geographically referenced database. Soil tests and other observations may also be repeated periodically, so that changes in these databases can also be related to the changes observed in the yield data.

Building a GIS database offers unique opportunities for analyzing the data using GIS spatial analysis tools. These require some learning, and probably some consulting assistance, but the power of such analyses is worth the extra effort.

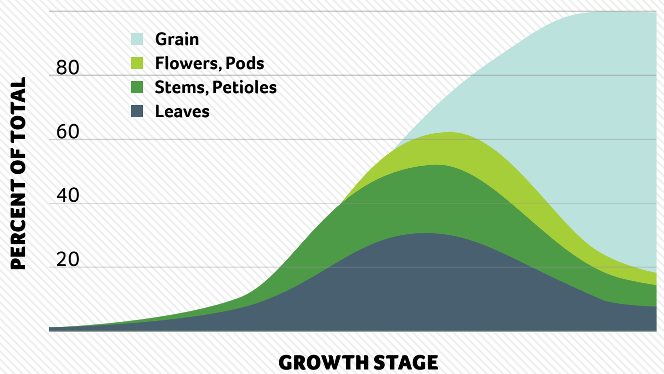
The availability of detailed data sets on each field, and especially detailed yield data, offers some interesting new possibilities for on-farm research. Treatments can be applied with variable-rate equipment and results measured with yield monitors at harvest. Plot work can actually be done without any hand measurement or staking of plots.

On-farm research is not a replacement for traditional small plot work, but it offers some new opportunities for management systems comparisons and for evaluating how research from experiment stations can be applied on the farm. It is also expanding opportunities for university and industry researchers to partner with farmers in conducting their research projects.

Site-specific technology is rapidly being absorbed into common practice, because it just makes good sense. For the first round of farmers, it was a new system. For most farmers, components of site-specific management will become a common way of managing crops. Variable-rate controllers are standard equipment on planters and sprayers. Combines have yield monitors as standard equipment, and other components of site-specific systems will become the norm. Farmers who do not learn to use global positioning systems (GPS) and GIS tools may not be able to take full advantage of the new technology. However, most will find it to their advantage to at least work with a dealer or consultant who can help them implement some of the new tools on their farm. Some may not recognize it, but site-specific farming is a part of every farmer's future.

FIGURE 8. PHOSPHORUS ACCUMULATION AND REDISTRIBUTION IN SOYBEANS DURING THE GROWING SEASON

SOYBEAN PHOSPHORUS
lbs./ac.



INTEGRATED, INTENSIVE, SITE-SPECIFIC SYSTEMS FOR SOIL AND CROP MANAGEMENT

GRID SAMPLING, guided by GPS, provides more accurate soil test data.

VARIABLE RATE FERTILIZER application can improve efficiency.

VARIABLE RATE SEEDING, variety changes and starter fertilizer can adjust for soil properties and productivity.

CROP SCOUTING with new digital technologies improves field records.

ON-THE-GO YIELD MONITORS can quickly track variability in the field.

High-Tech Tools for Site-Specific Crop Nutrient Management

Nitrogen

Soybean plants
may accumulate more than
300 lbs./ac. of nitrogen.

Nitrogen and Nitrogen-Fixation

Importance of Symbiotic Nitrogen-Fixation

Soybean plants may accumulate more than 300 pounds of nitrogen per acre in making a 50 bushel per acre yield. Without adequate nitrogen, dry matter production will be limited, photosynthesis will be short-changed, and yields will be poor. Soybeans rely on symbiotic nitrogen-fixation to acquire the majority of the nitrogen needed to produce maximum economic yield (MEY). Field studies across the U.S. have shown that the typical symbiotically fixed proportion of the total nitrogen accumulated by soybeans ranges from 40 to more than 90 percent. The soybean crop's reliance on symbiotic fixation for most of its nitrogen needs has caused most agronomists to consider soybeans a "living nitrogen factory." As it turns out, the soybean nitrogen factor is actually a protein factor because the majority of the nitrogen fixed and accumulated by soybeans ends up in the seed as protein. Soybean seed contains about 40 percent protein.

The average nitrogen accumulation rate by soybeans has been measured at about 3 pounds per acre per day with maximum nitrogen accumulation rates between 5 and 7 pounds per acre per day, which coincides with the period of maximum nitrogen-fixation. Maximum nitrogen-fixation usually occurs between blooming (R1-R2) and beginning seed (R5). By maturity, 65 percent of all the nitrogen fixed and absorbed may be found in the seed, with more than 200 pounds of nitrogen per acre removed by 50 bushels of seed at harvest.

The nitrogen-fixation system involves a symbiotic relationship between the soybean plant and specialized bacteria, *Bradyrhizobium japonicum*, which form nodules on the roots. Symbiotic nitrogen-fixation is an energy demanding process. Energy products of photosynthesis are moved from leaves to the roots, benefiting the bacteria in the nodules. In turn, effective soybean root nodules absorb N_2 gas from the atmosphere (which is 78 percent N_2), after which it is converted into usable nitrogen, and amino acids, and ultimately into protein.

Light intensity and potassium supply affect the energy status of the plant, which determines the rate of nitrogen-fixation. Research in North Carolina has shown that phosphorus deficiency has a direct impact on the energy metabolism of nodules, in addition to effects on plant growth. Adequate phosphorus and potassium must be provided for soybeans to maximize nitrogen-fixation and transport of nitrogen from the roots to shoots and seed. High nitrogen-fixation rates also depend on a favorable soil pH, adequate levels of secondary nutrients and micronutrients, optimum soil moisture, aeration, and temperature throughout the growing season, sustained root growth, and a healthy and efficient population of Bradyrhizobia.

Inoculation and Nodulation

If soybeans have not been planted in a field in the last three to four years, or if past soybean crops have had poorly nodulated roots, inoculation of the soybean seed with large numbers of viable (live) Bradyrhizobia is highly recommended at planting. Similarly, if considerable topsoil movement has occurred during land leveling, inoculation is probably warranted. An inoculant can be applied to the seed by thorough mixing, just prior to loading the seed in the planter hopper-box or drill, or by in-furrow placement of dry or liquid inoculants at planting. This is also an opportune time to seed-apply any molybdenum (Mo) that may be required. Inoculants which include molybdenum and/or fungicides which have not been kept separate from the Bradyrhizobia should be avoided. Prolonged exposure of the Bradyrhizobia to fungicides and/or molybdenum may kill the bacteria. Inoculants with expiration dates that have passed should not be purchased because the numbers of viable bacteria may be too low to be beneficial. In addition, inoculants should be stored in a cool, dark place (preferably a refrigerator) until ready for use.

Nodules usually become visible within one to two weeks after the Bradyrhizobia infect microscopic "root hairs." Nitrogen-fixation activity can be detected within three weeks after emergence (VE) and will usually continue until near maturity (R6-R7). Individual nodules function for about six to seven weeks and then begin to decay. So, continued new root development is vital to sustained nitrogen-fixation and achievement of high yields. The interiors of active nitrogen-fixing nodules are dark pink to red, while nonfunctional nodules have green or white interiors.

Soil fertility conditions that favor good soybean growth, root development, and high yields also favor the survival of Bradyrhizobia in the soil. In addition to direct effects on soybean growth, deficiencies of lime, phosphorus, potassium, and other nutrients may cause Bradyrhizobia numbers to decline to less than one percent of the numbers present in the soil compared to when lime, phosphorus and potassium needs have been met.

Some believe that 20 to 30 pounds of nitrogen per acre may stimulate early soybean growth and give plants a competitive advantage over weeds without a measurable reduction in nodulation and nitrogen fixation. Considerable evidence indicates that an abundance of available soil nitrogen, or the application of significant fertilizer nitrogen prior to planting, may not significantly increase yields. Large amounts of applied nitrogen often: 1) reduce root-hair infection by Bradyrhizobia, 2) reduce the number and size of nodules per plant, 3) delay nodulation, 4) reduce the nitrogen-fixation activity of nodulated roots, and 5) reduce the total amount of nitrogen symbiotically fixed.

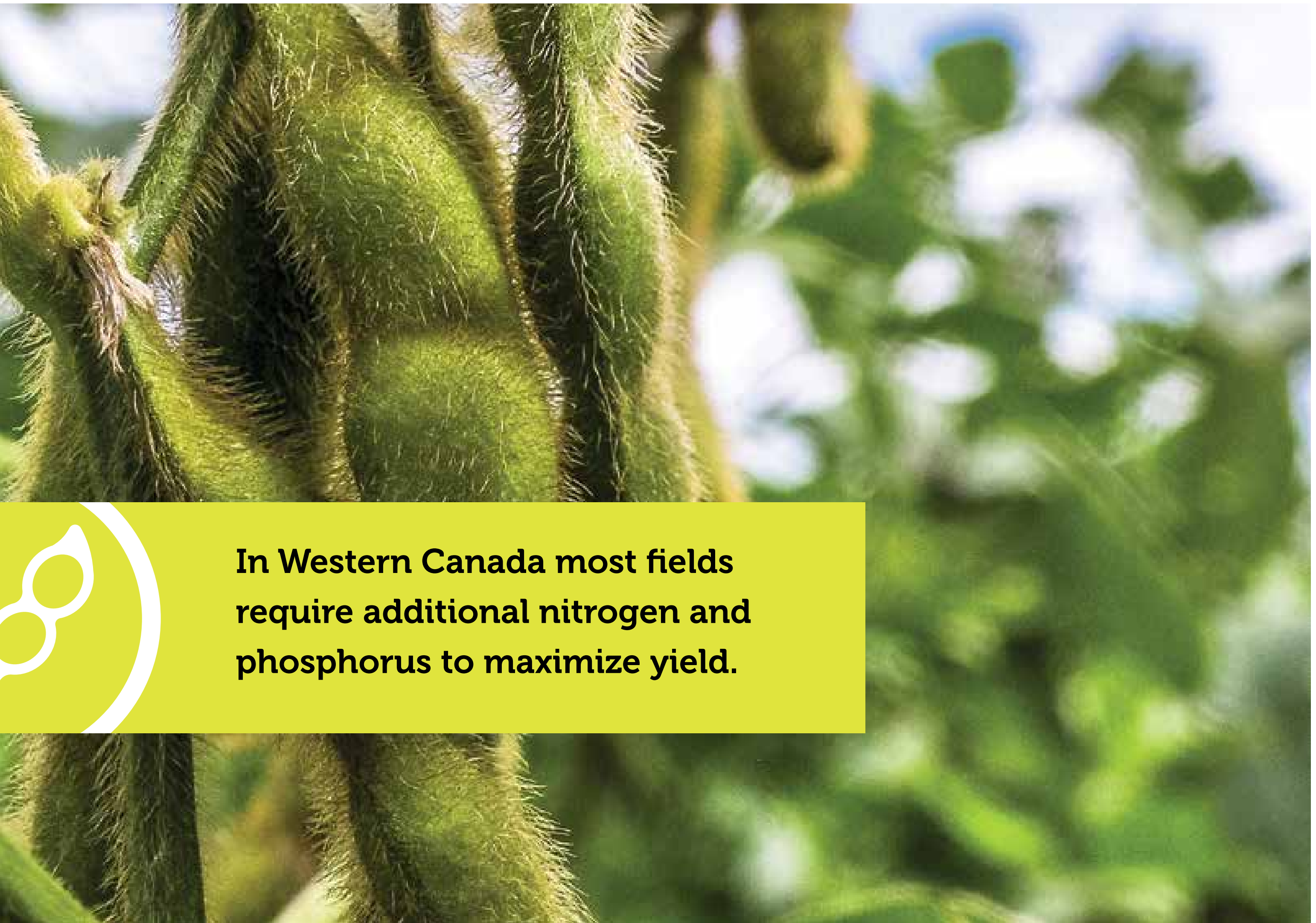
a. Starter Nitrogen Fertilization

Banded applications of starter nitrogen fertilizers at planting, as with broadcast applications, have generally failed to show significant and economical yield increases. Questions have been raised about the value of using starter fertilizers containing nitrogen with no-till and other conservation tillage systems for soybeans. However, research in Minnesota found that nodulation and symbiotic nitrogen-fixation were not different among six tillage systems investigated.

Soybeans rely on symbiotic nitrogen-fixation to acquire the majority of the nitrogen needed to produce maximum economic yield (MEY).

THE PRIMARY SOURCES OF FERTILIZER MATERIALS CONTAINING NITROGEN

Source	Formula	K_2O	P_2O_5	MG	S	N
				%		
Anhydrous ammonia	NH_3					82
Ammonium nitrate	NH_4NO_3					33-34
Ammonium sulfate	$(NH_4)_2SO_4$					21
Urea	CH_4N_2O					46
Calcium nitrate	$Ca(NO_3)_2$					15.5
DAP	$(NH_4)_2HPO_4$		46			18
MAP	$NH_4H_2PO_4$		52			11



In Western Canada most fields require additional nitrogen and phosphorus to maximize yield.

b. Sidedressed Nitrogen Fertilization

Some scientists think that applying nitrogen later in the season during flowering to pod filling (R1-R6) may enhance flower retention, pod numbers, and seed size. While many studies show no benefit from this practice, others have shown yield increases of as much as 28 to 32 percent when 150 pounds of nitrogen per acre were applied to indeterminate soybeans during initial bloom (R1-R2). Seed yield increases appear more pronounced than total dry matter production from nitrogen applied during pod filling.

Many agronomists believe that the soybean yield potential needs to be in the high range (above 50 to 55 bushels per acre) before benefits to midseason nitrogen fertilization are likely. As soybean yields have generally increased in recent decades, there are many more growers producing above these yield levels, and there is growing evidence that high-yield soybeans can benefit from nitrogen applications at the right time and rate.

Recent studies have shown economic yield responses to Nutrien's ESN Smart Nitrogen applied at modest rates (about 40 to 80 pounds of nitrogen per acre) just before flowering (just before R1 growth stage). ESN's controlled nitrogen release can provide supplemental nitrogen during pod-fill while minimizing inhibitory effects of nitrogen on nodules and fixed nitrogen.

c. Foliar Nitrogen Fertilization

Since early-season, soil-applied nitrogen may inhibit nodulation and result in less reliance on nitrogen-fixation, there has been some interest in foliar nitrogen applications similar to those used for cotton in parts of the U.S. Repeated foliar applications of 5 to 10 pounds of urea nitrogen per acre at the early reproductive stage (R1-R3) at seven to 10 day intervals have increased yields several bushels per acre. However, studies have shown that both soil applied and foliar applied urea nitrogen are equally absorbed by determinate soybean plants, with an uptake efficiency of 65 percent. This indicates that root activity during pod filling does not necessarily decline as some have observed.

Soybean Recovery of, and Contribution to, Soil Nitrogen

While soybeans have been observed to contribute to the buildup of soil nitrogen in many studies, other work has demonstrated that it actually depletes the soil nitrogen by as much as 70 pounds per acre per year. This mining of soil nitrogen is probably more likely to occur in soils with high available nitrogen contents or a readily-mineralized organic nitrogen pool and may actually be more due to the absence of high carbon (C) to nitrogen ratio crop residue such as corn stalks than the presence of soybean residue.

Many universities credit crops following soybeans with 20 to 40 or more pounds of nitrogen per acre. In studies using labeled nitrogen, it has been shown that soybeans are capable of removing or scavenging large amounts of nitrogen and has the potential to help reduce the leaching of nitrate-nitrogen to groundwater. While soybeans can scavenge residual nitrogen from previous crops or nitrogen applications, post-harvest periods can result in nitrogen loss due to limited biomass being returned to the soil to immobilize nitrogen compared to a crop like corn.

Soybeans should be managed to derive the maximum benefit from symbiotic nitrogen-fixation. There is potential for economic benefits from soil applications, or sprinkler system injection applications, in the range of 20 to 40 pounds of nitrogen per acre, made from beginning pod (R3) to beginning seed (R5), on well-managed, irrigated fields. Until more work is done with different soybean varieties, at more locations, soybean growers might want to consider this practice on some of their fields before implementation on the whole farm.

Phosphorus

Phosphorus is
essential for proper growth and development.

Phosphorus is essential for proper growth and development and is involved in several vital functions in crop plants. Some of the essential functions are:

- photosynthesis and respiration
- energy storage and transfer
- cell division and enlargement
- oxidation-reduction reactions
- sugar transport
- seed formation
- transfer of hereditary traits

Sufficient available phosphorus is also associated with early root formation and growth and improved quality. In soybeans, phosphorus plays a major role in nodule formation and symbiotic nitrogen-fixation.

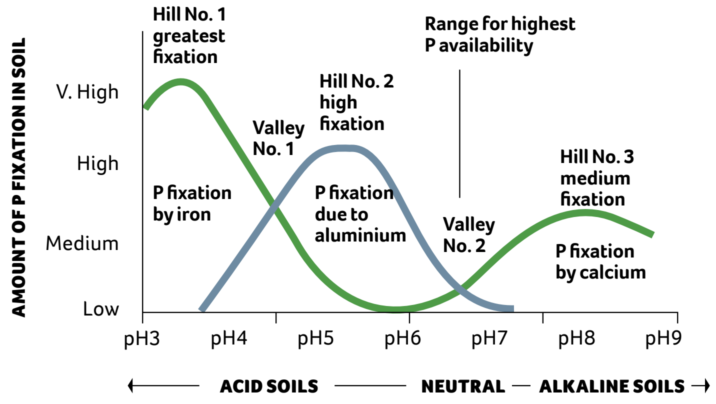
Phosphorus Soil Reactions

Phosphorus is taken up by plants from soil water as the orthophosphate anion. There are two forms of this anion that are utilized by plants: the primary orthophosphate ion ($H_2PO_4^-$) and the secondary orthophosphate ion ($HPO_4^=$). Phosphate fertilizers contain soluble forms of phosphorus that are immediately available to plants. However, this soluble phosphorus is subject to reactions in soils that may reduce its availability to plants. In alkaline soils, phosphorus may form sparingly soluble calcium phosphates. In acid soils high in aluminum (Al) and/or iron, phosphorus may be tied up in relatively insoluble aluminum and iron phosphate mineral products. The soil pH range of maximum availability of phosphorus is from about 6 to 7.

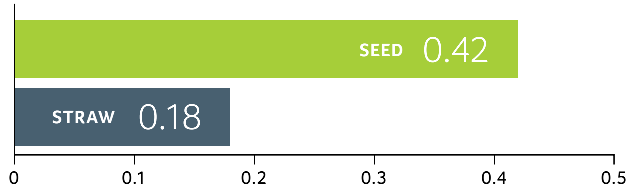
Phosphorus Removal

Soybeans require about 1 pound of P_2O_5 per bushel of yield produced. Most of the phosphorus is concentrated in the seed. A 60 bushel per acre soybean crop will require about 58 pounds P_2O_5 to produce and will remove approximately 48 pounds P_2O_5 in the harvested crop. Consequently, soil phosphorus can be depleted in soybean production if phosphorus fertilizer is not used.

PEAKS AND VALLEYS OF PHOSPHORUS FIXATION



PHOSPHORUS CONCENTRATION IN SOYBEAN COMPONENTS



Phosphorus Deficiency

When sufficient phosphorus is not available to a soybean crop, yields will decrease. In addition to reduced yields, other phosphorus deficiency symptoms may occur. Some symptoms indicative of phosphorus deficiency in soybeans are:

- small, dark-green or bluish leaves
- spindly, thin stems
- reduced size and number of root nodes
- upward curling leaflets
- disoriented canopy
- delayed maturity

Phosphorus Fertilization

In the production of many crops, proper phosphorus fertilizer placement is often important in optimizing yields. Phosphate movement is very limited in most soils – consequently phosphorus must be placed where it is accessible to plant roots. One of the most common practices is broadcasting phosphorus before primary tillage operations. In conventional tillage systems, this results in fairly uniform mixing of phosphorus fertilizer within the depth of the plow layer. In conservation tillage systems, repeated broadcast applications without soil mixing results in stratification and higher concentrations of phosphorus near the soil surface. Band placement concentrates phosphorus within a zone in the soil and minimizes fertilizer contact with the soil.

However, the method of phosphorus fertilizer placement is usually not as critical in soybean production as in some other crops. For example, banding phosphorus generally does not provide the advantage over broadcasting that it does in corn. There are several possible explanations for this. One is that the early season requirements of soybeans for phosphorus is relatively low (See Table 3). The plant's root system and ability to forage for phosphorus is well developed when phosphorus demands are highest. Other reasons are that the physiological traits of soybean roots make them less able to utilize nutrients in a concentrated band, and soybeans are often planted later in the spring when soil temperatures are warmer and more favorable for nutrient uptake. Placement of fertilizer in direct seed contact should be avoided since soybean seedlings are rather susceptible to injury.

Several sources of fertilizer phosphorus are available, both granular and liquid. The common granular sources range in P_2O_5 concentration from about 46to 52 percent. Liquid fertilizers consist mainly of polyphosphate compounds and usually have analysis of 10-34-0 or 11-37-0. Commonly available phosphorus fertilizers are of equivalent agronomic effectiveness. The decision of which phosphorus fertilizer source to use should be based on factors such as price, availability, and preference.

PHOSPHORUS-DEFICIENT SOYBEANS

TABLE 3. SOYBEANS TAKE-UP OF PHOSPHORUS THROUGHOUT THE GROWING SEASON

Growth stage	P_2O_5 uptake		
	Days	lbs./ac.	% of total
Emergence to 6-leaf	51	12	9
6-leaf to full bloom	16	28	21
Full bloom to maturity	36	92	70

Yield= 100 bu./ac.

TABLE 4. PROFITABILITY OF PHOSPHORUS FERTILIZATION OF SOYBEANS IN DIFFERENT TILLAGE SYSTEMS AND ROW WIDTHS

Row width, inches	Tillage system	P_2O_5, lbs./ac.		Response	Return to P
		0	92		
		Yield, bu./ac.			$/A
7	Chisel	44	60	16	133
	No-till	44	56	12	87
30	Chisel	30	44	14	110
	No-till	30	41	11	76

P_2O_5 $0.55/lb; soybeans – $11.50/bushel.

Phosphorus is essential for proper growth and development and is involved in several vital functions in crop plants.

High yielding soybeans remove large quantities of phosphorus from soils. Maximum daily uptake can be as high as 2.7 pounds of P_2O_5 per acre. To achieve and maintain high yields, phosphorus must be provided from fertilizer and the soil. Several university studies have documented excellent soybean yield responses to phosphorus. Table 4 shows the profitability of phosphorus application to a soil testing low in phosphorus under different tillage systems and row widths.

Response to fertilizer phosphorus is related to soil test level, environment, and soybean variety. Phosphorus application to soybeans should be based on soil test results. The likelihood of soybean response to fertilizer phosphorus in soils testing relatively low in available phosphorus is high (Table 5). In one study, raising soil test phosphorus and potassium levels from low to high increased soybean yields by 43 percent. Building soil phosphorus to high levels is a capital investment that insures that phosphorus will not be a limiting factor in achieving optimum soybean yields.

TABLE 5. PROBABILITY OF SOYBEAN RESPONSE TO PHOSPHORUS AT VARIOUS SOIL TESTING LEVELS

Soil test P level	Probability of profitable response, %
Very low	96 to 100
Low	70 to 95
Medium	40 to 70
High	10 to 40
Very high	0 to 10

THE PRIMARY SOURCES OF FERTILIZER MATERIALS CONTAINING PHOSPHORUS

Source	Formula	K_2O	P_2O_5	MG	S	N
				%		
Superphosphate	$Ca(H_2PO_4)_2$		20		11	
Triple superphosphate	$Ca(H_2PO_4)_2$		40-46			
DAP	$(NH_4)_2HPO_4$		46			18
MAP	$NH_4H_2PO_4$		48-52			11
Ammonium Polyphosphate	NH_4PO_3		34			10
Rock Phosphate	PO_4		38			

Potassium

Each soybean plant
requires a minimum level of
raw materials for MEY production.

Functions of Potassium in Soybeans

One of those raw materials is potassium. Few soils are capable of supplying the potassium needs of high yielding soybeans for an extended period of time without recharging the soil reserves with fertilizer containing potassium.

Potassium performs a number of functions essential for plant growth, high seed yields, and profitable soybean production. It helps plants to better tolerate stress brought on by leaf, stem, and seed diseases. It improves nodulation for better nitrogen-fixation. It improves drought tolerance by controlling the opening and closing of leaf pores (stomates). Soybeans can benefit from including potassium in a balanced nutrition program for the following reasons:

- **enzyme activation** – involved in over 60 plant enzyme systems
- **photosynthesis** – helps turn sunlight, carbon dioxide, and water into plant sugars
- **respiration** – prevents excessive plant use of sugars destined for seed formation
- **translocation** – moves sugars into storage to avoid a slow-down in the rate of photosynthesis
- **starch formation** – helps convert sugars into starch for storage in seed
- **water use efficiency** – regulates leaf pore opening and closing to conserve water
- **protein synthesis** – helps to convert nitrogen into amino acids and quality proteins
- **disease resistance** – reduces stem, leaf, and seed diseases
- **grain quality** – fewer shriveled seeds and less dockage

Potassium Deficiency

Potassium deficiency and certain herbicide injury symptoms appear similar. Symptoms develop as irregular yellowing along the margins of older leaves since potassium is mobile and can be translocated to new growth regions. Deficiency is likely on sandy, low cation exchange capacity (CEC) soils, or where roots are restricted due to compaction, drought, nematodes, or stress due to crop injury. In high-yield fields, plant tissue analysis can help to detect potassium shortages. At first flower, the uppermost mature trifoliate leaf should contain between 1.5 and 2.5 percent potassium for optimum production.

Potassium Uptake and Utilization Patterns

Uptake patterns show clearly that soybeans need potassium every day. The amount will increase by growth stage until the seedlings have developed into mature plants. Total uptake in the above ground plant parts of soybeans yielding 50 bushels per acre would be about 135 pounds of K_2O, with about 70 pounds leaving the field in the seed.

New Jersey scientists determined where potassium concentrates as soybeans reach maturity and just prior to leaf fall, summarized in Table 6.

TABLE 6. TOTAL NUTRIENT ACCUMULATION IN SOYBEAN PLANT PARTS JUST PRIOR TO LEAF FALL

Plant part	Percent accumulation		
	N	P_2O_5	K_2O
Leaves	23	16	25
Petioles	3	6	14
Stems	8	14	22
Pods and seed	66	64	39

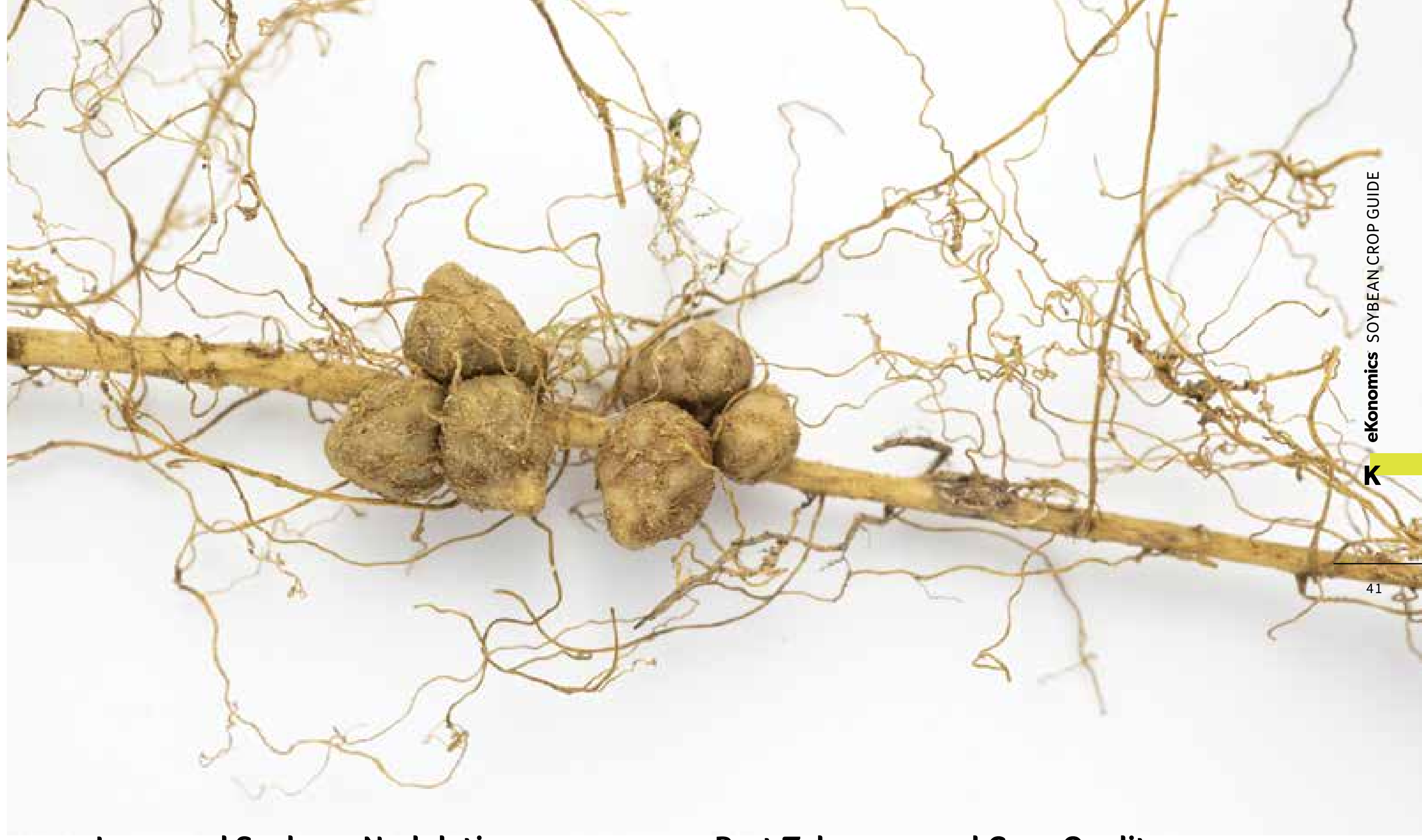
Determining Soybean Requirements for Potassium

Potassium required to grow a crop of soybeans is provided in part from the soil's nutrient reservoir and the remainder from the fertilization program. In addition, each soil will differ in its nutrient storage capacity and its ability to supply soybean nutrient needs throughout the growing season. Such differences exist in each and every field. They influence the time, rate, and method of application of potassium for highest nutrient use effectiveness.

Thus, certain basic ingredients are essential to formulating the fertilization program and then its method of delivery for optimum soybean response. These include recent soil analysis results (preferably following the harvest of the previous crop), nutrient uptake requirements for the desired soybean yield goal, knowledge of previous crop lime and fertilization practices, as well as an understanding of how potassium interacts with other nutrients and production practices.

Nutrient Interactions Are Yield and Profit Generators

Knowing how soybean nutrient needs change with grain yield helps in fine tuning fertilizer needs. Understanding how specific inputs, such as potassium, interact with other nutrients and production practices provides added opportunity for improved profitability. Some of the interactions involving potassium nutrition are well documented.



Improved Soybean Nodulation

Phosphorus plus potassium boosted nodule numbers from 365 to 1,090 per cubic foot of soil and increased yield from 24 to 46 bushels per acre. In another study, potassium improved yield, nodule numbers per plant, and seed protein production (Table 7).

TABLE 7. INFLUENCE OF POTASSIUM ON SOYBEAN YIELD AND NODULATION

K_2O, lbs./ac.	Yield, bu./ac.	Nodules /plant	Seed protein production, lbs./ac.
0	26	59	662
120	55	114	1,289

Pest Tolerance and Crop Quality

Proper potassium nutrition can improve tolerance to a variety of crop pests and stresses. For example, potassium improved susceptible variety tolerances to the cyst nematode and improved grain yield. Potassium has helped improve the effectiveness of some fungicides and by itself has provide some measure of greater plant tolerance to certain diseases. Potassium can improve tolerance to moisture and temperature stresses. During weather stress seasons, potassium helped keep shriveled, moldy, and purple-stained (cercospera) seed to a minimum (Table 8).

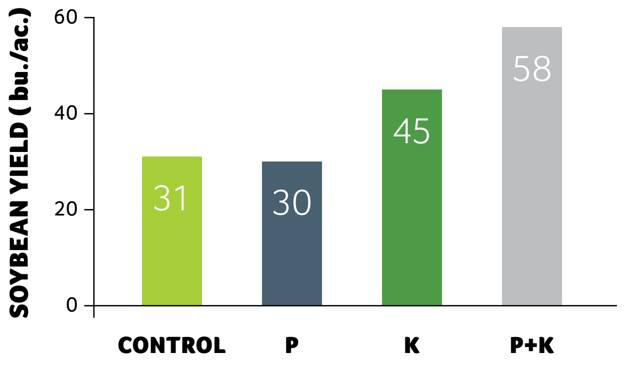
TABLE 8. POTASSIUM IMPROVES SOYBEAN YIELD AND SEED QUALITY

K_2O, lbs./ac.	Yield, bu./ac.	Shriveled/ diseased seed, %	Dockage, cents/bu.
0	38	31	54
120	47	12	22
Improvement	9 bushels	19%	$0.32 /bushel

Top Profit Yield

In one study, potassium combined with phosphorus and other high yield inputs improved grain yield on responsive soils. The boost from 40 to 50 bushels per acre provided for nearly a $2 return for each dollar invested in phosphorus and potassium (data not shown). On a lower potassium soil, the response was even greater.

PHOSPHORUS AND POTASSIUM NEARLY DOUBLE SOYBEAN YIELDS ON A RESPONSIVE SOIL



During Years of Moisture Stress Potassium Still Pays

Long term Ohio studies with soybean show response to potassium was greatest during years of moisture stress. Although potassium does not protect against extreme drought, it does combine with other top management inputs to minimize losses.

TABLE 9. SOYBEAN RESPONSE TO POTASSIUM UNDER MOISTURE STRESS

K_2O, lbs./ac.	Good year, bu./ac.	Moisture stress year, bu./ac.
0	56	35
50	59	44
100	60	52
Response to K	4	17

* Medium potassium soil test level. Ohio long term research.

TABLE 10. THE PRIMARY SOURCES OF FERTILIZER MATERIALS CONTAINING POTASSIUM

Source	Formula	K_2O	P_2O_5	MG	S	N
				%		
Muriate of potash	KCl	60-62				
Sulfate of potash	K_2SO_4	50			18	
Potassium magnesium sulfate	K_2SO_4-$MgSO_4$	22		11	22	
Potassium nitrate	KNO_3	44				13
Monopotassium phosphate	KH_2PO_4	34	51.5			

Sources of Fertilizer Potassium

The major sources of fertilizer potassium provide at least two nutrients essential for plant growth. See Table 10. Most are available in granular and soluble forms for best fit with either liquid or dry material fertilization programs. Although muriate of potash (KCl) is the dominant source for soybeans, other sources fill special crop needs by providing potassium, phosphorus, nitrogen, or available magnesium and sulfur.

Time and Method of Potassium Fertilization

Fertilizer potassium for soybeans can be applied preplant incorporated into the soil, broadcast on the residue covered soil surface of conservation tilled fields, placed at planting in a band below and to the side of the seed, sidedressed while the crop grows, through irrigation water systems, or in an emergency as a foliar applied product. The goal is to supplement soil potassium reserves with fertilizer to prevent potassium from becoming a soybean yield limiting factor.

Broadcasting potassium prior to primary tillage places it in the active root zone for optimum plant use efficiency. For sandy soils subject to potassium leaching, a split application, with half applied preplant and the remainder applied prior to first flower stage of growth often increases effectiveness. Where soybeans are double-cropped with a small grain such as wheat, some of the potassium can be applied to the previous crop where leaching and/or potassium-fixation is not a problem. Soybeans are good users of residual potassium left over from the previous crop.

Sulfur

Sulfur is often classified as the fourth major nutrient in plant growth.

Sulfur

Sulfur is often classified as the fourth major nutrient in plant growth. This essential element performs vital functions which allow legume crops, such as soybeans, to convert atmospheric nitrogen into high quality protein in the seed. Other functions of sulfur in soybean production are equally important and have resulted in a greater awareness of the need for sulfur in the fertilization program.

Sulfur is contained largely in the organic fraction of the soil and is released for plant use as organic materials decompose. Sulfur from other sources continues to decline as restrictions are placed on atmospheric sulfur emissions and as less sulfur is contained in high analysis fertilizers. At the same time, the need for sulfur has increased as soybean yields have steadily improved and as growers become more aware of the economic importance of using sulfur and how it functions within the soil and the plant.

The soybean plant requires sulfur for both vegetative and reproductive growth. Each plant must have a strong root system for nutrient and water absorption, a well nodulated root system for optimum nitrogen-fixation, and enough leaf area for photosynthesis to generate the sugars needed for full maturity and maximum development of quality seed protein and oil. Sulfur is a component of two of the 20 amino acids (cysteine and methionine) utilized in the synthesis of plant protein. It results in more effective use of nitrogen during protein synthesis. Sulfur helps maintain a high rate of photosynthesis. The disulfide bond is involved with stabilizing the three-dimensional structure of many enzymes which is necessary for enzyme activity.

Sulfur deficiency symptoms are seldom visible on high yielding soybeans. New growth will often develop light green leaves and stems under severe deficiency. In other cases plant growth rate will be less than optimum, and a deficiency can best be detected through plant tissue analysis for sulfur and nitrogen. Such shortages are most likely to occur on sandy, low organic matter soils in high rainfall regions. Other conditions that help to generate crop response include planting seed on cool, moist soils (minimum tillage) or where organic matter decomposition is slower. Sulfur in the sulfate form ($SO_4^{=}$) is subject to loss by leaching below the plant root system in very sandy soils.

The quantity of sulfur needed by soybeans is not the only measure of its importance to high yield, high quality protein and oil formation. The primary objective is to insure that each plant has access to sulfur in the amount needed during each growth stage. This can be difficult since factors other than soil reserves influence availability and crop use. Some of these external forces that can prevent plant use of available sulfur include soil compaction, stress due to drought, or by tissue injury by insect and/or disease problems.

Soybean requirement for sulfur, based on research at two yield levels, is about 25 pounds per acre at the 50 bushel per acre level and nearly 35 pounds when yields approach 100 bushels per acre. As with nitrogen, sulfur must be available all season long. It is needed for effective use of nitrogen where nearly 70 percent must be available from full bloom through pod filling to mature seed. The distribution of sulfur in vegetation and seed reveals that nearly one pound of sulfur is contained in each five bushels of soybean seed removed from the field.

Sources of sulfur available for use in agriculture are presented in the Table 11. Elemental sulfur and sulfur as a coating on urea are not readily available for plant use and must first be converted to the $SO_4^{=}$ form by soil microorganisms. Availability of sulfur from gypsum (calcium sulfate) will be slower than water soluble sources such as ammonium sulfate, potassium sulfate or sulfate of potash magnesia (K-Mag). New sulfur-enhanced phosphate fertilizers, like Nutrien's MAP+MST can be a good way to supply phosphorus and sulfur in the same homogenous granule. Micronized sulfur in MAP+MAT oxidizes faster than other elemental sulfur fertilizers.

Crop response to the application of sulfur can be very site-specific. High response areas can be characterized as highly productive, but very sandy (low CEC), low organic matter soils in high rainfall regions. Such soils contain a very limited residual amount of sulfur which is also subject to loss from the root zone by leaching. Thus, a general application of 20 to 30 pounds of sulfur per acre is often recommended for each cropping season. To minimize leaching losses and to insure late season availability, about half of the sulfur can be preplant applied with the remainder applied sidedress with potassium prior to early pod fill. Slow-release sulfur sources, like Nutrien's MAP+MST, are also effective in reducing leaching losses of sulfur.

Sulfur nutrition is a management controlled production input and should not be a yield, quality, or profit limiting factor. It is an essential part of a balanced nutrition program designed to generate optimum soybean yield and profitability.

TABLE 11. COMMON SOURCES OF SULFUR

Source	Formula	% S
Ammonium sulfate	$(NH_4)_2SO_4$	24
Ammonium thiosulfate solution	$(NH_4)_2S_2O_3 + H_2O$	26
Elemental sulfur	S	85
Gypsum	$CaSO_4 \cdot 2H_2O$	12-18
Magnesium sulfate	$MgSO_4 \cdot 7H_2O$	14
Potassium sulfate	K_2SO_4	18
Potassium thiosulfate	$K_2S_2O_3$	17
Potassium magnesium sulfate	$K_2SO_4 \cdot 2MgSO_4$	10
Sulfur coated urea	$CO(NH_2)_2$+S	10

Calcium and Magnesium

Soybean calcium and magnesium nutrition is tied to liming for soil pH management.

Calcium and Magnesium Nutrition of Soybean

Calcium and magnesium are each essential to successful soybean growth. A 50 bushel crop will contain nearly 75 pounds of calcium and 32 pounds of magnesium per acre in the above ground plant parts. At maturity, nearly 15 pounds of the magnesium will be in the seed and removed from the field. Plant tissue analysis (uppermost mature trifoliate leaves) at first flower provides an indication of the calcium and magnesium status of the crop. The sufficiency range for calcium is 0.6 to 1.4 percent while sufficient magnesium would exist between 0.3 and 0.8 percent. Calcium and magnesium nutrition of soybean are closely tied to liming for pH management. In properly limed soils, additional calcium is rarely needed, although magnesium supplementation may be needed if calcitic lime is used and magnesium is low, and/or high potassium rates are applied.

The basic functions of calcium and magnesium for optimum soybean development are well documented by research. Calcium provides structure for cell walls, improves the uptake of other nutrients, helps to activate growth regulating enzyme systems, neutralizes natural occurring plant organic acids, and improves plant resistance to disease. Magnesium is also needed for cell division and activation of enzyme systems. In addition, magnesium serves as the central atom in the chlorophyll molecule and is key to the photosynthetic process. It also is involved with protein formation, phosphorus metabolism, seed formation, and plant respiration.

Visible deficiency symptoms for calcium are rare since the lime program essential for adjusting soil acidity usually provides an adequate level of calcium. Magnesium deficiency, however, is more prevalent in soybeans on sandy soils in high rainfall regions and that receive high yield management. This can be due to the fact that magnesium can be leached below the soybean root zone on sandy soils, high yields require a higher rate of available magnesium, and to the competitive influence of potassium on magnesium absorption by soybean roots. A visible deficiency of magnesium usually exists as an interveinal chlorosis of the older soybean leaves. When the deficiency is marginal, plant tissue analysis will be required to identify deficient regions in the field.

Dolomitic limestone does not always provide the needs of high yield soybeans. When soil pH is above about 6.2, the availability of magnesium from liming materials declines, and the need for soluble sources can develop. These sources can provide the needs for magnesium when in-season deficiencies are detected, when soil potassium levels are very high, or when liming materials are applied to low magnesium soils just prior to planting. Common magnesium sources include magnesium sulfate (20 percent), magnesium sulfate or epsom salts (9.8 percent), potassium-magnesium sulfate (11 percent), kieserite (17.5 percent), and dolomitic limestone (6 percent).

Liming

Liming to adjust soil acidity to a pH of 6.5 to 7.0 is a management practice essential for high soybean seed yield and profitability. This fundamental practice will reduce the detrimental effects of excess iron, aluminum, and manganese. It will provide calcium and magnesium (from dolomitic limestone) for plant growth. It improves the availability and plant use effectiveness of many of the essential nutrients and certain herbicides. It increases Bradyrhizobia effectiveness and tends to increase crop residue production resulting in improved soil structure and biological activity.

The effectiveness of limestone materials is dependent on two major characteristics. The particle size or fineness of grind will determine the rate of reaction with soil acidity. The smaller the particle size, the greater the surface area exposed to soil acidity and the faster will be the reaction to neutralize the soil acidity. The second feature relates to the chemical make-up, purity, and neutralizing value of the specific liming material. The neutralizing value of each liming material is expressed as a percentage of the neutralizing effectiveness of pure calcium carbonate. Thus, an effective liming material will neutralize soil acidity by the reaction of either the carbonates, oxides, or hydroxides from the lime source with hydrogen (H) on the soil cation exchange complex to form water and carbon dioxide. The calcium and magnesium (dolomitic stone) then replace hydrogen and become available for plant absorption.

Soil testing has proven reliable in determining the quantity of limestone required to adjust the soil pH to the desired range for soybean production. For best results, apply the limestone and incorporate it into the soil where the soybean root system and nodules will be developing. Apply the limestone at least three months before planting to allow the liming material enough time to dissolve and to neutralize the soil acidity. Where magnesium is believed deficient and either calcitic or dolomitic limestone is applied close to seeding, consider applying a soluble source of magnesium in the fertilization program.

TABLE 12. NEUTRALIZING VALUE (CALCIUM CARBONATE EQUIVALENT, %) OF AGRICULTURAL LIMING MATERIALS

Source	%
Pure calcium carbonate	100
Dolomitic limestone	95-108
Calcitic limestone	85-100
Calcium hydroxide (slaked lime)	120-135
Calcium oxide (burnt or quick lime)	150-175
Basic slag	50-70
Marl	50-90
Wood ashes	40-50
Gypsum (land plaster)	0
Various byproducts	40-90

Calcium and magnesium nutrition of soybean are closely tied to liming for pH management.

Micronutrients

Micronutrients are required
in relatively small
amounts but can produce
impressive results.

Micronutrients

Six of the 17 elements essential for plant growth (zinc, manganese, copper, molybdenum, boron, chloride, and nickel) are absorbed by soybeans in amounts less than a half pound per acre. The seventh element, iron, is taken up at rates between 1 and 2 pounds per acre (Table 13).

With high yield soybeans, there will be a greater need to consider micronutrients as an integral component of the complete nutrient management program. Iron, molybdenum, zinc, and magnesium are the micronutrients most likely to be deficient in soybean production in North America. With the exception of chloride and molybdenum, the availability of these nutrients generally decreases with an increase in soil pH.

TABLE 13. APPROXIMATE MICRONUTRIENT UPTAKE FOR THE PRODUCTION OF HIGH SOYBEAN YIELDS (60 bu./ac.)

Micronutrients (lbs./ac.)	
B	0.10
Cu	0.10
Fe	1.70
Mn	0.60
Mo	0.01
Zn	0.20
Ni	—

From Martens and Westerman (1991), citing Mengel (1980), in Micronutrients in Agriculture.

Functions of Micronutrients in Plants

The listing of the specific functions of the different micronutrients helps explain why it is often difficult to detect deficiencies. The listing in Table 14 also helps to target the plant part where a deficiency is most likely to occur.

Availability of Micronutrients in Soil and Determination of Micronutrient Needs

Maintenance of the soil pH in the optimum range of about 5.8 to 6.5 will help prevent many micronutrient imbalances. If the soil pH drops to 5.2 or lower, manganese can become toxic. At pH levels above 6.5, the availabilitities of iron, zinc, and manganese are reduced. Coupling field history with knowledge of extractable soil micronutrient levels and soil pH can help in the development of a micronutrient management program.

The total concentration of a micronutrient in the soil is not a good indicator of plant availability. Some micronutrient soil tests have been developed and calibrated for specific regions (e.g. Mehlich 1 or 3, DTPA, AB-DTPA, Modified Olsen's, hot water extraction, etc.), which can aid the diagnosis and prevention of deficiencies. Micronutrient management for soybeans should consider the extractable soil levels, soil acidity, soil moisture and temperature, soybean variety (genetics), and interactions with other crop production inputs. The best way to diagnose micronutrient deficiencies, and to assess the need for micronutrients, is to use regionally calibrated soil tests along with plant tissue analyses. Plant tissue analyses can be used to diagnose nutrient deficiencies and to monitor the crop's nutrient status. Monitoring can help point out existing or potential problems before visual symptoms develop.

Micronutrient Fertilization – Methods, Sources, and Rates

To avoid micronutrient deficiencies, banded soil applications are often preferred over broadcast applications. In other instances, foliar sprays are used to prevent or correct deficiencies of specific micronutrients. Care should be used, especially with soil banded and foliar applications, because of the relatively narrow range between sufficiency and toxicity for many of the micronutrients. In many regions of North America, when the soil pH is 6.5 or lower, molybdenum is recommended as a seed treatment prior to planting, at rates of 0.2 to 0.4 ounces per acre. Extreme caution should be used with molybdenum treated seed to ensure that it is not fed to livestock. Forage/feed with greater than 10 ppm molybdenum can be toxic to ruminant animals. With the exception of molybdenum, all other micronutrient applications should be targeted to the soil and/or foliage.

Iron, manganese, and zinc are often applied as sulfate salts or as chelates (e.g., FeEDDHA, MnEDTA, ZnEDTA). Banded applications of these nutrients may include 1 to 5 pounds per acre of the nutrient with an acidifying fertilizer. Care should be taken to avoid direct seed contact. Higher broadcast rates are usually required, compared to banded rates, and often range from 4 to 15 pounds per acre or higher. Because of the soil chemistry involved, broadcast soil applications of inorganic iron are frequently ineffective, except at relatively high rates, and are not generally recommended. Research indicated that when MnEDTA was applied as a starter fertilizer in the row, soybean yield decreased as a result of displacement of manganese on the chelate by iron, which increased iron uptake and decreased manganese uptake.

Chelated sources, lignosulfonates, oxides, oxysulfates, and frits can also be effective in preventing micronutrient deficiencies. The rates and timing

TABLE 14. THE FUNCTIONS OF MICRONUTRIENTS IN PLANT DEVELOPMENT

Plant growth function	B	Cl	Cu	Fe	Mn	Mo	Zn
Enzyme systems			●	●	●	●	●
Protein formation	●		●	●		●	●
Hormones and cell division	●						●
Chlorophyll formation			●	●	●		
Disease resistance		●					
Photosynthesis		●		●	●		
N, Fe and/or P metabolism	●		●	●	●	●	●
Crop maturity		●					
Seed formation	●		●				●
Sugar/starch translocation	●	●					●

of these, and the other sources mentioned, are governed by soil and climatic conditions. Oxides, oxysulfates, and frits have varying degrees of efficacy because of low water solubility and reduced availability in soil and may need higher application rates to achieve desired results. Considerable research has shown low water solubility to limit micronutrient fertilizer efficacy. Care should be exercised with all sources to avoid phytotoxicities. Selection of the source should consider these factors, compatibility with N-P_2O_5-K_2O and other fertilizers, and cost.

Typical rates for foliar applications of iron, manganese, and zinc range from 0.2 to 1.0 pounds per acre per application, with one or two repeat applications. Foliar applications are typically made during the early vegetative growth stages (V4-V8) to as late as the early reproductive stages (R1-R3). Foliar iron should be applied very early, often at first trifoliate, to be effective. Multiple applications may be required.

Soybeans are thought to have lower boron requirements than sugarbeets and cotton. Infrequent responses have been observed in past research. Recent work in the south has indicated that the addition of boron, with foliar sprays of certain insecticides used to control leaf and pod-feeding insects, may contribute to yields greater than those achieved by the insecticide alone. Ongoing research may result in refined recommendations for soybeans.

All possible inputs of micronutrients (fertilizers, manures, irrigation waters, etc.) should be considered when developing a micronutrient fertilization program for high-yielding, high-quality soybeans. If soil and plant tissue tests indicate fertilization needs, appropriate rates, methods, and timing should be used to provide optimum nutrition and minimize potential phytotoxicity.

Courtesy of IPNI

Soybean Zn deficiency symptoms including whirling and interveinal chlorosis.

Conclusion

An increasing world population and greater interest in a balanced, nutritious diet will result in continued growth in world demand for soybeans and soybean products. Soybean yields have steadily increased in the last 40 years, and will continue to increase as a result of improved genetics, biotechnology, and improved management. Crop nutrient management must be improved on many acres in North America to allow the soybean producers to MEY, and to sustain those yields, while providing high quality soybeans to the market.

Management practices continue to evolve through research, farmer experiences, and technology advancements. Today's soybean grower has access to more technology and information and more opportunities and challenges than ever before. As the global soybean market requires that growers become more astute in capitalizing on market trends, more expertise will be needed to assist with crop production input management. Growers are paying more attention to soybean management to take advantage of soybeans' profit potential. Systematic approaches will utilize the best information and technological support available.

High yield management, to lower unit costs, will provide the greatest opportunities and flexibility in developing marketing strategies. High yield management should center around integrated best management practices (BMP), including forward-looking nutrient management plans. Other key components of successful high yield management include:

Good records

Good records – preferably those that can be easily accessed and readily interpreted – provide a snapshot of the present, a concise look at the past, and a guide to the future. More information can be stored and retrieved now than in the past with the aid of site-specific technology tools. These records, preferably computerized, require agronomic and economic expertise to be used to their fullest advantage. Sound agronomic interpretation of the large amounts of data being collected is key to taking full advantage of data-collection technology.

Realistic yield goals

While realistic yield goals may seem more important for rotational crops like corn or wheat, they contribute to sound soybean nutrient input decisions. Yield goals that are 10 to 15 percent higher than past yield averages are a good starting point.

Variety selection and seeding rates

Once site specific yield constraints are determined, varieties can be selected which are more tolerant of the identified constraints or which are more responsive to higher inputs. Seeding rates can be adjusted for parts of fields where germination may be historically poor due to poor soil physical conditions, wetness, drought, or other factors.

Conservation tillage for maximum soil productivity

With glyphosate tolerance now available in many commercial varieties, there is an increasing opportunity to limit tillage on many acres to reduce soil loss, minimize compaction, and to improve tilth. With more zone tillage and no-tillage, nutrients stratify closer to the soil surface which can affect uptake efficiency. The interactions among tillage systems, moisture and nutrient availability, crop yields, and soil productivity will need to be taken into account.

Crop rotation

Rotating soybeans with corn has provided yield advantages of 10 to 15 percent for both crops. Where soybean is double-cropped with wheat or other crops, there is an increased nutrient demand with greater harvest removals of nutrients. Nutrient additions must be kept in balance with harvest removal and increased yield potential for all crops in the rotation.

Integrated pest management

Good weed control programs allow soybeans to maximize response to other production inputs. Insect and disease control, through integrated pest management and resistant or tolerant variety selection, enables growers to gain the maximum return on their nutrient investment.

Irrigation/drainage management

Site-specific yield monitoring is showing that poor surface and/or internal drainage is robbing yields in many fields. Where irrigation is practiced, irrigation management is being improved through land shaping and installation of field drains to accommodate surplus water. With improved moisture management, yields are increasing as well as harvest removals of nutrients.

Diagnostics/crop monitoring

Tissue analysis and other tools can help identify "hidden hunger" before substantial yield losses occur.

Regular field scouting, to include tissue analysis, is a BMP that frequently pays dividends. Growers have the ability to couple crop scouting records with input and yield records through geographic references. Yield variability can be better explained and can be accurately quantified. Management changes can be evaluated based on hard data.

Nutrient management is one of the many different yield-determining factors that a soybean producer faces and must learn to master. Integrating nutrient management as a central component in the crop production system will help ensure that MEY can be reached and that soil and water resources are protected.

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