Corn

Nutrient Management Guide



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Nutrien
Feeding the Future

The production of high-yielding, quality corn requires sound management, appropriate soil conditions, balanced nutrients, adequate moisture and heat, effective pest control, and a carefully selected hybrid. Although this booklet focuses on nutrient management for maximum economic corn production, the importance of other yield-determining factors must not be overlooked.



Corn

History

Corn (*Zea mays L.*) is indigenous to the Western Hemisphere, believed to have originated in Mexico. The earliest record of corn dates to about 5000 B.C. and shows that even at that time, it was totally dependent on man for its survival.

Corn is one of the most adaptable and variable members of the grass family, with biotypes adapted to climates from the tropics to the north temperate zone, from sea level to 12,000 feet elevation and growing periods (planting to maturity) from six weeks to 13 months. The hybrid yellow dent corn that dominates the U.S. Corn Belt, Canada, and Europe is derived from highly selected varieties from eastern North America and developed by carefully planned and documented inbreeding and hybridization.

In addition to the more widely grown yellow dent corn, special varieties of corn have been developed for specific uses like popcorn, sweet corn, or varieties with special genes for types of starch, sugar, protein, oil, etc., bred to meet specific food or industrial uses.

Uses of Corn

Each fall, North American farmers harvest more than 14 billion bushels of corn. Roughly 40 percent of the crop is used to produce fuel, 35 percent is used as animal feed, and 15 percent is exported.

Nearly 2 billion bushels of corn are processed annually by the corn wet milling industry. Wet milling involves soaking corn in warm water, a process known as steeping. The steep water is drawn off, and the softened kernels go to de-germinating mills and separators, where the germ is removed and its oil extracted. The remaining parts – starch, gluten, and hulls – are ground and passed through screens for hull removal. The starch and gluten are then separated, and the starch is washed and dried to be used as starch or converted into sweeteners or ethanol.

Production practices for corn are generally the same, whether grown for livestock feed, food, or industrial uses. As specialized varieties become more significant, there may be reasons to adjust practices for specific types.



The Many Uses of Corn

2% **Food**
Americans eat little whole kernel corn, but it is consumed in processed foods.

2% **Starch**
This extract thickens foods and is used in numerous industrial products, such as biodegradable plastics.

1% **Beverage and Alcohol**
Corn-derived alcohol is used for some directly consumed beverages.

3% **Sweeteners**
Corn syrup is used as a replacement for sugar in a host of products, like soda and candy.

34% **Animal Feed**
Feed for cattle, hogs, and poultry continues to be a large market for corn.

38% **Fuel Alcohol**
Ethanol is used as a fuel or a fuel additive.

14% **Exports**
The U.S. is the largest exporter of corn in the world.

10% **Ending Stocks**
Corn held at year's end provides a sustained food supply in bad crop years.

The Kernel
Extract from the germ is used as cooking oil. Versatile starch can be a food, a component in building materials, or can be converted to ethanol fuel or corn sweeteners. The hull, or shell, is high in protein and is an important source of livestock feed.



Geographic Distribution of Corn

Though a probable native of Mexico, corn is now grown throughout much of the world. Table 1, Corn Production in Major Growing Countries, indicates that the U.S. produces approximately 25 percent of the world supply.



TABLE 1: CORN PRODUCTION GLOBALLY.

	2020/2020	2021/2021	2022/2023 (proj)	
			Jan	Feb
Country	Million Metric Tons			
United States	358.45	382.89	348.75	348.75
China	260.67	272.55	277.2	277.2
Brazil	87	116	125	125
Canada	13.56	16.61	14.54	14.54
India	31.65	33.6	32	32
Indonesia	12.6	12.7	12.9	12.9
Mexico	27.35	26.76	27.6	27.6
Russian	13.87	15.23	14	14
Ukraine	30.3	42.13	27	27
Others	68.68	70.98	67.67	67.7
World Total	1,129.50	1,216.00	1,155.93	1,151.36

Source: Foreign Agricultural Service/USDA 3 February 2023 Global Market Analysis.

What Can You Get From a Bushel of Corn?

A typical bushel of corn weighs 56 pounds and contains approximately 72,800 kernels. Most of the weight is the starch, oil, protein, and fiber, with some natural moisture.

Just a sampling of products that can be extracted from a bushel of corn:

- 32 pounds of starch
- 33 pounds of sweetener
- 2.5 gallons of fuel ethanol
- 11.4 pounds of 20-percent gluten feed
- 3 pounds of 60-percent gluten meal
- 1.6 pounds of corn oil



Nutrient Content

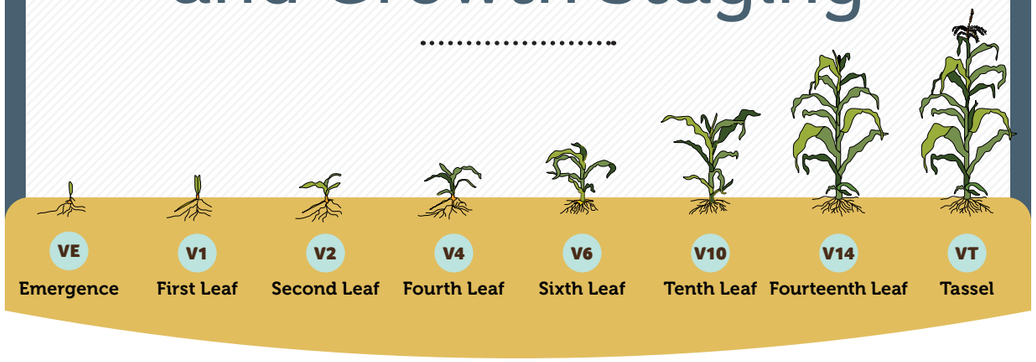
A corn crop producing 180 bushels per acre absorbs a total of ~530 pounds per acre of nitrogen, phosphorus, and potassium, plus various secondary nutrients and micronutrients (IPNI Estimates of Nutrient Uptake and Removal). The list on the right shows the total nutrients typically absorbed in producing a 180-bushels-per-acre corn crop. The amount of nutrients removed in the crop depends upon what parts of the plant are harvested. Most corn is harvested as grain, but if the crop is harvested as silage or if the stover is also removed, the amount of nutrients taken from the field will be substantially greater. A nutrient management plan for the corn crop must provide adequate levels of all nutrients at all stages of growth and account for the replacement of the total amounts of each nutrient removed in the harvested crop.

Corn removes approximately 0.67 pounds nitrogen, 0.35 pounds phosphorus pentoxide, and 0.25 pounds potassium oxide for each bushel of grain harvested (IPNI Estimates of Nutrient Uptake and Removal).

180 bushels per acre corn absorbs:

- ~180 pounds per acre nitrogen
- ~97 pounds per acre phosphorus pentoxide (P_2O_5)
- ~252 pounds per acre potassium oxide (K_2O)

Corn Development and Growth Staging



Vegetative

VE Emergence

The first leaf or the spike leaf appears above the ground. The seed absorbs water and oxygen for fermentation. The radicle root emerges from the tip of the kernel. Soil temperature should be 50-55 degrees Fahrenheit with moisture present for optimal emergence. Planting depth is critical for this stage – too deep can delay emergence and too shallow can create a weak plant.

V1 First Leaf

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.

V2 Second Leaf

Nodal roots are emerging farther into the ground and seminal roots begin to grow.

V4 Fourth Leaf

Nodal roots are farther in the ground and take up more volume. Leaves are developing off the stem of the plant. At this point of growth, the leaves are primarily growing more than the root system.

V6 Sixth Leaf

Six leaves with collars have formed. The growing point emerges above the soil surface, height increases, and nodal roots are established in the lowest below-ground nodes of the plant. Scouting is suggested at this stage for weeds and pests. Nutrient uptake begins to increase rapidly, and nutrient application should be timed properly. Ear and tassel shoots begin forming, so nutrient deficiencies at this stage can impact later yields.

V10 Tenth Leaf

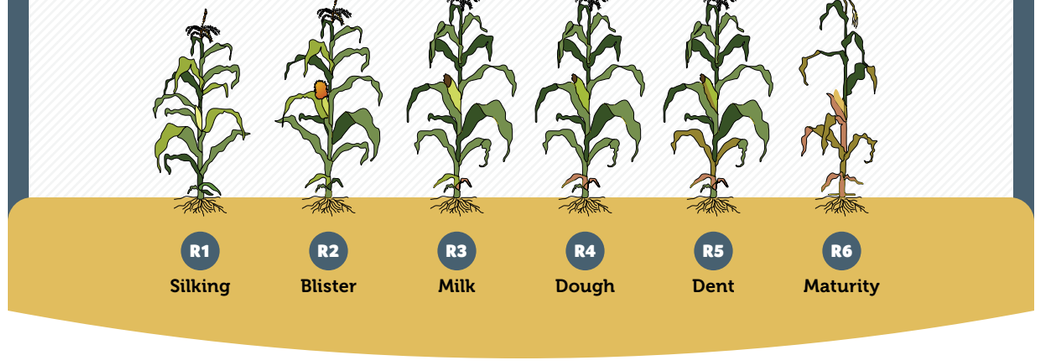
During this stage, brace roots have developed in the lower above-ground nodes. Nitrogen and water demands are at their highest, and plants are easily susceptible to drought, heat, and nutrient deficiencies. Weed control is critical during this stage of growth because of early competition. Maximum number of rows per ear is being determined at this time. The number of potential maximum kernels per row is determined from about this stage to tasseling (VT).

V14 Fourteenth Leaf

Rapid growth happens during this stage. Flowering will begin in approximately two weeks. Plants are sensitive to heat and drought stress. Growers should scout during this stage for root lodging issues and diseases.

VT Tassel

Kernels start developing in rows, and the final potential ear size is determined. The last branch of the tassel is visible. Silks may or may not have emerged. Nitrogen and water demands are high for the crops. Heat and drought will affect the number of kernels. During this stage, growers should scout for insects and diseases.



Reproductive

R1 Silking

During this stage, flowering begins and silk is visible on the outside of the husks. The first silks are attached to potential kernels near the base of the ear. Maximum plant height is achieved, pollination is occurring and the potential number of kernels is being determined. Nutrient needs are high for fertilization.

R2 Blister

At this stage, silks darken and are drying out. Kernels are about 85 percent moisture and will soon fill with starch. Environmental stress can reduce yield potential and final grain count.

R3 Milk

Silks are dried out. The kernels are turning yellow and a milk-like fluid can be squeezed out of the kernels. Any stress at this point will cause kernel abortion at the tip of the ear.

R4 Dough

Starch materials inside the kernels have a dough-like consistency. Nutrients and starch are accumulating, with kernels being at 70 percent moisture. Environmental stress at this point can cause reduced yield by reducing kernel size and cause kernels to be shallow or chaffy. Impact of frost on grain quality can be severe with 25 to 40 percent yield reduction.

R5 Dent

At this stage, most of the kernels are dented. Moisture is declining to about 55 percent. Stress will reduce kernel weight. Many growers will harvest for silage soon.

R6 Maturity

At maturity, a black layer forms at the bottom of the kernel, blocking any movement of dry matter and nutrients from the plant to the kernel. Kernels will be around 30 to 35 percent moisture and are physiologically mature. At this stage, grain is not ready for storage, but maximum dry weight has been attained. Disease and pests can result in physical damage and grain loss. Scouting is suggested for ear drop from pest damage.

Growth Stages of Corn

Corn hybrids typically grown in the North American Corn Belt require from 85 to 125 days to reach maturity. In general, the full-season (120 to 125 days) hybrids will have a higher yield potential. However, good hybrids in the earlier maturity categories have been developed and have helped to move the boundaries of the Corn Belt farther north. These same hybrids can be useful in the central Corn Belt to provide flexibility in planting date or to get an earlier start on harvest. Usually the best yields are obtained with hybrids selected for a full-season maturity for the given growing region, because they make the most efficient use of the growing season resources.

Table 2, Vegetative and Reproductive Stages of a Corn Plant, illustrates various growth stages of corn, which have been designated as a tool to help guide scouting and management decisions. Pest management recommendations, hail damage assessment, nutrient deficiency assessment, and other growth-related decisions depend on having a standardized growth staging system.

Nutrient Uptake Pattern

The relative amounts of nutrients taken up at each stage of growth will differ. Nearly 70 percent of the nitrogen, 50 percent of the phosphorus pentoxide, and 70 percent of the potassium oxide used by the crop are taken up by the time the ears are pollinated, which is usually about the mid-point of the growing season. Table 2, Vegetative and Reproductive Stages of a Corn Plant shows the relative timing of uptake of major nutrients and nutrient partitioning within the plant at specified growth stages. (Bender et al., 2014).

TABLE 2: VEGETATIVE AND REPRODUCTIVE STAGES OF A CORN PLANT.

Growth Stage							
Plant Part	**V2**	**V4**	**V10**	**V14**	**VT/R1**	**R4**	**R6**
Percent of Total Uptake							
Nitrogen							
Leaves	1	2	15	37	42	35	23
Stalk	2.5	5	8	21	28	17	13
Tassel/cob	0	0	0	0	5	8	6
Grain	0	0	0	0	0	23	58
Phosphorus							
Leaves	1	2	9	22	27	21	12
Stalk	0	1	4	13	20	14	6
Tassel/cob	0	0	0	0	4	8	2
Grain	0	0	0	0	0	24	80
Potassium							
Leaves	2	4	12	32	37	30	24
Stalk	1	3	11	22	32	24	29
Tassel/cob	0	0	0	0	5	16	14
Grain	0	0	0	0	0	17	33
Sulfur							
Leaves	2	3	11	28	32	29	27
Stalk	1	1	4	13	18	14	11
Tassel/cob	0	0	0	0	4	8	6
Grain	0	0	0	0	0	25	57

+50% of nutrient has been absorbed by the crop.

Nutrient Management

Nutrient management planning is becoming increasingly important in achieving high yields and profitability. Concerns for improved nutrient utilization efficiency, agronomic response, and environmental stewardship require that nutrient applications – from fertilizers, manures, or as industrial byproducts – be based on sound scientific principles. Proper credits should be given for current soil nutrient levels, the anticipated release of nutrients in the soil from recent past applications of manure or byproducts, the decomposition of legumes or other cover crops, and the addition of nutrients in irrigation waters. Nutrient management plans can be relatively simple or very complex. Good nutrient management plans include:

- Field information that identifies soil types and important characteristics that may require nutrient management adjustments, e.g., excessive drainage, poor drainage, rooting depth, available soil moisture, slope, erosion, etc.
- Recent soil test results (within the last two to three years)
- Past cropping history and yield records
- Nutrient sources available for use and their nutrient content
- Application placement and timing appropriate for the cropping and tillage system, and anticipated release rates (if derived from organic sources)
- Realistic yield goals for the planned crops and anticipated crop nutrient removal
- Appropriate environmental nutrient management considerations, (e.g. sandy soils with shallow groundwater, strongly sloping soils adjacent to sensitive water bodies, etc.). If grassed waterways or filter strips are present or planned, the nutrient management plans may also consider ways to maintain these areas for their optimum performance in collecting and filtering sediments and nutrients

Every nutrient management plan should be periodically reviewed and be flexible to ensure that targeted agronomic, economic, and environmental objectives are being satisfied.



Soil Sampling and Testing

Representative soil samples and tests are the foundation of a successful nutrient management plan. Each area in the field with distinctive differences in soil productivity/crop yield potential should be sampled separately. Soil tests can be reviewed and combined with yield results and yield goals to develop a site-specific nutrient management plan. Combining geographic information systems and agronomic knowledge, nutrient applications can be made to specific parts of fields that are most likely to respond or where fertility levels need to be built. With accurate yield monitoring records, nutrient additions can be adjusted to account for unusually high nutrient removal or for surplus levels in specific field locations.



Soil Sampling Techniques

Since wise nutrient management depends on a reliable soil-test result, accurate soil sampling is essential. Samples are usually collected from the plow depth, 0 to 6 inches or 0 to 8 inches deep (depending on laboratory calibrations and recommendations), for conventional tillage and for reduced tillage systems, including no-till. Because of the potential rapid acidification in the upper few inches of undisturbed soil in no-till systems, separate soil samples should also be collected from 0 to 2 or 0 to 4 inches deep every two to three years, to better monitor the need for agricultural limestone (see the section on liming).
If fertilizer phosphorus and/or potassium are banded, one soil core in the band should be collected for every 20 cores between bands, if crop rows are greater than 30 inches apart. If crop rows are less than 12 inches apart and fertilizers have been banded, one soil core should be collected in the fertilizer band for every eight samples between bands. If the fertilizer band location is not known, samples should be collected randomly. Soil samples need to be collected at the same time from year to year, at a similar soil moisture and soil temperature, to permit better tracking of trends.

Representative soil samples and tests are the foundation of a successful nutrient management plan.

Isolating irregular areas will improve the quality of a soil test:

- Eroded knolls
- Old stack bottoms or manured areas
- Entrance and edges of fields
- Waterways, depressions, or wet areas
- Alkaline or saline areas

Recommendations

Soil testing laboratories are operated by private businesses, universities, and some fertilizer companies. The soil-testing methods and the fertilizer and lime recommendations will often vary among labs. Fertilizer recommendation approaches commonly observed among labs include the soil buildup and maintenance approach and the nutrient sufficiency approach.
The buildup and maintenance approach promotes sufficiently high fertilizer rates to raise soil-test levels over a relatively short period: one to two or two to five years. This is followed by annual application recommendations to maintain soil-test levels by adjustments for crop removal. Soil-test levels are usually built high enough to make the nutrient non-limiting, even if fertilizer is not applied. The sufficiency approach is similar to the buildup and maintenance approach, except that the buildup of soil fertility is usually much slower, and the soil-fertility level is built to a lower level. The target soil-fertility level is low enough to make crops dependent on annual fertilization for optimum yields. Economic considerations, land tenure, and other management factors of individual growers determine which approach is most appropriate.

If no phosphorus was applied to a soil testing high to very high in phosphorus, in a corn-soybean rotation, soil-test phosphorus would usually decline two to three parts per million per year. Soil-test potassium levels will often drop by five to eight parts per million per year without potassium applications. Substantial yield losses can occur if soil-test levels are allowed to decline below optimum levels. It may take several years of higher fertilizer rates to restore optimum productivity. Sampling on three-to-four-year intervals is considered sufficient for most situations to monitor fertility needs and to guard against nutrient mining.

Site-Specific Systems

There are multiple approaches to site-specific agriculture. Grid-based approaches (practiced at multiple resolutions – e.g., 5 acre grids, 2.5 acre grids, 1 acre grids, etc.) are utilized as well as management zone-based approaches dependent upon soil survey information, yield maps, electrical conductivity mapping, etc. Each of these different approaches has their merits and their drawbacks. One thing to keep in mind when selecting a zone size is that finer resolutions can help identify optimum resolutions (one can actually scale to a coarser resolution), but coarse-textured resolutions cannot be used to identify optimum finer resolutions. So if one is considering a site-specific approach, initially a finer resolution would be preferred (obviously depending upon availability of operating capital to pay for it).

The question often asked is, “What is the optimum approach to nutrient management? Grid or zone? What size grid?” The unfortunate answer is that it depends. Different agronomists have different approaches that are favored. Generally, greater field variability favors more detailed sampling. One may also consider the ability to manage smaller areas. The size of field grids that can be managed may be used to guide the detail of sampling. The only way to know which approach/resolution is right for a given field is investigation.

The first goal of site-specific management is to characterize a field in order to accurately identify areas that require different management practices.

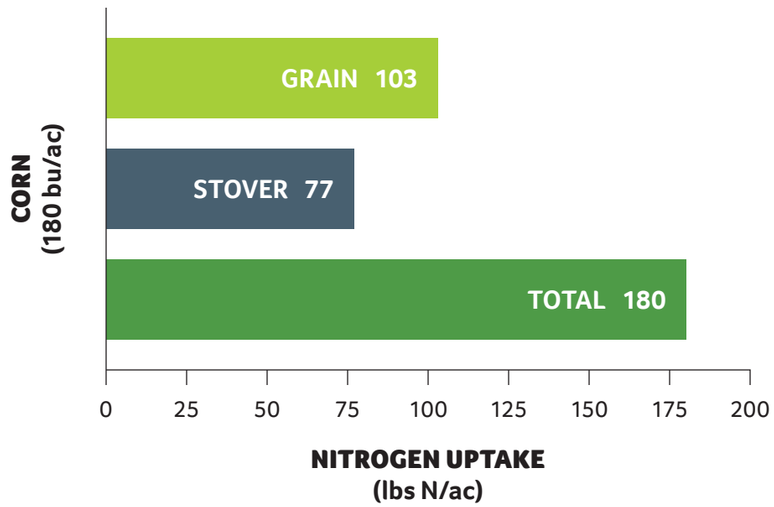


During the growing season, it is important to keep records of all production practices.

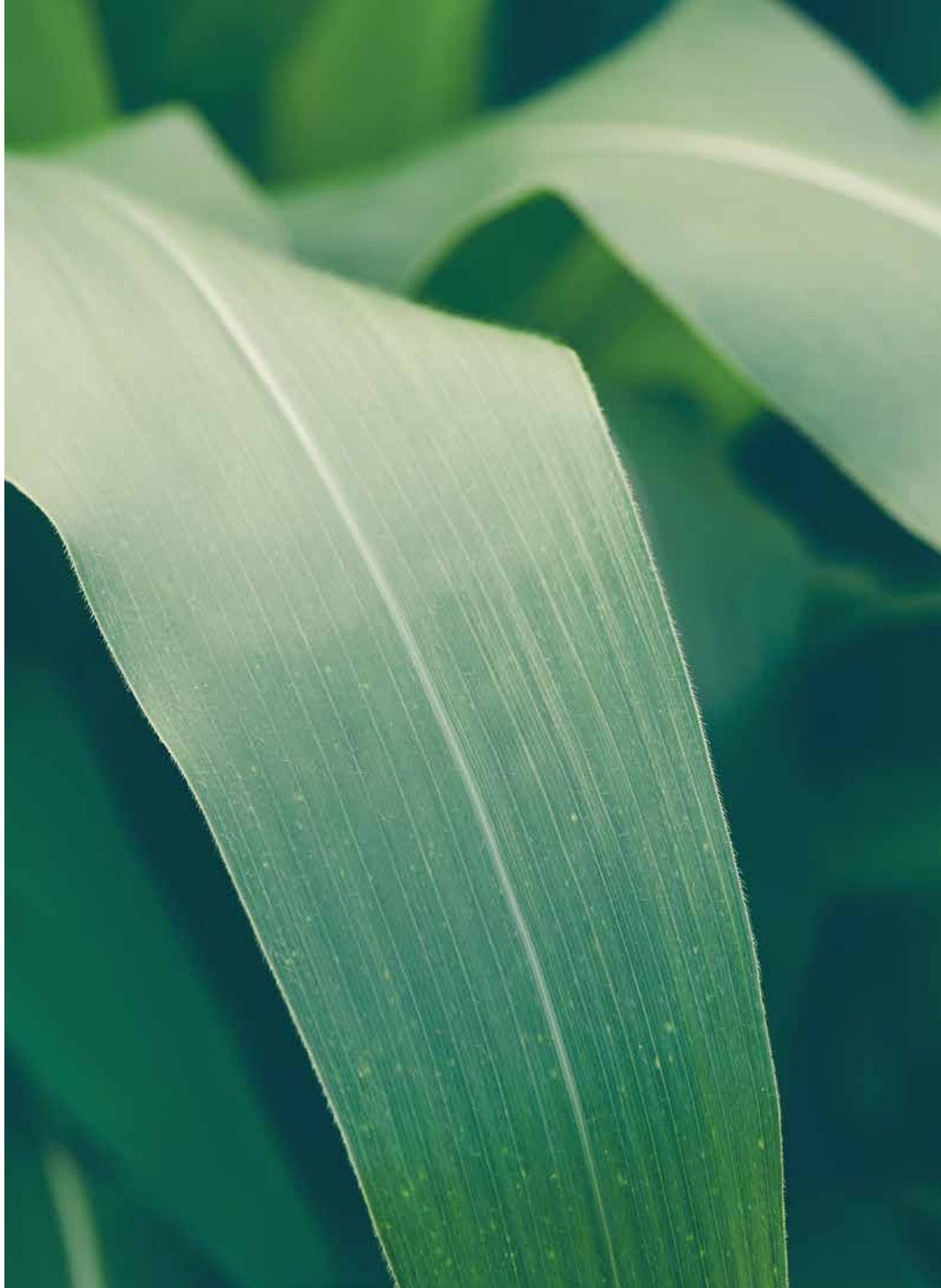
Nitrogen

A typical grain corn bushel

requires about 1.0 pound N total nutrient uptake during the growing season, due to uptake inefficiencies.
The graphic shows where the nitrogen goes, assuming a high-efficiency nitrogen uptake system for a 180 bu/ac yield.



Source: IPNI Estimates of Nutrient Uptake and Removal



Physiological Role

Under severe nitrogen deficiency, corn may exhibit some or all of the following symptoms:

- Plant is pale and yellowish green
- Spindly stalks
- Reduced yield and quality
- Stunted growth

Physiological Role

Nitrogen is necessary for making chlorophyll, and is directly involved in photosynthesis. Each molecule of chlorophyll contains four nitrogen atoms, surrounding the magnesium atom at the core. When nitrogen is limiting, chlorophyll production slows, diminishing both the deepness of the green color of the leaves and the crop's ability to convert solar energy into biochemical energy/biomass.

All proteins and enzymes contain nitrogen in the form of amino acids. Protein content of corn, an important part of its feed value, is directly related to nitrogen nutrition. In addition, proteins are often charged molecules and require potassium in the cell water to keep their shape.

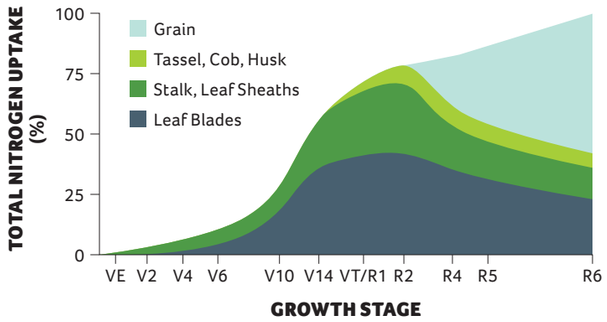
Enzymes are important in carbon fixation as well. When nitrogen is deficient, the energy generated from photosynthesis slows, and, as a result, the overall vigor of the plant declines.

The root system becomes less prolific, and the uptake of most other nutrients in the plant declines. The lower concentration of nutrients in nitrogen-deficient corn is shown in the Figure 1 below. These figures are averages of observations in Illinois and Ontario. The figures indicate only a small increase in potassium concentration because nitrogen tends to increase potassium uptake only when soil potassium levels are high. When soil potassium is low, added nitrogen stimulates growth dilution of the potassium in the plant.

Nitrogen increases concentration of many other nutrients in the leaves of corn (from Illinois and Ontario University data).

Nitrogen is also a component of vitamins. Increasing nitrogen supply enhances plant production of carotene (a precursor to vitamin A), the B vitamins (riboflavin, thiamin, and nicotinic acid), and the cytokinin growth hormones.

FIGURE 1: NITROGEN UPTAKE IN CORN DURING THE GROWING SEASON.



Source: University of Illinois

Deficiency Mechanism and Symptoms

Nitrogen deficiency in young corn causes the entire plant to be pale and yellowish green, with spindly stalks. Later, V-shaped (progressing along the midrib with the V pointing toward the plant) yellowing may appear on the tips of the leaves. Nitrogen is mobile within the plant. Thus, yellowing begins on the lower, older leaves and progresses up the plant as the nitrogen is moved up to the newer growing tissues.

Uptake and Utilization Patterns

Corn takes up nitrogen as inorganic forms, either ammonium or nitrate ions. While most of the uptake is usually in the nitrate form, certain corn hybrids have a higher requirement for ammonium than others. One reason for a benefit from ammonium nutrition is that nitrate must be reduced to ammonium forms in the plant. This reduction process requires energy that could otherwise be used in grain formation. Most studies show productivity is greatest with nitrogen taken up in both forms.

Very little nitrogen is taken up by corn in the first month after planting. Once the crop reaches a height of about 1 foot (V6 stage, refer to page 8 however, uptake increases very rapidly. The nitrogen supply before silking can affect the number of kernels set in the ear.

In the past it has been observed that corn takes up less than 30 percent of its total nitrogen after silking. However, today's hybrids may take up as much as 40 percent or more of their nitrogen after silking. Modern varieties maintain green leaf color and photosynthetic capacity longer into grain fill than older varieties. This trait may have positive implications for the impact of corn production on the environment, since the crop would be more effective in removing and immobilizing nitrate mineralized from the soil in the later part of the growing season.

Nitrogen Placement and Timing

Surface Applications

Surface applications of ammonium nitrogen sources are susceptible to volatile losses of ammonia. This is particularly true of urea, because after it is applied, it raises the pH near the granule as it hydrolyzes to release its ammonium. Potential ammonia losses increase as the pH increases. Other factors that increase ammonia losses from surface-applied urea are:

- Temperatures greater than 55°F
- Crop residues on the soil surface
- High rates of application (over 100 pounds of nitrogen per acre)
- A moist soil surface rapidly drying
- Soil with low cation exchange capacity (CEC)
- Soils with neutral to alkaline pH

The loss of ammonia from surface-applied urea or urea-containing solutions may be reduced by the use of an urease inhibitor. The chemical compound nitrogen-(n-butyl)thiophosphoric triamide (NBPT) inhibits the enzyme that converts urea to ammonia, effectively slowing the conversion of urea to ammonia and preventing buildup of high concentrations of ammonia susceptible to volatile losses. On average, the use of the urease inhibitor has increased yield by 4.3 bushels per acre when applied with urea and 1.3 bushels per acre when applied with urea-ammonium nitrate solutions. However, in conditions where risks of volatile losses from urea were high, NBPT has increased yields by as much as 20 bushels per acre.

For no-till corn, subsurface placement (2 to 6 inches) of UAN solutions by knife or coulter generally produces better yields than broadcasting urea or UAN. Subsurface placement virtually eliminates ammonia volatilization losses. Strip or dribble applications on the surface deliver intermediate results, but do not provide the opportunity for simultaneous application of herbicides.

Timing

Fall, spring and sidedress? Especially in the eastern half of the U.S., better efficiency is achieved by applying nitrogen as close to the time before uptake as possible. In high-loss potential situations, nitrogen applied at sidedress may give better results than that applied at planting. However, when relying on sidedress applications, applying 20 to 30 pounds per acre of nitrogen in the starter can minimize the risk of running short if the sidedress application is delayed by wet weather. Ammonium in starters can also enhance the availability of phosphorus fertilizers.

Post-emergent application of nitrogen solutions should avoid contact with foliage if possible. If the fertilizer solution contacts leaves, scorching can occur and sometimes translates into yield reductions.

Fall application should only be used in areas with little risk of leaching over the winter and the following spring. In these areas, fall application should be made only after the soil temperature at 4 inches has declined to 50°F or lower. A nitrification inhibitor such as nitrapyrin or dicyandiamide (DCD) can be used to slow the conversion of ammonium to nitrate and thus further protect against leaching and denitrification losses from the nitrate form.



The amount of nitrate in the lower portion of the stalk at harvest can be a good indicator of the nitrogen status of the crop.

The Nitrogen Cycle

While there are about 37,000 tons of nitrogen in the atmosphere above every acre of the earth, this nitrogen is in the dinitrogen form and must undergo fixation into ammonium or ammonia forms in order to be available to plants.

Rate Recommendations

Expected Yield. Historically, nitrogen recommendations have been based largely on expected yield (sometimes referred to as yield goal). Typically, 1.1 to 1.3 pounds of nitrogen was recommended per bushel of expected yield. Recent research indicates the nitrogen need per bushel of production is likely lower than these traditional values. Current recommendations from most Midwestern universities have decoupled nitrogen-rate recommendations from yield goals based on indications that yield goal is poorly correlated with nitrogen needs. Local research should be the basis of nitrogen-rate decisions. In any situation, a realistic, attainable expected yield should be used.

Maximum Return to Nitrogen. Many of the Midwestern universities now promote an economic recommendation strategy that relies upon an average response of corn to nitrogen. Some states delineate different geographies with different recommendations, but not all of them.

Late Fall or Early Spring Nitrate Tests. In some situations, nitrogen from previous crops, previously applied manures, or soil mineralization may be available. Tests for soil nitrate in the spring or fall can be indicators of supply from such sources. The early spring or late fall test is used most often in the arid parts of the Corn Belt, west of the Missouri River. Samples are collected to a 2- to 3-foot depth, and the total nitrate-nitrogen present is deducted from the usual recommendation.

The Pre-Sidedress Soil Nitrate Test (PSNT). This can be a good indicator of situations where nitrogen input can be reduced. In the eastern Corn Belt, it is more robust than the early spring test, as there is less time between sampling and the period of rapid nitrate uptake by the corn crop. Generally, PSNT sampling is done to a depth of 1 foot when the corn is 6 to 12 inches tall. Levels exceeding 22 to 25 parts per million indicate little chance of response to nitrogen. Very low PSNT values, less than 10 parts per million, indicate little expected contribution from the soil, and thus full rates of nitrogen should be applied. In the range in between, the test is less reliable for predicting optimum rates of nitrogen, and other factors (amount and analysis of manure applied, legume credits, etc.) need to be considered in determining rate.

Soil Organic Matter. Since soil organic matter contains 5 percent nitrogen, some have considered it to be an indicator of nitrogen supply from the soil. However, much of the soil's organic matter can be in fractions that do not mineralize easily, and mineralization is affected strongly by soil moisture and temperature. Also, for long-term production, it is more desirable to maintain rather than mineralize soil organic matter. Nitrogen mineralized from the soil may be counted on for supplying stover and root nitrogen, but the nitrogen in the harvested portion of the crop should be supplied by some form of external input. Otherwise, soil quality may degrade in the long term.

The content varies widely among manures, so it is advisable to have manure analyzed in order to give credit for its ability to supply nitrogen to the crop.

Stalk Nitrate Test. The amount of ammonia in the lower portion of the stalk at harvest can be a good indicator of the nitrogen status of the crop. The stalk nitrate test can be used as a diagnostic tool to validate the recommendation used for the current crop.

Previous Crop. Corn following plowdown of a forage stand with 50 percent or more legume (alfalfa, clover, etc.) may require as much as 100 pounds per acre less nitrogen. The nitrogen contribution is smaller if the stand contains less legume, or if the stand has only been grown one year. Corn following soybeans may have a slightly lower nitrogen requirement (10 to 40 pounds per acre less) than corn following corn, but often has a higher expected yield.

Livestock Manures. These contain nitrogen in both ammonium and organic forms. The content varies widely among manures, so it is advisable to have manure analyzed in order to give credit for its ability to supply nitrogen to the crop. Consult recommendations for proper manure sampling to ensure reliable results. In liquid manure, 50 to 75 percent of the nitrogen is in the ammonium form. In solids, the ammonium fraction comprises 12 to 30 percent of the total nitrogen. The ammonium is rapidly available, but subject to volatile losses of ammonia if the manure is not incorporated quickly. The organic nitrogen fraction is slowly available and can contribute nitrogen for several years. About 30 percent of the organic nitrogen in manure is available in the first year after application. Note that while volatile losses are lowest in cool, wet conditions, soil compaction from liquid manure spreaders can be a significant concern in these conditions. Application by direct injection is preferred for liquid manures.



Environmental Concerns

Nitrate in Groundwater

Soil nitrogen not used by the crop is particularly susceptible to leaching in the form of nitrate. Leaching losses of nitrate are undesirable for several reasons. First, nitrate losses can result in substantial financial loss due to wasted nutrient and lost crop yield arising from the shortage of nitrogen. Second, nitrate in groundwater impacts drinking water quality and may represent a health impact when nitrate-nitrogen concentrations exceed 10 parts per million. Third, nitrate leached to aquatic systems may contribute to eutrophication, particularly in marine estuaries. However, when applied using 4R nutrient management principles of Right source, Right rate, Right time, and Right place, nitrogen losses can be greatly reduced or virtually eliminated. Thus, it is important to ensure that best management practices are used. Much recent research has shown benefits of what are called "enhanced-efficiency fertilizers" in controlling nitrogen losses. These include urease and nitrification inhibitors and slow- and controlled-release fertilizers, which can significantly reduce losses by leaching, denitrification, and volatilization.

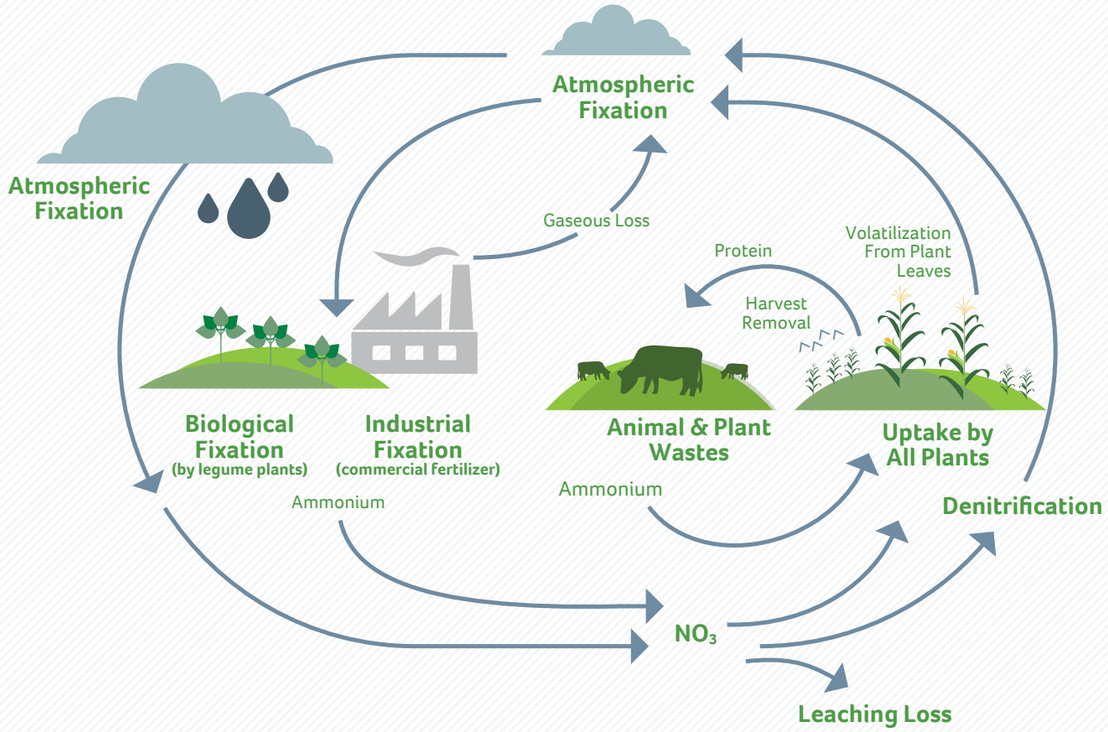
Nitrous Oxide Emissions

In the processes of denitrification and nitrification, small quantities of nitrous oxide are released to the atmosphere. While the total loss of nitrogen is not significant agronomically (usually less than 2 percent), nitrous oxide is a potent greenhouse gas and can cause stratospheric ozone depletion. Nitrous oxide is considered to be about 300 times more effective at trapping heat than carbon dioxide. Because of its stability, it persists a long time in the atmosphere. Fortunately, as with nitrate leaching, when nitrogen is applied according to 4R management principles for economically optimum yields of corn, the enhanced corn growth can result in buildup of soil organic matter and increased soil carbon storage. Manure sources of nitrogen may produce larger emissions of nitrous oxide than fertilizer sources.

The Nitrogen Cycle

While there are about 37,000 tons of nitrogen in the atmosphere above every acre of the earth, this nitrogen is in the dinitrogen form and must undergo fixation into ammonium or ammonia forms in order to be available to plants. Fixation can occur as oxidation by lightning in small amounts, but most occurs by either biological or industrial processes. Because ammonium easily converts to nitrate and nitrate can be lost by leaching or denitrification as well as being taken up by plants, it is difficult to keep large quantities of available nitrogen in the soil.

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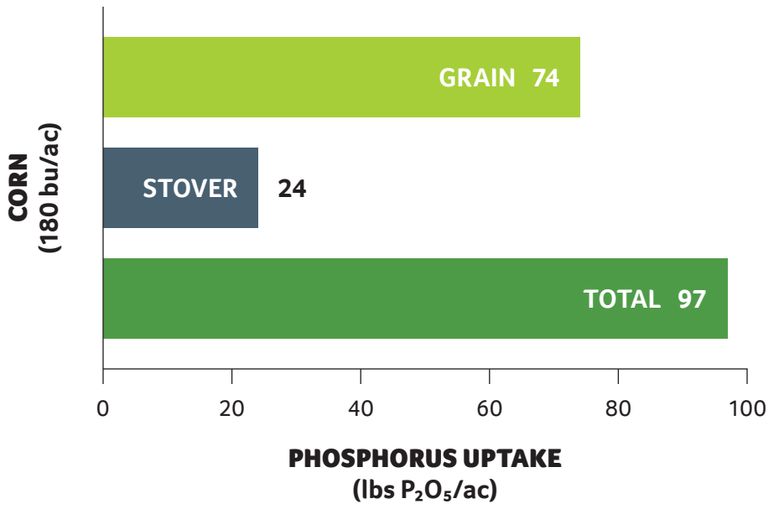


Phosphorus

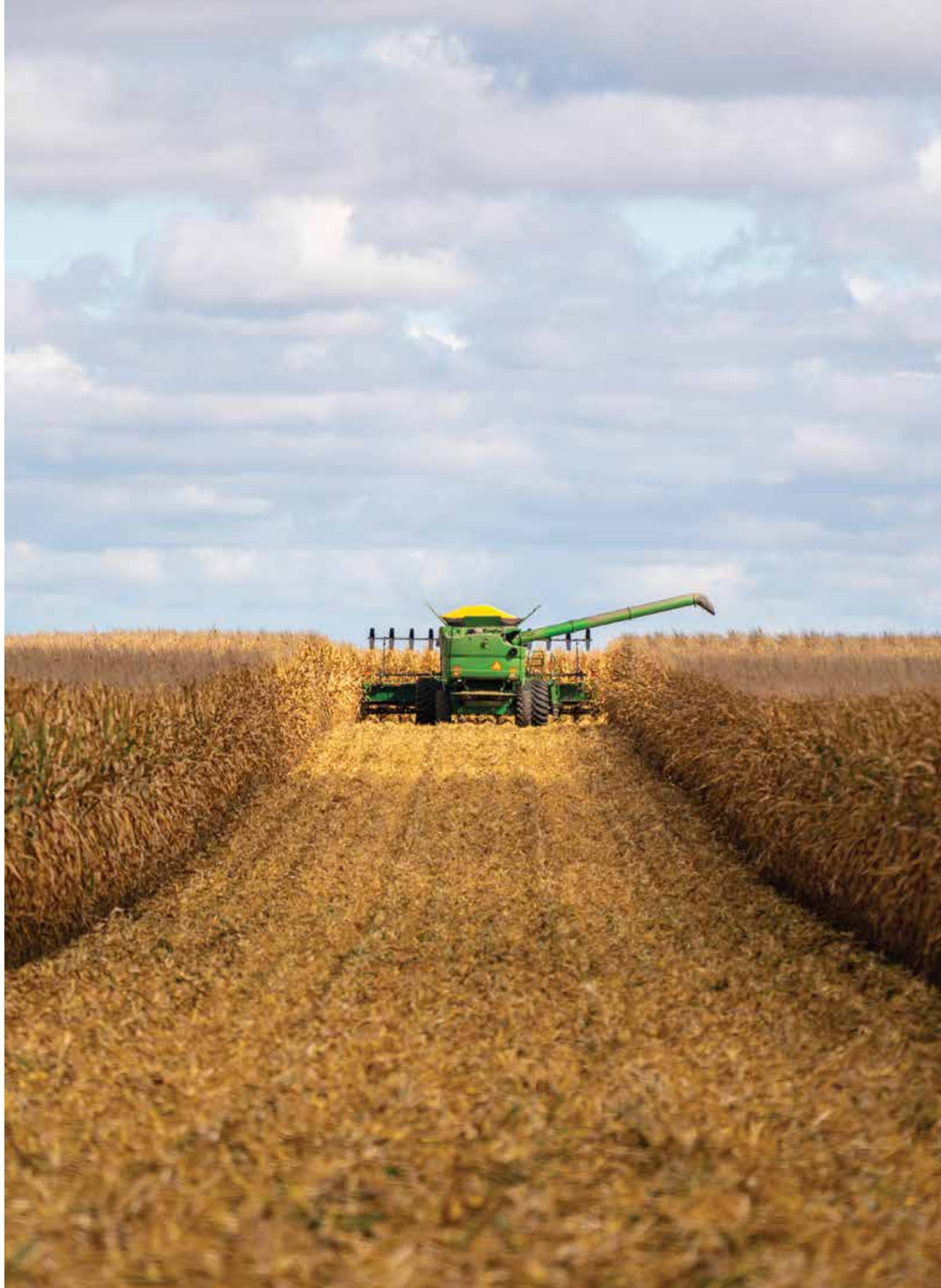
A typical corn bushel

requires about 0.54 pounds P_2O_5 total nutrient uptake during the growing season, due to uptake inefficiencies.

The graphic shows where the phosphate goes, assuming a high-efficiency phosphate uptake system for a 180 bu/ac yield.



Source: IPNI Estimates of Nutrient Uptake and Removal



Under severe phosphorus deficiency, corn may exhibit some or all of the following symptoms:

- Purpling of leaves and stems
- Reduced leaf and plant size
- Delayed maturity
- Incomplete grain fill and reduced yield

Phosphorus enters the corn plant through root hairs, root tips, and the outermost layers of root cells. Beneficial fungi, called mycorrhizae, also enhance phosphorus uptake. Phosphate is important for energy transfer processes in the corn plant. Processes requiring the energy that phosphorus-containing compounds provide are:

- Photosynthesis and the storage of sunlight energy
- Formation of simple sugars
- Use of sugars and starch for corn growth
- Transfer of energy during plant chemical reactions
- Maintenance and transfer of corn's genetic code
- Development of new plant cells
- Germination, size, number, and viability of seed

Corn typically requires 0.54 pounds of phosphorus pentoxide per bushel of yield produced.

Phosphorus deficiency usually appears when plants are young. Young plants develop shoots faster than roots, causing high phosphorus uptake requirements per unit of root length. Often soil-solution phosphorus concentrations are inadequate to meet these high requirements. Inadequate phosphorus leads to the buildup of carbohydrates and sugars, causing a dark green or reddish-purple leaf color. Later symptoms include spindly stalks that are either barren or have twisted ears with incomplete grain fill. Delayed maturity may also occur.

Reactions of Phosphate in Soils

Phosphate fertilizers contain soluble forms of phosphorus that are immediately available to plants. However, when they are applied to soils, phosphorus fertilizers react with certain constituents in the soil to form new compounds that are not as plant-available in the season of application. This process is termed "fixation." Phosphate reactions with iron, aluminum, calcium, and magnesium are well documented. Many of the compounds formed, however, do release phosphorus into plant-available forms over time, depending on field conditions and pH. Maintaining the soil pH between 6.0 and 7.0 usually maximizes release rate and, therefore, phosphorus availability for the crop.

Soil organic matter and manure also contain phosphorus, a portion of which is released as plant-available forms in a process called mineralization. This release also occurs over many years. The phosphorus used by a corn crop in a particular growing season therefore comes not only from the phosphorus fertilizer or manure applied in a particular season, but also from such materials applied in previous years.

Soil testing is essential for tracking the success of a phosphorus fertilization plan. Soil-test phosphorus levels should be built to and maintained at values that ensure maximum economic yields (MEY) for the individual grower. The influence of soil-test levels on corn grain yield is shown in Table 4 Effectiveness of Phosphorus Placement Methods below. This is a theoretical graph that represents the types of relationships commonly produced from research trials. At low soil-test levels, 20 to 70 percent yield reductions have been reported, depending upon the soils and environments in which corn is grown. University fertilizer recommendations usually include higher rates at lower soil-test values to increase phosphorus concentrations to levels that are optimum for corn yields. The scatter in the data shows that no one yield reduction can be predicted for a given soil-test level. However, soils with lower soil-test levels have a greater chance of producing increased yields when fertilized.

In addition to increasing yields, phosphorus fertilization can also hasten maturity and thereby lower grain moisture. An example of a reduction in corn grain moisture is shown in Table 3. This table shows that economic returns to phosphorus fertilization come not only from yield increases, but also from savings in drying costs.



Phosphorus Placement and Timing

Phosphorus reduces drying costs – economic returns to phosphorus fertilization come not only from yield increases, but also from savings in drying costs.

Proper phosphorus placement is essential for optimizing yields. Phosphate does not move very far within the soil. Consequently, phosphorus must be placed where it is accessible to corn roots. The objective of various placement methods is to create a high probability that plant roots will come in close contact with the applied phosphorus. A second objective in soils that can fix large quantities of phosphorus is to minimize the contact of phosphorus fertilizer with the soil. In such situations, less soil contact may result in greater availability of phosphorus to plants.

One of the most common practices has been broadcasting phosphorus before primary tillage operations. In conventional tillage systems, this has resulted in fairly uniform mixing of phosphorus fertilizer within the depth of the plow layer. Where soil test levels are higher, roots have a good chance of finding phosphate. However, in conservation tillage systems, repeated broadcast applications without soil mixing creates higher concentrations of phosphorus near the soil surface. Where soils are warm, soil test levels are optimum to high, and when moisture is adequate throughout the growing season, roots proliferate near the soil surface. In such cases, broadcast applications are appropriate since they place fertilizer near the zone of greatest root activity.

TABLE 3: REDUCTION IN CORN GRAIN MOISTURE.

Phosphorus Pentoxide Rate (lb/ac)	Corn Grain Yield (bu/ac)	Grain Moisture (%)	Drying Costs ($/ac)
0	145	27.0	–
20	158	26.0	3
40	169	25.5	5
80	174	24.6	8
120	179	24.2	10

Drying costs were $0.02 per point above 15.5 percent.

Source: Ohio State University.

TABLE 4: EFFECTIVENESS OF PHOSPHORUS PLACEMENT METHODS.

	Year 1		Year 2	
Placement	Fall Chisel	Ridgetill	Fall Chisel	Ridgetill
Low soil test phosphorus				
Control	81	81	87	92
Broadcast	98	87	122	118
Surface band	107	98	108	127
Subsurface band	105	108	132	138
High soil test phosphorus				
Control	157	154	154	145
Broadcast	154	153	148	149
Surface band	157	151	148	154
Subsurface band	157	153	149	154

Phosphate rate applied was 43 pounds phosphorus pentoxide per acre.

Source: University of Minnesota.

Band placement concentrates phosphorus within a zone in the soil. This minimizes fertilizer contact with the soil and can increase the probability of access by plant roots. Band applications include planter banding or starter applications, deep banding, surface strips, point injection, and high-pressure injection. Band applications have been shown to be superior to broadcast applications at lower soil-test levels, cold and wet soil conditions, and in soils that fix substantial quantities of applied phosphorus. Banding may also be advantageous when phosphorus concentrations are stratified and moisture becomes limiting during part of the growing season. Both of these situations can occur in conservation tillage systems. An example of the effectiveness of various placement methods is shown in Table 4. In this example, placement had more of an effect on corn yields at lower soil-test levels.

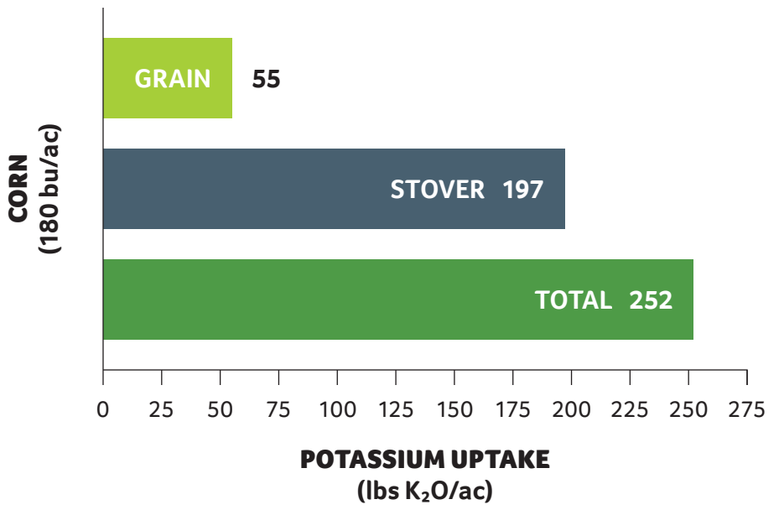
Starter phosphorus, usually placed in a band to the side and below the seed, can give excellent growth and yield response even when phosphorus soil tests are very high. Response is more dependent on environmental conditions than on soil-test levels. Cool or excessively wet soils often give good starter response. Recent research has shown that corn hybrids can differ markedly in starter response as well.

Phosphate placed in direct contact with the seed has been shown to increase early growth of corn under some conditions. However, the nitrogen and potassium that usually accompany liquid starter fertilizers can have harmful effects upon seedlings if applied at rates that are too high. The magnitude of the effects of nitrogen and potassium upon germination depends upon soil moisture at the time of application and the quantity of precipitation shortly after planting.

Potassium

A typical grain corn bushel

requires about 1.4 pounds K_2O total nutrient uptake during the growing season, due to uptake inefficiencies. The graphic shows where the potassium goes, assuming a high-efficiency potassium uptake system for a 180 bu/ac yield.



Source: IPNI Estimates of Nutrient Uptake and Removal



Since potassium nutrition is management-controlled, there is little reason for insufficient potassium to limit corn growth. Researchers have identified its functions and how it contributes to plant growth and grain development. The following information is based upon research and includes decision-making facts needed to make the right decisions about potassium nutrition and fertilizer use for optimum yield, grain and silage quality, profitability, and protection of soil and water quality.

Under severe potassium deficiency, corn may exhibit some or all of the following symptoms:

- Slow growth rate
- Leaf discoloration; older leaf edges turn yellow then brown
- Reduced yield and quality
- Weak, spindly stalks
- Poor stress tolerance
- Lodging

Functions of Potassium

Potassium promotes corn growth in several ways. It functions to improve corn disease resistance, water- and nitrogen-use efficiency, tolerance to stress, as well as yield, and quality of grain and forage. Potassium works behind the scenes and a shortage, although not always visible to the eye, can have a great influence upon the pocketbook. Corn benefits from 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 respiration and loss of grain 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 the grain
- **Water-use efficiency**
  regulates leaf pore opening and closing to conserve water
- **Protein synthesis**
  helps to convert nitrogen into amino acids and quality proteins
- **Crop quality**
  improves disease resistance, market value, and harvestability

Indicators of Potassium Deficiency

A potassium shortage can be masked by other crop stress symptoms. These might result from drought, insect injury, diseases, excessive temperature at silking, or even an insufficient amount of any of the other essential nutrients. The following conditions are warning signals that potassium might be limiting corn growth and profitability.

- **Thin stands**
  seedling vigor declines and disease susceptibility increases
- **Slow growth rate**
  potassium stress slows both photosynthesis and protein formation
- **Leaf discoloration**
  older leaf edges turn yellow then brown, but the midrib stays green
- **Leaf diseases**
  low leaf potassium reduces plant tolerance to stress and resistance to disease
- **Poor nitrogen response**
  potassium teams with nitrogen for protein formation, photosynthesis, etc.
- **Delayed silk emergence**
  up to a week's delay shortens the window for grain fill
- **Stalk lodging**
  internal stalk tissue breakdown allows invasion by stalk rot organisms
- **Chaffy, loose grain ears**
  poor grain fill near the ear tip cuts yield and test weight

Under severe potassium deficiency, corn may exhibit some or all of the following symptoms:

- Thin stands
- Chaffy, loose grain ears
- Delayed silk emergence

Potassium Uptake and Utilization Patterns

When does corn need potassium? Every day. The amount increases by growth stage until seedlings become fully mature plants. Over 80 percent of the total potassium requirement must be in the plant by silking time. Uptake then slows in quantity but not importance during the critical period of grain formation. The peak rate of absorption per day occurs just prior to silking.

Uptake per unit of root length present is also an important expression of potassium requirement. Corn grows shoots faster than roots during early growth stages. Therefore, soils sometimes fail to meet the high requirement of each root segment, and potassium deficiency results during the V10 to V12 growth stages.

Corn requirements for potassium are similar to the total amount of nitrogen needed for optimum growth. However, nutrient uptake requirements by plant growth stage can be quite different.
If potassium stress occurs, it will likely happen during the V10 to R1 growth stages. Thus, total plant potassium needs must be in place prior to this critical corn growth period. On medium- or fine-textured, high CEC (cation exchange capacity) soils, a preplant application of potassium fertilizer usually supplies crop demand. On sandy soils in high-rainfall regions, however, the soil nutrient reservoir can be too small to store the full potassium supply needed by high-yielding corn. In that case, soil potassium plus preplant applied fertilizer can be supplemented by a sidedress application prior to silking. A productive soil has certain basic features. It must be fertile and capable of supplying the quantity of inputs, including potassium, that are essential for corn to develop at an optimum rate through each stage of plant growth.



Corn Has a Big Appetite for Both Nitrogen and Potassium

Potassium absorbed by high-yielding corn grain is about the same as for corn silage. Nutrient removal from the field, however, is considerably greater for silage. As crop yields go up so does corn's requirements for potassium. With a 200-bushels-per-acre grain crop, total uptake is partitioned with about 190 pounds per acre in the stover and nearly 50 pounds per acre leaving the field in the grain. When corn is grown for silage, potassium removal is nearly four fold greater than for grain. Scheduled replacement is especially critical for the following crop.

Determining Corn Requirements for Potassium

Potassium required to grow a crop of corn is provided in part from the soil's nutrient reservoir and the remainder from the fertilization program. The total amount of fertilizer potassium needed by a corn crop is very site-specific and will change from one field to another or from one area in a field to another. Thus, certain basic ingredients are essential to formulating the fertilization program and then its method of delivery for optimum crop response. These ingredients include recent soil analysis results, nutrient uptake requirements for the target yield goal, knowledge of previous crop management practices, as well as certain cultural practices (tillage) and climatic conditions, which interact with potassium availability and uptake by corn. Soil testing provides a measure of the soil's potassium reserves and an estimate of likely crop response to applied fertilizer. Since potassium moves very little in most soils, a maximum of 50 to 60 percent of fertilizer potassium is absorbed by corn during the season of application when soil supplies are low, even with BMPs and favorable growing conditions.

One exception to this would be in sandy soil types with low CEC (less than 10). Under these conditions, potassium can be leached below the rooting zone, making the percentage of potassium absorbed from fertilizer sources higher.

Corn yield goal establishes the amount of fertilizer potassium needed to replace the expected removal in crop harvest. This quantity can vary somewhat among hybrids. A corn crop yielding 180 bushels per acre absorbs about 1.4 pounds of potassium oxide per bushel of corn produced. About 0.25 pounds of potassium oxide is locked up in each bushel of grain and destined for export from the field at harvest time.

Soil characteristics, climatic conditions, grower circumstances, and other factors influence the rate of potassium to be applied to corn. In the long term, potassium rates should be such that soil-test potassium is built to and maintained at levels that ensure maximum economic yield (MEY) for the individual grower. Recent soil-test inventories show many corn producing areas in North America are below optimum soil-test potassium and would benefit from some buildup of soil potassium.

Sources of Fertilizer Potassium

The major sources of fertilizer potassium provide at least two nutrients essential for plant growth. See Table 5. Most are available in granular and soluble forms for best fit with either liquid or dry material fertilization programs. Although muriate of potash (potassium chloride) is the most common source for corn, other sources meet special crop needs by providing not only potassium but also phosphate, nitrogen, or readily available magnesium and sulfur.



Over 80 percent of the total potassium requirement must be in the plant by silking time.

Time and Method of Potassium Fertilization

The right balance of nitrogen with potassium can improve corn grain and forage yields and improve input-use efficiency.

Fertilizer potassium for corn 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 corn yield-limiting factor.

Except for highly erodible soils or extremely sandy, low organic matter soil, fertilizer potassium can be applied in the fall with agronomic results similar to spring applications. Unlike nitrogen, soil temperature is not a factor for timing of fall-applied potassium. Broadcasting potassium prior to primary tillage places it in the active root zone for optimum plant-use efficiency. For sandy soil subject to potassium leaching, a split application, with about half preplant and the remainder applied about 40 days after planting, usually provides the potassium needed for high-yielding corn. Fertigation with potassium is not widely practiced except to respond to an emergency shortage, deliver programmed nutrition for sweet corn, or under special production situations.

Corn will respond to starter potassium on many soils. However, starter alone is seldom enough for top-profit yields (see Table 5) because of the large potassium requirement of corn. To protect against potential seed injury, no more than about 10 pounds of nitrogen and potassium oxide per acre should be applied in direct seed contact on medium- or fine-textured soils. Potassium should not be placed with the seed on sandy soils. Starter bands placed to the side and below seed depth allow higher rates and are the preferred band placements.

Low-testing soils can be built up over a period of years when the amount of potassium applied to the soil exceeds crop requirements. In general, the quantity of fertilizer needed to build the potassium soil-test level by 10 parts per million is 80 to 120 pounds of potassium oxide per acre.

Balance the Benefits From Nitrogen Plus Potassium

The right balance of nitrogen with potassium can improve corn grain and forage yields, boost forage quality, improve input-use efficiency, and provide better protection of groundwater. For example, potash improved the quality of nitrogen-fertilized corn silage (175 pounds per acre) by reducing fermentation losses by 5 percent, increasing the carotene content sixfold, and nearly tripling total protein production. The environment benefited when nitrogen-use efficiency by corn was improved when potassium helped plants to capture nearly 25 percent more of the applied nitrogen and lowered the risk of unused nitrogen moving down to groundwater. At the same time, growers benefit as nitrogen and potassium teamwork helps generate higher yields, lower unit costs, and greater profits. (See Table 6.)

TABLE 5: THE PRIMARY SOURCES OF FERTILIZER MATERIALS CONTAINING POTASSIUM.

Source	Formula	Potassium Oxide	Phosphorus Pentoxide	Magnesium	Sulfur	Nitrogen
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	–	–	–

TABLE 6: INFLUENCE OF POTASSIUM ON CORN YIELD AND NITROGEN EFFICIENCY.

Potassium Oxide (lbs/ac)	Grain (bu/ac)	Nitrogen Efficiency (bu/100 lbs N)	Nitrogen Uptake (lbs/ac)
None	133	87	173
60	140	93	182
120	165	110	214

Sulfur, Calcium, and Magnesium

Understanding how sulfur, calcium and magnesium work together helps ensure a healthy crop.



Sulfur

Under severe sulfur deficiency, corn may exhibit some or all of the following symptoms:

- Yellowing symptoms in younger leaves
- Stunted plants
- Reduced yield and quality

Often overlooked, sulfur can be the "weak link" in many soil fertility and plant nutrition programs. Increased crop yields, government restrictions on atmospheric sulfur emissions, increased use of higher analysis fertilizers, and a greater awareness of crop sulfur needs are contributing to an increased need for sulfur fertilization. It is absorbed by corn roots in the sulfate form and is required for the synthesis of certain amino acids (cysteine and methionine), protein formation, and photosynthesis. A 200-bushel-per-acre corn crop takes up 24 pounds of sulfur per acre with about 14 pounds per acre removed in the grain at harvest.

Determining Sulfur Requirements for Corn

Most sulfur in the soil is bound in the organic matter and cannot be used by plants until it is converted to the sulfate form by soil bacteria (mineralization).

On deep, low organic matter, sandy soils with little or no clay in the subsoil, plants will likely respond to applications of 10 to 20 pounds of sulfate-sulfur per acre with preplant fertilizers or with sidedressed nitrogen. If elemental sulfur is used, fall applications of somewhat higher rates may be needed to permit conversion and a supply of at least 10 to 20 pounds per acre of sulfate-sulfur by early spring when growth accelerates.

Indicators of Sulfur Deficiency

In the field, sulfur deficiency and nitrogen deficiency are often confused. Sulfur is immobile within the plant and does not readily move from old to new growth. With sulfur deficiency, yellowing symptoms, or leaf striping, first appear in younger leaves, whereas with nitrogen deficiency, the yellowing appears on the older leaves first. In less severe situations, visual symptoms may not be noticeable.

TABLE 7: CORN RESPONSE TO NITROGEN AND SULFUR SUPPLY.

	Nitrogen Rate (lbs/ac)			
	0	75	150	Average
Sulfur Rate (lbs/ac)	**Yield (bu/ac)**			
0	63	128	145	112
10	79	143	153	125
20	92	146	155	131

Source: Soil Fertility Manual, PPI, 1995.



Symptoms of both nitrogen and sulfur deficiencies may appear as stunted plants, with the general yellowing of leaves. The best way to diagnose a sulfur deficiency is with plant tissue analysis. Desirable total nitrogen to total sulfur ratios range from 7:1 to 15:1. Wider ratios may point to possible sulfur deficiency, but should be considered along with actual nitrogen and sulfur concentrations in making diagnostic interpretations. Nitrogen application on soil with marginal sulfur supply may induce sulfur deficiency (See Table 7).

Sources of Fertilizers

Common sulfur sources and their sulfur content are: ammonium sulfate (24 percent), ammonium thiosulfate (26 percent), elemental sulfur (greater than 85 percent), gypsum (12 to 18 percent), magnesium sulfate (14 percent), potassium sulfate (18 percent), potassium thiosulfate (17 percent), potassium magnesium sulfate, and sulfur-coated urea (10 percent). With the exception of elemental sulfur and sulfur-coated urea, these sources are water soluble. Some irrigation waters may contain significant quantities of sulfur. When the irrigation water exceeds about five parts per million sulfate-sulfur, a sulfur deficiency is unlikely.

Liming, Calcium, and Magnesium

Maintaining proper soil pH is a key element of sound soil fertility management. Chemistry and availability of most nutrients are affected by soil pH. Calcium and magnesium needs are usually supplied by proper soil liming. These two nutrients are not commonly deficient in properly limed soils. Liming needs are determined from a soil pH measurement and a measure of the soil buffer capacity or CEC. A common method employs a pH measurement of a soil:water suspension and a comparison with the pH in a soil:buffered-solution suspension. The amount of pH depression of the buffered solution is calibrated with the amount of lime needed. At a given pH, clay soils with a higher CEC will require more lime to raise the soil pH to a desired target than will a sandier soil with a lower CEC. The desirable pH range for optimum corn production is 6.0 to 6.5. Soils with a pH 0.2 to 0.3 units below the recommended level should be considered for liming. Liming to maintain an optimum soil pH reduces the risk of toxicities from aluminum and other metals, improves the physical condition of the soil, stimulates microbial activity, increases the CEC in some variable charge soils, increases the availability of several nutrients such as nitrogen, phosphorus, and molybdenum, supplies calcium and magnesium for plants, and improves the symbiotic nitrogen fixation by alfalfa, soybeans, and other legumes in the crop rotation.

Calcitic and dolomitic aglime are the most common lime sources. As aglime dissolves in soils, the carbonate reacts with the hydrogen ions displaced by the calcium (and/or magnesium) on the CEC, to raise soil pH. Calcium or magnesium do not directly neutralize soil acidity. This explains why gypsum has a calcium carbonate equivalent (CCE) of zero and has no direct effect on soil pH. The purity of the liming material is expressed as CCE, with all liming materials rated in comparison to pure calcium carbonate (CCE=100). The smaller the lime particle, the faster it will react in neutralizing soil acidity. The effective neutralizing value or effective calcium carbonate equivalent (ECCE) of a liming material is determined by both the chemical purity and the size of the lime particles (See Table 8).



SULFUR DEFICIENCY.

The ECCE of a liming material can be estimated using the formula: ECCE = %CCE x 0.50 (% passing 8-mesh + % passing 50-mesh). Thorough mixing in the tillage zone is also necessary for the optimum lime reaction. Aglime should be incorporated to adjust the soil pH to the desired level in the entire plow layer before no-till crop production is initiated. The pH can be maintained in the desired range by surface applications afterward. Surface liming of no-till systems about every three years, based on soil tests, should be adequate.

Pelletized lime and fluid products are made from finely ground aglime and will chemically react the same as good quality aglime. Pelletized aglime is usually made from aglime ground to pass at least a 70-mesh sieve, and with the aid of clay or synthetic binders, formed into pellets in the five-to-14-mesh range. Fluid aglime is commonly a 50 percent mixture of aglime particles that have been ground to pass a 200-mesh screen, plus 50 percent water and a small amount of clay or other suspending agent. The choice among good aglime, pelletized lime, and fluid lime is often based on cost, uniformity of application, and time permitted to raise soil pH to desired levels.

TABLE 8: LIME PARTICLE FINENESS EFFECT ON ACIDITY NEUTRALIZATION.

Years After Application		
Mesh Size	1	4
Percent Reacted		
Coarser than 8	5	15
8 to 20	20	45
20 to 50	50	100
Finer than 50	100	100



A 200-bushels-per-acre corn crop takes up 24 pounds of sulfur per acre with about 14 pounds per acre removed in the grain at harvest.

Magnesium

Magnesium, as the central atom in the chlorophyll molecule, aids the plant in photosynthesis. It is also required for cell division, protein formation, phosphorus metabolism, plant respiration, and the activation of several enzyme systems. Magnesium is taken up by the plant as the the divalent magnesium cation. A 200-bushels-per-acre crop takes up about 65 pounds per acre, with about 25 pounds per acre removed in the grain at harvest. It is mobile and easily translocated from older to younger tissues. When deficiencies occur, the older leaves are affected first with a loss of color between the leaf veins, beginning at the leaf margins or tips and progressing inward. Leaves appear striped, with yellowing and browning of leaf tips and edges as symptoms progress (which may be confused with potassium deficiency), resulting in lowered photosynthesis and overall crop stunting.

If soil test magnesium levels are below 25 to 50 parts per million (50 to 100 pounds per acre), extractable magnesium is usually considered low and application is warranted at about 10 to 40 pounds of magnesium per acre. If a magnesium deficiency is detected by plant tissue analyses (see Table 9 below) before the six- to eight-leaf stage, a soluble magnesium source may be applied and watered into the soil by irrigation or rainfall. Common magnesium sources include dolomitic lime (6 to 12 percent), magnesium chloride solution (7.5 percent), magnesium sulfate (16 to 18 percent), and potassium magnesium sulfate (11 percent). All of these sources are water soluble except dolomitic lime. Small amounts of magnesium can be applied to growing crops through foliar fertilization to correct or prevent developing deficiencies, but the preferred approach is to soil-apply the required amounts before planting.

Calcium

Calcium is taken up by plants as the divalent cation, calcium ion. It improves the root absorption and translocation of other nutrients, activates growth-regulating enzyme systems, is needed for cell wall formation and normal cell division, and contributes to improved disease resistance. Along with magnesium and potassium, calcium also helps to balance organic acids, which form during cell metabolism. Symptoms of calcium deficiency, found in the new growth because it is not readily translocated, include slowed root development and slowed new leaf growth, with leaf tips sticking together. Calcium deficiency is not likely when the soil is properly limed. As soils become more acidic, crop growth is often restricted by toxic soil concentrations of aluminum and/or manganese, not a calcium shortage. When deficiencies occur, they are most commonly observed in acidic, sandy soils where calcium has been leached by rain or irrigation water, or in strongly acidic peat and muck soils where the total soil calcium content is low.

TABLE 9: CALCIUM, MAGNESIUM, AND SULFUR LEVELS IN CORN AT DIFFERENT GROWTH STAGES.
Common calcium sources and their calcium content are: calcitic limestone (32 percent), dolomitic limestone (22 percent), hydrated lime (46 percent), and gypsum (22 percent).

Plant Part	Calcium	Magnesium	Sulfur
	Percent		
Whole plants less than about 12 inches tall	0.30 to 0.70	0.15 to 0.45	0.15 to 0.50
Leaf below the whorl prior to tasseling	0.25 to 0.50	0.13 to 0.30	0.15 to 0.50
Ear leaf at initial silking	0.21 to 1.0	0.20 to 1.0	0.21 to 0.50



Micronutrients

Micronutrients are required

in relatively small amounts but produce impressive results.



Under severe micronutrient deficiency, corn may exhibit some or all of the following symptoms:

- Plant is pale and yellowish green
- Spindly stalks
- Reduced yield and quality
- Distinct striping of leaves
- Deformed leaves and tissues
- Delayed maturity

Seven of the 17 elements essential for growth are absorbed by corn in quantities of less than 2 pounds per acre each. These elements, boron, copper, iron, manganese, molybdenum, zinc, and nickel, are known as micronutrients because they are required by plants in such small amounts. The eighth nutrient classified as a micronutrient, chloride, is more abundant in corn plant tissue than calcium, magnesium, or sulfur. Chloride is the biologically active form of the element chlorine, the primary form present in plants and soils, and the form applied as fertilizer. The element chlorine is referred to as chloride in discussion of plant nutrition. Regardless of their concentration in corn tissue, each micronutrient is responsible for specific plant functions and thus each is equal in importance to any other essential element for high-yield corn production.

Functions of Micronutrients in Plants

The function of any nutrient is the origin of the symptom of its deficiency. A listing of the specific functions of each micronutrient will help to illustrate why the detection of a deficiency in corn is often difficult. The listing also helps to target the plant part where a deficiency symptom is most likely to occur. For example, iron, manganese, and copper are each involved with chlorophyll formation, and a shortage will likely trigger a visible yellowing of plant tissue. Zinc, boron, and molybdenum are each involved with protein formation, which is less likely to trigger a visible symptom. (See Table 10.)

TABLE 10: THE FUNCTIONS OF MICRONUTRIENTS IN PLANT DEVELOPMENT.

Plant Growth Function	Boron	Chloride	Copper	Iron	Manganese	Molybdenum	Zinc
Enzyme systems		X	X	X	X	X	
Protein formation	X		X	X		X	X
Hormones and cell division		X					X
Chlorophyll formation			X	X	X		
Disease resistance		X					
Photosynthesis	X		X	X			
Nitrogen, iron, and/or phosphorus metabolism	X		X	X	X	X	X
Seed formation	X		X				X
Sugar/starch translocation	X	X					X

Availability of Micronutrients in the Soil

The total concentration of a micronutrient in the soil is usually a poor indicator of its availability to the corn plant. Tons of iron and manganese might exist in soil but be limiting to plant growth because they exist in a form unsuitable for absorption by roots. The content of boron, zinc, copper, or chloride in soils might range from a few to several hundred pounds per acre and adversely affect plant growth as either a deficiency or toxicity. Thus, micronutrient management for high-yield corn production should include consideration of the conditions regulating their availability, such as soil acidity, soil temperature and moisture, genetics, and/or interactions with other corn production inputs.

Need for Micronutrient Fertilization Programs

Liming a strongly acidic soil to a pH level of about 6.0 to 6.5 impacts the availability of all micronutrients except chloride. Iron, zinc, copper, boron, and manganese become less available to corn while molybdenum availability actually increases. Soils high in organic matter are often in need of copper and/or boron. Alkaline soils and/or soils that are high in phosphorus tend to be responsive to applied zinc. Sandy soils are more likely to be in need of micronutrients than soils high in clay content. Cold, wet soils often trigger zinc deficiency in young corn plants. Dry soils late in the season can lead to inadequate boron absorption by corn roots. Land leveling or removal of higher organic matter topsoil often triggers a shortage of zinc. Low chloride in precipitation and limited use of potassium chloride fertilizer has created low chloride soils in parts of the Great Plains and Canadian Prairie soils, leading to corn yield response to applied chloride fertilizers. Such conditions justify the existence of a strong micronutrient component for many high-yield corn nutrient management programs.

The Margin is Narrow Between Deficiency and Toxicity

Excess levels of some micronutrients can be of equal concern for corn growers. The boundaries for deficiency and excess get close for boron, copper, and zinc. Sensitivity differs between crops and sometimes even between varieties. Midwest researchers report that the relative sensitivity of corn to micronutrient deficiency is low for boron and molybdenum, medium for copper, iron, and manganese, and high for zinc. Excess levels of iron and manganese can often be alleviated by liming acid soils. Excess levels of boron, zinc, or copper are seldom a problem in corn production. In some situations, excess levels of one or more micronutrient metals (zinc, iron, copper, or manganese) can reduce uptake of other metals and induce imbalance or deficiencies.

Determining Micronutrient Needs

The following conditions deserve consideration when determining the need for micronutrients. Knowledge about corn needs for specific micronutrients is a starting point. Soil testing has its limitations, but can be helpful as it provides the best measure of soil nutrient reserves and allows corrective action for an anticipated shortage before the crop is planted. Other factors beyond a soil test may also indicate micronutrient need. Crop history and field scouting records help to pinpoint previous problem areas and gain some insight as to how the corn crop responded to treatments. Plant analysis provides a good evaluation of the micronutrient status of a plant when soil tests and field scouting are not conclusive. For best results, soil and plant analysis should be used together to detect shortages and to develop effective micronutrient management programs. Understanding interactions of micronutrients with other crop production factors can greatly enhance the chances for success in managing micronutrients.



Placement and Timing Micronutrients

Decisions relating to the application of a micronutrient are often dependent upon site-specific conditions and the stage of plant development at the time of problem detection.

Broadcast applications are often most convenient, require higher rates for response, and sometimes, such as with iron on alkaline soils, are rendered useless by the soil conditions that originally created the need for treatment.

Band placement concentrates the source, which minimizes soil tie-up and improves root absorption. A summary of Kentucky field trials evaluating methods of zinc application to corn showed band placement to be better than either broadcast or foliar methods (see Table 11). Band placement of zinc, manganese, and copper with acidic fertilizers such as MAP and ammonium sulfate has been shown to improve micronutrient availability in high-pH soils.

Foliar sprays have a limited application rate and some risk of foliar injury but do allow for the use of a minimum of product and rapid absorption and correction of deficiencies. Foliar treatments may need to be repeated to maintain plant health.

Seed coating fits best with molybdenum applied with the inoculation for legume crops.

TABLE 11: THE EFFECT OF APPLICATION METHODS OF ZINC ON CORN GRAIN YIELDS.

	Corn Response			
	0-5	5-10	10-15	15+
Application Method	**Percent of Trials Showing Response**			
Broadcast (31 sites)	55	6	19	20
Row (28 sites)	29	21	29	21
Foliar (31 sites)	26	36	6	32

Source: University of Kentucky.

Sources of Micronutrients

Waste and byproduct sources must be analyzed for nutrient content and be field tested to establish crop-use effectiveness for that micronutrient source. An analysis often discloses that irrigation water also serves as a micronutrient source. Many commercial sources are available and are effective when accompanying instructions are followed.

To provide for the variety of field needs, applicators have access to micronutrients in many forms. For example, the chelates help to protect the nutrient from being altered to an unavailable form. Soluble forms, such as sulfate salts of the micronutrient metals, fit the need for application as foliar sprays, in liquid fertilizer formulations, or through irrigation systems. Soluble chelated micronutrients are also effective for foliar applications and may provide greater compatibility in mixed formulations. A "jar test" for compatibility should always be conducted for the intended mixture. Granular-sized products blend well with other nutrient sources or can be applied directly to the soil. Granular micronutrient fertilizers should contain at least 30 to 50 percent of the nutrient in water-soluble form for adequate availability to crops. Homogeneous granulated fertilizers respond to the need for uniformity of application by each particle containing a specific nutrient ratio and micronutrient content.



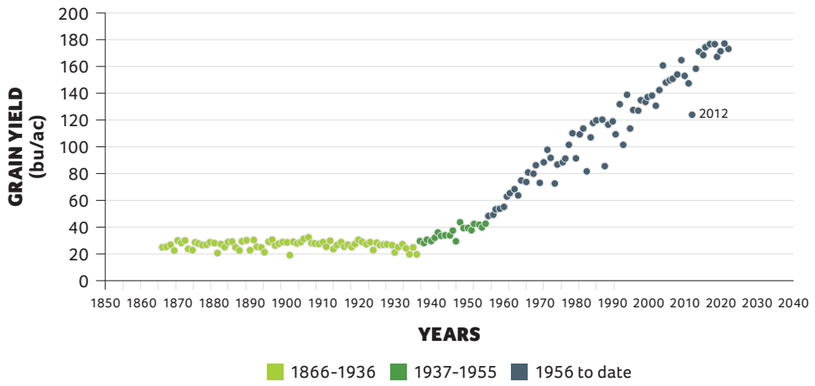
The Future of Corn Production

As of this writing (February 2023), the average yield for U.S. grain corn was trending toward 180 bu/ac, which is why we used this example throughout the guide in reference to nutrient removal rates. It is important to note that average yields continue to move higher as hybrids, nutrient and fertilizer management, and integrated pest management practices improve over time. Many readers of this guide may be hitting yield averages well above 200 bu/ac, depending on where they live and farming practices.

U.S. Yield Trends

Figure 2 shows the average corn yield for the U.S. since 1866. Note the rapid improvement in yield over the past 50 years. In fact, the annual rate of corn yield improvement more than doubled to about 1.9 bushels per acre per year and has continued at that steady annual rate ever since (Nielsen 2023).

FIGURE 2: ANNUAL U.S. CORN GRAIN YIELDS AND HISTORICAL TRENDS SINCE 1866.



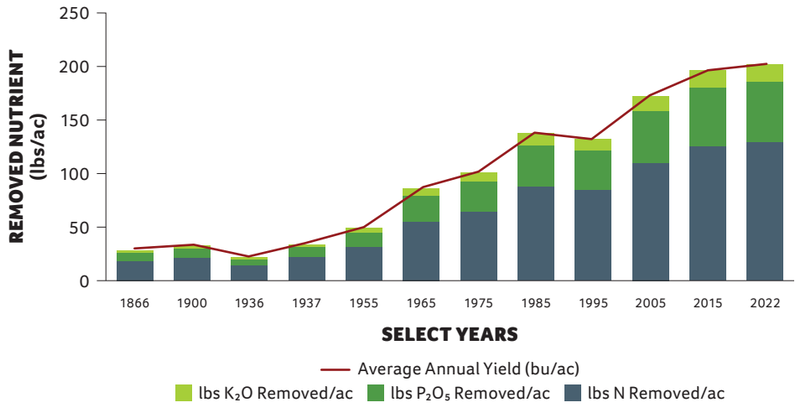
Source: Data derived from annual USDA-NASS Crop Production Reports.
Graph and caption from Dr. Rob Nielsen Historical Corn Grain Yields in the U.S. (Purdue University).

Nutrient Removal Trends (Grain Only)

In Figure 3 below, we graph out how many lbs/ac of key plant nutrients are removed from the soil each year, as determined by yield. For simplicity, we picked a few key years to model out based on new developments in yield (see Figure 3).

The two figures clearly show a lockstep trend of increasing annual yield and tandem nutrient removal. If these nutrients are not replaced, typically through fertilizers, manures, composts, etc., the soil will begin to lose its productive capacity.

FIGURE 3: NUTRIENT REMOVALS FOR NPK BASED ON THE AVERAGE ANNUAL YIELD FOR THE U.S.



Source: Annual USDA-NASS Crop Production Reports.

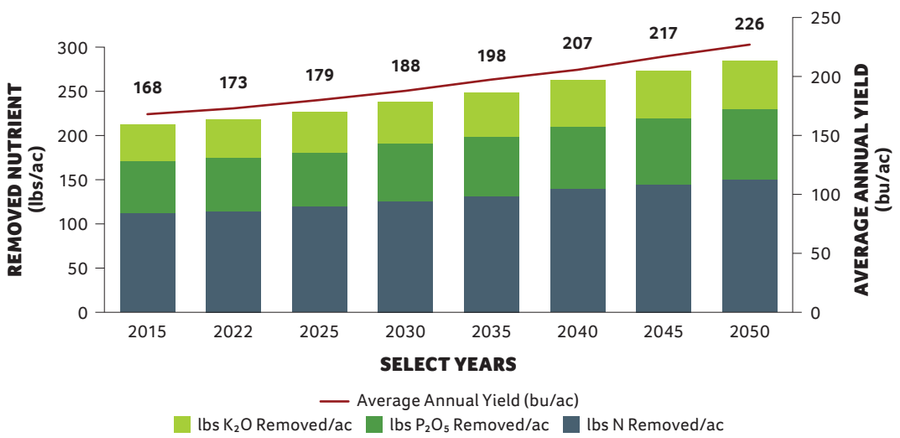
Future Nutrient Removal Trends

Based on the current annual rate of corn yield improvement (1.9 bushels per acre per year), we can make some projections on where corn yield AND nutrient removal trends might be headed, based on current technologies and practices (Nielsen 2023), (Figure 4).

Figure 4 shows that nutrient removals are expected to increase with yields and that the historical removal of nutrients will be much larger in magnitude. These nutrients will need to be replaced to maintain soil productivity and profitability.

In the next exercise, we will walk through how to calculate the lbs/ac of NPK needed to satisfy the removal rate for your fields and recent yield performance.

FIGURE 4: PREDICTED NUTRIENT REMOVALS FOR NPK BASED ON THE AVERAGE ANNUAL YIELD INCREASE FOR THE U.S. OF 1.9 BU/AC/YEAR.



Source: Annual USDA-NASS Crop Production Reports.

How many nutrients should you be applying (assumes stover is left on field)?

1) 1 bushel of corn removes the following (*IPNI Estimates of Nutrient Uptake and Removal*):

- 0.67 lbs N/ac
- 0.35 lbs P_2O_5/ac
- 0.25 lbs K_2O/ac

2) Multiply each value by your current yield or potential yield goal to look at removal rates:

- 0.67 lbs N/ac x _____ bu/ac yield = _____ total N removed (lbs/ac)
- 0.35 lbs P_2O_5/ac x _____ bu/ac yield = _____ total P_2O_5 removed (lbs/ac)
- 0.25 lbs K_2O/ac x _____ bu/ac yield = _____ total K_2O removed (lbs/ac)

3) Advanced Exercise: Determine how many lbs/ac of NPK you need to apply to match your yield goal from Step 2 based on the efficiency of nutrient use by the crop (*IPNI Estimates of Nutrient Uptake and Removal*):

- _____ total N removed (lbs/ac) ÷ (0.7 efficiency) = total lbs N/ac to apply
- _____ total P_2O_5 removed (lbs/ac) ÷ (0.3 efficiency) = total lbs P_2O_5/ac to apply
- _____ total K_2O removed (lbs/ac) ÷ (0.6 efficiency) = total lbs K_2O/ac to apply

4) Talk to your local crop input retailer for help on converting the application rates to your preferred fertilizer products.

Conclusion

A successful crop management plan should systematically identify resources available and potential limiting factors and, to the extent possible, work to optimize the use of the resources and eliminate the limiting factors. As each is identified and corrected, another becomes the next most important. By addressing them one by one, field production potential can be increased and limiting factors systematically eliminated. Through this process and through continued increases in genetic yield potential and improved technology, average U.S. corn yields continue to increase at about 2 bushels per acre per year.

Management practices for corn production are constantly evolving through research, farmer experience, and technology improvements. Today's corn growers have more technology, more information, and more opportunities than their predecessors. They operate in a global production-marketing-utilization system, and as such face more challenges in developing those opportunities. A systematic management approach utilizes the best information and consulting support available. Today's corn growers have a better chance of optimizing the use of their capital, physical, and human resources to produce higher yields of higher quality grain for more demanding and discriminating markets, all at a lower cost of production per bushel, and in a more environmentally friendly manner.

High yield management generally increases fertilizer use, but that is not necessarily a negative factor for environmental concerns. On the contrary, high grain yields are accompanied by more vigorous root systems and increased crop residue at the end of the season. Healthy, high-yield crops are more effective in protecting the soil against erosion and in improving soil health. Each 50-bushels-per-acre corn yield increase produces about a ton of additional stover as well as more below-ground root mass to help hold soil in place. (Note: 1 pound per acre of grain results in an additional 1 pound per acre of stover plus .75 pounds per acre of root dry matter.) A healthy crop managed for high yield also will be less susceptible to pest problems, so will often require less pesticide use. Balanced fertility for high yields also means more efficient nutrient use. High phosphorus and potassium help the plant utilize soil nitrogen more efficiently, leaving less to cause water quality concerns. So high yield management is environmentally beneficial management. Adequate and balanced fertility for the crop also supports a healthy soil microbiome for healthier soils and sustainable crop production.



Farmers need a strategic production plan, developed around best management practices (BMPs) to ensure that all important details are considered. More important are the potential interactions among practices, since most management decisions affect other decisions that have to be made. Some of the key BMPs and their potential interaction with nutrient management include:

Realistic Yield Goal

The yield goal is the target for the production plan. It should be challenging yet realistic and achievable in a good year. A goal that is 10 to 15 percent higher than the previous high for the field is a good starting point. Be sure to adjust fertilizer plan to your new yield goal.

Good Records

Records have always been important. Now they are essential. Good records, preferably computerized, track use of nutrients, changes in soil tests, and removal by crops. Site-specific records, geographically referenced, along with yield monitor data help track variability within the field. They serve as a summary of the past, a snapshot of the present, and a guide for the future. They are also important documentation for what has been done in each field.

Pest Management

Weeds compete with crop plants for water, space, sunlight, and nutrients. Insects damage roots, vegetation, and grain quality and reduce efficiency in nutrient use. In the process, they cut yields and profits. Diseases degrade plant health, grain quality, and in other ways reduce yield potential. A sound integrated pest management program is an essential BMP to help gain maximum return on nutrient investment.

Hybrid Selection

Choosing the right hybrid is critical. Select hybrids adapted for the local soil and climate. Spread risk with a range of maturities. Be sure to consider any specific nutrient limitations in making a selection. Local test plots and previous experience are important. Most hybrids will be replaced in a few years, so always have some new ones under evaluation.

Rotation

Most corn is grown in rotation with other crops, depending on the geographic area and local markets. The corn/soybean rotation is most common. Yield advantages of 10 to 15 percent are common benefits to both crops from the rotation, due to breaking of past cycles, nutrient cycling, and root zone characteristics. Be sure to account for nutrient needs for all crops in the rotation.

Tillage

There is a continuing shift to less tillage in growing corn. Better nutrition and more vigorous genetics help support that shift. The benefit is to reduce erosion loss, which removes valuable soil and nutrient resources from the field and can result in water quality problems. Zone tillage systems offer some of the benefits of tillage to help incorporate nutrients, loosen soil, and increase early-season soil temperature, while maintaining a substantial residue cover to protect against erosion. Under reduced tillage, there is more stratification of nutrients, which can reduce uptake efficiency. There is also an increase in response to starter fertilizer when tillage is reduced.



Plant Population, Row Spacing

There is a trend to increase plant populations, with 32,000 to 36,000 plants per acre commonly grown in central Corn Belt areas and under irrigation. This increases the need for maintaining high fertility levels to meet the needs of each plant. Row spacings of 30 inches or less are most common. Narrower rows allow for higher plant populations. Higher populations tend to be more responsive to banded nutrients.

Planting Date

Planting delays reduce yield potential. In most of the Corn Belt, the best planting dates are usually about the first week of May. Delays cut yield potential by about 1.5 bushels per acre per day. The objective is for the corn crop to be pollinating before the hottest days of summer.

Diagnostics

Regular field scouting is a BMP that farmers often overlook. Identifying problems during the growing season and documenting them with geographically referenced notes and photographs provide important information for explaining yield variability and for preventing recurrence of problems in future years. Use tissue analysis and other tools to identify "hidden hunger" in crops. Yield losses can be substantial even before visible symptoms are noted.



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