Fertilizer Use for Horticultural Crops in the U.S. during the 20th Century

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SUMMARY. Tremendous changes have occurred during the past century in the sources and methods for supplying nutrients for horticultural crops. Reliance on animal manure, cover crops, and animal tankage was insufficient to meet the crop nutrient demand for a rapidly expanding population. The Haber-Bosch process for ammonia synthesis (1910s) revolutionized the availability and affordability of nitrogen (N) fertilizer. Discovery of large-scale deposits of rock phosphate in South Carolina (1860s) and Florida (1880s) alleviated widespread nutrient deficiencies. Acidification of rock phosphate and bone material significantly improved phosphorus (P) availability for plants. Discovery of potassium (K)-bearing minerals in New Mexico (1920s) and later in Canada (1960s) now provide a long-term nutrient source. Modern fertilizer technology allows nutrients to be applied in the correct ratio and amount to meet crop needs. Advances in understanding plant nutrition, coupled with slow-release fertilizers, foliar fertilization, soluble nutrients, and the development of soil and tissue testing have all improved the yield and quality of horticultural crops. Future developments will likely focus on fertilization in an increasingly competitive global economy, while requiring sophisticated management to minimize environmental impacts.

The 20th century has been a time of unprecedented change in food production practices in the United States. Advancements in

areas such as plant nutrition, improved genetics, pest control, irrigation, farm mechanization, and transportation have combined to radically transform the horticultural industry. Despite the tremendous changes in the nature of fruit and vegetable production during the past 100 years, many of the same issues, such as nutrient efficiency, crop quality, labor costs, marketing, and profitability, are still concerns of farmers today. The intent of this paper is to review the development of the fertilizer industry and highlight the contributions that fertilizer has made toward improvement in horticultural production.

Nutrient use in the 19th century

Crop production during the last half of the 19th century was on the verge of embracing modern technology. Although ancient civilizations understood the importance of soil fertility, their options to meet crop nutritional requirements were limited to fallowing, animal manures, and cover crops (White, 1970). Improved understanding of mineral nutrition by notable scientists [e.g., Sprengel-Liebig law of the minimum (van der Ploeg et al., 1999)] and the establishment of land grant colleges with the Morrill Act (1862) and the Hatch Act (1887) set the stage for rapid advances to occur. During this period, urban populations were rapidly growing, transportation improved, and processing markets developed—all providing key incentives for major changes in horticultural production.

Prior to this time, fresh-market horticulturists primarily fertilized their fields with large applications of animal manure, frequently provided from nearby city stables and on-farm animals. Application rates of 124 to 247 cartloads/ha (50 to 100 cartloads/acre) of manure were made annually (Becker, 1984). The demand for plant nutrients was so great that during the 1840s horse manure was regularly shipped by boat from Albany, N.Y., to New York City, a distance of over 241.4 km (150 miles) (Hedrick, 1950). Not surprisingly, these vegetable growers were among the first to adopt the use of guano, rock phosphate, superphosphate, and muriate of potash in search of less expensive and more convenient nutrient sources (Becker, 1984). Similar to today, it was noted that although

manure is an excellent nutrient supply, “we must seriously consider its costs” (Cox, 1919). Farmers in New Jersey were paying \$6.61/t (\$6/ton) of manure at an application rate of 22.4 t·ha⁻¹ (10 tons/acre) per year. Cox (1919) noted that this is “quite a tidy sum of money to charge against a crop.”

While important nutrient inputs were obtained from manures and cover crops, Jethro Tull’s experiments on intensive plowing had shown definite benefits from frequent cultivation. In addition to controlling weeds and preparing a uniform seedbed, regular tillage increases the rate of organic matter mineralization and stimulates nutrient release, yet this nutritional benefit became less important as the organic matter content of the soil declined after years of cropping (Warkentin, 2000).

The yield loss due to a shortage of plant nutrients was well recognized during the 19th century, yet there were few feasible and affordable options to increase their supply. Prof. L. Stockbridge warned in 1873 that “We are all agreed ..., that if we are to support our present dense population, if we are to supply food from our soil in its present condition, we must go outside our home resources to do it. The farming of the United States up to this hour has not been a proper culture, but a system of spoliation, and our population in the future has either got to starve or we must adopt some other course.” (Ibach and Mahan, 1968).

Fertilizer use entering the 20th century

Leading agriculturists had long recognized the importance of labor and production expenses in horticultural crop production (Taylor, 1947). In North America, the low population density at this time emphasized “output per person,” rather than “output per acre.” Harris (1883) reported, “Compared with nearly all other countries, our labor is expensive... and the only thing to do is to raise large crops per acre.” As a result, manure (and later fertilizer) was generally applied to crops requiring the most labor per acre. For example, the labor expended on 0.4 ha (1 acre) of onions (*Allium cepa*) or carrots (*Daucus carota*) would be the same as on a 4.0-ha (10 acres) field of barley (*Hordeum vulgare*). “Crops which require a large amount of labor can only be grown on very rich land...and they must get great crops or they cannot pay

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their labor bill" (Harris, 1883). There were clearly many demands on crop producers to enhance productivity and profitability to feed a rapidly growing population.

Crop production during this time was much more dependent on legumes to supply N, the nutrient considered the most yield-limiting for plant growth today. For this reason, the fertilizer material sold in greatest volume was P rather than N. In fact it was not until the latter half of the 20th century that sales of N surpassed those of P (Fig. 1).

NITROGEN. Guano. The dramatic crop responses seen by the users of imported Peruvian guano (dried sea bird manure) during the 1840s to 1870s were well publicized in the farm publications of that time (Skaggs, 1994). Guano rapidly became popular for vegetable farmers because it substituted for fresh fertilizer materials (like stable manure and urban wastes) that were already in use or being imported on to the farm, but were frequently too expensive or difficult to obtain in sufficient quantity. Fertilization with guano would not have been adopted so rapidly if existing nutrient sources and practices had been adequate.

Guano use was also compatible with the contemporary notion of recycling—in that guano nutrients originated from marine life, excreted by seabirds, transported for application to crops, and ultimately returned to the ocean again (Wines, 1985). However, the richest sources of guano were disproportionately high in N (containing relatively little P or K), and it became apparent that guano applications generally stimulated vegetative growth, but did not always increase yields. Despite extravagant claims that individuals were able to purchase "*worn out land, apply guano, and pay for the land, guano, and proceeds from the first crop*" (Wines, 1985), the effects of guano transformed many nutrient-exhausted soils in the agricultural landscape.

Animal by-products. Animal by-products were not commonly used as commercial fertilizers in the U.S. until slaughterhouses became sufficiently large to economically process and transport the by-products. The unsalable parts of the animal carcass were first rendered to remove commercially valuable fats, and then the remaining material was dried, ground, and sold

Fig. 1. Consumption of inorganic nitrogen, potassium, phosphorus in North America since 1955 (FAO, 2003); $P \times 2.29 = P_2O_5$, $K \times 1.2 = K_2O$, 1000 t = 1102.3 tons.

as "tankage." By the late 19th century, the large meat packers were among the nation's largest fertilizer producers.

During this same time, the plant nutritional value of fishmeal was also becoming accepted. After the fish were cooked and the oil extracted, the remaining scrapmeal was dried and bagged. The use of raw fish as fertilizer was well known in coastal regions, but the more easily transported dried material was found to be a convenient and acceptable substitute for increasingly expensive and scarce Peruvian guano in the late 19th century.

Naturally occurring inorganic sources of N were also developed during the late 19th century. Chilean sources of mined sodium nitrate ($NaNO_3$) became the most important supplier of fertilizer N (other than natural organics and manures) until after World War I and the commercial adoption of the Haber-Bosch process. As alternative sources of N became available for crop production, the sole reliance on manures and cover crops gradually diminished (Taylor, 1947).

PHOSPHATE. Adequate P supplies were severely lacking in most of the long-cultivated agricultural lands in the eastern U.S., and no readily available sources were accessible to alleviate crop deficiencies. Animal manure additions were a satisfactory source of N as livestock consumed N-fixing forages and hay; however, the recycled manure did not provide any new inputs of P, K, or other essential nutrients for the

rapidly expanding food production industry.

Through the mid-19th century, ground bones were treated with sulfuric acid to form single superphosphate [$Ca(H_2PO_4)_2 + CaSO_4 \cdot 2H_2O$]. Difficulty in establishing the purity and water solubility of the superphosphate led to many ineffective products and frequent allegations of fraud, fostering a suspicion of the entire fertilizer industry. Due to variability in raw materials, many of the P fertilizers frequently fell short of the advertised chemical analysis. Leading brands of bone-derived superphosphate averaged approximately 2% P (4.6% P_2O_5), far lower than the phosphate materials commonly used today [up to 24% P (55.0% P_2O_5)].

The initial development of domestic phosphate rock resources in South Carolina during the 1860s was the turning point for providing an alternative for bone-derived P. Subsequent discovery and development of vast phosphate deposits in Florida continues to supply a high-quality, low-cost P source. Development of the Florida deposit was followed closely by the discovery of rock phosphate in Tennessee. In addition to Florida, phosphate is currently mined from large reserves in Idaho and North Carolina.

During the early years of the phosphate industry, there was a wide range in water solubility of fertilizer P sources. This characteristic probably received more attention than any other factor in

determining the agronomic effectiveness of P fertilizers. The solubility of commercial P fertilizers is no longer a major concern, since all significant P sources are sufficiently water soluble to optimize plant nutrition when properly used (Thompson, 1992). The exception is when rock phosphate is added directly as a nutrient source. The solubility of rock phosphate is generally quite low, with North Carolina and Tunisian rock generally having the greatest plant availability. The direct application of rock phosphate is generally recommended only in very acidic soils and where the rock is finely ground and well distributed in the soil (Bolland et al., 1988). More than a century ago, growers learned that rock P was not a preferred plant nutrient source if other soluble P-containing materials were available.

POTASH. Except for wood ash, there was no readily accessible source of potash prior to the mid-1800s. There were attempts to develop greensand (glauconite) marl in New Jersey during the 1860s, but this material [4% to 5% K (4.8% to 6.0% K_2O)] was bulky to transport and not sufficiently soluble to provide significant value as a K source (Tedrow, 2002).

Discovery of extensive K deposits in Germany in the 1860s marked the beginning of the modern potash industry. German imports were the most important source of potash in North America until the outbreak of World War I, when the sudden embargo on German potash led to severe shortages. Widespread K deficiencies were reported during the time of the embargo, especially with cotton (*Gossypium hirsutum*), potatoes (*Solanum tuberosum*), and fresh vegetable crops (Schreiner et al., 1938). This sudden loss of the sole potash supply spurred the search for alternative domestic sources, such as by-products from blast furnaces and cement mills, as well as seaweed. It was also during the embargo that the development of domestic potash deposits in California, Utah, and Nebraska occurred (Nelson, 1990). The discovery of large potash reserves in New Mexico during the late 1920s marked the beginning of large-scale potash production in North America. Vast potash reserves from Canada now serve as the major source of this nutrient for most of North America and many other parts of the world (Roberts and Stewart, 2002).

Fertilizer use in the early 20th century

Vegetable and fruit production was beginning to be radically transformed during the early 20th century. For example, between 1919 and 1934, the acreage of vegetables grown for sale in the U.S. increased 165%, while the population increased only 20% (Reid, 1940). Improvement in transportation and refrigeration began to provide consumers with fresh and high quality produce year-round, with harvests occurring in different locations depending on the season.

By the early 20th century, the importance of animal manures as a nutrient source was diminishing for fruit and vegetable production (Taylor, 1947). In modern terminology, the value of many types of manure at this time was approximately 0.5N–0.1P–0.4K (Salter and Schollenberger, 1938). Additionally, much of the manure N is present in a slowly available form that does not release N in close synchrony with the nutrient requirement of many crops. The commercial fertilizer equivalent of 0.9 t (1 ton) of manure could be purchased for \$1 to \$2 as 10N–2.2P–8.3K (10N–5P₂O₅–10K₂O) and the labor expense associated with applying 45.4 kg (100 lb) of fertilizer was much less than that with applying 0.9 t of manure (Salter and Schollenberger, 1938).

Although the potential indirect benefits of organic manures, such as changing the physical properties of soil was recognized, the diminishing importance of farm livestock (as tractors, trucks and automobiles replaced animal power) and the greater expense associated with manure handling and transportation combined to make this nutrient source less attractive.

The number of products and the chemical content of commercial fertilizers changed rapidly during the early part of the 20th century. Although the nutrient content of these fertilizers was relatively low compared with fertilizers used today, they were more concentrated, convenient to use, and more efficient in farming operations than the products that had been available earlier.

The raw materials used in preparation of these early commercial fertilizers were derived primarily from two sources—recycled by-products and mineral deposits. The nutrient content of these two materials is usually low,

so the fertilizer materials prepared from them was relatively low in total nutrients. Since there was no technology available for producing fertilizers containing more nutrients, there was relatively little change in the nutrient content of mixed fertilizers during this period.

Extensive research was conducted at most state and federal agricultural research stations across North America on vegetable crops during the first decades of the century, concluding that inorganic nutrient sources were equivalent or superior to organic sources. For example, reports from New Jersey indicated that “...we do not find any important superiority in manure over a proper commercial fertilizer... wherever manure has given important increase, these increases have been approached or surpassed by a proper commercial fertilizer” (Stewart, 1911). Besides the obvious benefits in boosting crop yields, quality, and farm profitability, farmers were encouraged to use fertilizer to avoid “*exhausting the plant food in the soil and that soil depletion means lean years ahead*” (Minch, 1917).

The increasing availability of commercial fertilizers also provided farmers the ability to apply specific nutrients to meet individual crop and soil requirements, instead of using the unbalanced ratio of nutrients that came in manure—determined largely by the animal feed composition (e.g., Tarkalson and Mikkelsen, 2003). The USDA and many state agricultural colleges recommended that farmers mix individual fertilizer components on their own farm. The rationale was that the farmers saved money by mixing fertilizers themselves and they could control the composition of the fertilizer blend (Sheridan, 1979). This was in contrast with Europe, where the fertilizer manufacturer would typically prepare the mixture of fertilizers for sale (Schreiner et al., 1938).

Early attempts at industrial fixation of N occurred using hydroelectricity to produce calcium cyanamide (CN₂Ca) at a plant built in Niagara Falls in 1908 (Nelson, 1990). Production at this plant eventually reached approximately 108,862 t (120,000 tons), but the war diverted this material from fertilizer use. A second cyanamide plant was built in Muscle Shoals, Ala., setting the stage for the establishment of the Tennessee Valley Authority-Na-

tional Fertilizer Development Center, which was responsible for much of the fertilizer technology developed during this century.

Despite the rapid adoption of new fertilizer materials, the lack of an adequate and affordable N source was still the primary nutritional factor limiting crop yields. During the early 20th century, the price of many of the traditionally used organic N sources, such as cottonseed meal, dried blood, and animal tankage increased due to their rising demand as animal feed. The increasing crisis looming from an inadequate N supply was described in a government report in 1924: "*What is done with the N problem in the next ten years will probably determine to a considerable degree whether American standards of living can be maintained. There seems no escape from the conclusion that unless... cheaper fixed nitrogen can be supplied to agriculture, steady decreases in crop production per acre will continue while our population is increasing...*" (Curtis, 1924, cited by Ibach and Mahan, 1968).

Development of the fertilizer industry after 1930

After extensive research and engineering, Fritz Haber and Carl Bosch succeeded in the first large-scale synthesis of ammonia (NH_3), with the first plant opening in Germany in 1911 (Smil, 2000). Much of the early NH_3 production capacity was used for explosives during World War I, but new fertilizer products slowly became available for agriculture when the fighting ceased. Manufacturing of NH_3 -based fertilizers began in the U.S. in 1921 with production of ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$. This was followed a few years later with production of NaNO_3 and then the introduction of solid urea $[\text{CO}(\text{NH}_2)_2]$. However, the use of inorganic N fertilizer was not widespread due to its perceived excessive cost. Despite this perception, by the late 1920s, inorganic N sources cost less than half the price of organic N sources per unit of nutrient. Normal superphosphate was still the major fertilizer material used in the U.S. Its price per unit of P was less than one-third the price per unit of N fertilizer (Ibach and Mahan, 1968).

Domestic production of NH_3 was about 281,227 t (310,000 tons) in 1939. By the end of World War II, annual NH_3 capacity in the U.S.

exceeded 1.45 million t (1.6 million tons)—most of which changed to private ownership following the end of the war (Smil, 2000). Since natural gas is the key component in the synthesis of NH_3 , many of the petroleum and gas producers also became major producers of fertilizer N during this time. The use of commercially produced N became more accepted as NH_3 (82% N), urea (46% N), and ammonium nitrate $[\text{NH}_4\text{NO}_3]$ (34% N) became readily accessible. The economic advantages of increasing the plant food content flowed from lower transportation, handling, bagging, storage, application and labor costs, resulting in considerable economic benefits at the factory and on the farm.

Changes in P sources also occurred during this time. The predominant P source for over 100 years had been normal superphosphate [8% P (18.3% P_2O_5)], with its production peaking in 1952. The introduction of triple superphosphate $[\text{Ca}(\text{H}_2\text{PO}_4)_2]$: 17 to 20% P (38.9 to 45.8% P_2O_5) resulted in this material becoming the most popular P source during the 1960s. With the subsequent development of the TVA process for production of monoammonium phosphate (MAP) $[\text{NH}_4\text{H}_2\text{PO}_4]$: 11N–23P–0K (52.7% P_2O_5) and diammonium phosphate (DAP) $[(\text{NH}_4)_2\text{HPO}_4]$: 18N–20P–0K (45.8% P_2O_5), these materials rapidly became the most widely used P fertilizers worldwide (Nelson, 1990).

Phosphorus is the eleventh most abundant element in the earth's crust. Rock phosphate for the production of fertilizer comes from a variety of worldwide deposits. Projections of future mineral P supplies indicate that reserves for several hundred years still remain in sedimentary deposits throughout the world (Roberts and Stewart, 2002), although the highest purity rocks are being utilized first.

The recognition of the essential role of micronutrients for plant growth was also critical to the growth of the horticultural industry (Maynard and Lorenz, 1979). As recently as 1927, large areas of now extremely productive organic soils in Florida were considered unsuitable for crop production (Allison et al., 1927). It was found that application of Cu to these soils enhanced plant growth. Positive yield responses for field-grown vegetables in this region have been seen from application of boron, copper, iron, manganese,

molybdenum, and zinc (Locascio, 1987). Although considerable progress has been made in understanding the specific micronutrient requirement of many crops, the chemistry of these elements and their behavior in soil is not as clearly understood as that of the primary nutrients. In soils with a long history of animal manures (Mikkelsen, 2000) or municipal compost application (Gouin, 1993), special care must be made regarding excessive micronutrient accumulation.

Fertilizer use in the modern horticulture industry

Fertilizer production now involves complex technology for transforming natural resources from their raw state into a form that can efficiently provide essential components for plant growth (Hochmuth, 2003). The modern nutrient marketplace must continually respond to the changing needs of the horticultural industry, where it is recognized that long-term productivity starts with the soil. A properly managed soil will provide the crop with sufficient nutrients for optimum growth and yield. Fertilizer manufacturers provide growers with the highest nutrient content possible to minimize transportation, handling, and application costs, thereby improving farm profitability.

High purity solution fertilizers offer multiple advantages for supplying plant nutrients. Modern controlled-release fertilizers provide benefits for improving plant growth, minimizing labor demands, and offering potential environmental benefits. Foliar fertilization has become more widespread with the use of consistently pure fertilizer materials and improved knowledge of plant physiology and crop response. Expanded use of soil and foliar analysis, along with geospatial techniques, allows the required nutrients to be utilized in the proper amount, at the proper time, and in the precise location where they are needed.

COMMERCIAL SOLUTION FERTILIZERS. The production of solution fertilizers has gained in importance since the 1950s. The use of N solutions based on urea-ammonium nitrate [UAN (28 to 32% N)] fills an important role in many soil fertility programs. The development of a simple process for production of ammonium polyphosphate [10N–15P–0K (34.4% P_2O_5) and 11N–16P–0K (36.6% P_2O_5)]

provided a method of producing clear solutions with a high nutrient content (Palgrave, 1991). The demand for high nutrient content solutions also led to the development of fertilizer suspensions where fine fertilizer particles and crystals are kept in suspension by means of a gelling agent, such as attapulgite or bentonite clay.

The use of solution fertilizers provides several potential benefits for horticultural production (Hagin and Lowengart-Aycicegi, 1999). For example, fertilizer solutions fit well with fertigation systems, where nutrients are precisely delivered through a pressurized irrigation system. Applying fertilizer through an irrigation system allows nutrients to be provided to the crop in multiple doses with minimum labor. By combining fertilizer with irrigation water, its direct placement in the active root zone can lead to increased efficiency. The frequent application of small quantities of fertilizer through the irrigation system also allows improved salinity management. Fluid fertilizers can be blended to meet the specific plant nutrient requirement, mixed with other agricultural chemicals, and then applied uniformly due to its homogeneous composition. The complete solubility of the added nutrients can provide immediate availability for plant nutrition. Precise placement of nutrient solutions applied as starter fertilizers help promote early-season plant growth with minimal application rates.

FOLIAR FERTILIZATION. Foliar fertilization practices involve application of dilute nutrient solutions directly to the plant vegetation. This practice generally results in rapid nutrient acquisition and almost immediate correction of many plant nutrient deficiencies. While plants are not well adapted for receiving large amounts of nutrients through their leaves, this practice is frequently considered as a supplement to a standard soil fertility program. The expense associated with repeated foliar sprays often limits this technique to relatively high-value crops.

There are a number of soluble materials that are well suited for foliar fertilization, but the majority of foliarly applied nutrients are micronutrients. The development of chelated micronutrient fertilizers allows rapid correction of plant deficiencies with low application rates. The availability of low-biuret urea (Mikkelsen, 1990) and other

specialty products (e.g., triazone-N) as foliar sprays can aid in mid-season N management for many crops. Additional advantages to foliar sprays are that much lower application rates are required than when nutrients are applied to soil, uniform application is easy to achieve, and the crop response is very rapid so deficiencies can be corrected during the growing season as soon as they are detected. Foliar nutrients are frequently added at the same time as other production chemicals are applied to the crop. Recent work has suggested that foliar fertilization of P and K can also provide systemic protection from some foliar pathogens (Reuveni and Reuveni, 1998).

CONTROLLED-RELEASE FERTILIZERS. Another major advance in fertilizer technology was launched during the 1950s with the development of controlled-release fertilizers (Atkins, 1979). The early products were based on urea formaldehyde and isobutylidene diurea, which release N as a result of microbial hydrolysis and degradation. A number of materials were tested as coating materials for urea and granulated fertilizers—the most successful early fertilizers were sulfur-coated urea and Osmocote (Shaviv, 2001). Currently used fertilizer coatings include materials such as polyurethane or polyolefin resins that provide enhanced control of nutrient release. Fertilizer release from some of these products is controlled by biological activity, while release from other materials is governed largely by temperature and moisture effects on the fertilizer shell. The chemistry and coatings can be adjusted to vary the nutrient release rate, ranging from several weeks to several years.

The use of controlled-release fertilizers offers many potential benefits to growers. When fertilizer release rates are synchronized with plant nutrient demand, superior plant performance and reduced nutrient loss are frequently reported (Shaviv and Mikkelsen, 1993). A single pre-plant application of controlled-release fertilizer for a crop grown under plastic may allow the full-season nutrient requirement to be met. The labor needs and equipment requirement for multiple nutrient applications is reduced, compared with a single application of controlled-release fertilizer. Potential environmental benefits may also result from reduced nutrient losses to air and water. Since

the price of controlled-release fertilizers can be from two to 10 times more than that of soluble fertilizers per unit of nutrient, these specialized materials are typically used for higher value crops where their benefits justify the additional expense.

SOIL TESTING. The extensive use of soil testing has become well established since the 1940s (Westerman, 1990). Traditionally, these predictive techniques were developed to establish the requirement for lime and fertilizers to meet production goals, with a focus on nutrient deficiencies. More recent applications have used soil testing as an environmental tool to locate areas of adequate or excessive fertilization. Use of soil testing to identify areas where specific nutrients are needed is still important today for economic and environmental purposes. With widespread adoption of site-specific fertilization techniques, it is now possible to manage the fertility in fields with highly variable soils and optimize crop production.

A successful soil-testing program relies on local interpretation of the data and knowledge of specific crop responses to nutrient additions. Many recommendations currently used in North America are based on decades-old field experiments conducted using out-of-date production systems, with obsolete cultivars, or extrapolated from agronomic crops. Unfortunately, there is insufficient effort to update these historic nutrient recommendations, even with the renewed emphasis on farm sustainability and environmental quality.

PLANT TISSUE ANALYSIS. The use of plant analysis has become an essential fertilization aid for many horticulturists (Jones, 1997). This technique is commonly used by growers and consultants to monitor plant performance and then make mid-season corrections to the plant nutrient status. Growers typically have easy access to overnight services to deliver tissue samples to the laboratory where highly automated analytical procedures return results directly to internet-accessible computers. This rapid information exchange makes tissue testing a very useful tool for monitoring crop health. Considerable work remains to understand the optimal ratio of foliar nutrients for various crops and stages of growth, and thereby determine the most appropriate way to correct single and multiple

plant nutrient deficiencies (Mills and Jones, 1997).

RETURN TO MANURES AND COVER CROPS? There is interest in returning to earlier fertilization practices for horticultural crop production. Improved utilization of animal manures and recycled municipal products should be encouraged, especially where a local surplus of these materials may result in over-application and negative water quality impacts. Composts derived from urban and manure products can fill an important role in crop production (Power and Dick, 2000). Additionally, use of leguminous green manures may also provide a useful production role for inputs of N. However, increased pressure to produce more food on a limited amount of high-value farmland has frequently restricted increased adoption of cover crops. With mounting interest in land preservation and wildlife conservation, it is not likely that the amount of cultivated land will greatly increase in North America in the coming years. Moreover, green manures do not supply additional P, K, or other nutrients removed from the soil in harvested crops. However, the use of leguminous cover crops can contribute to the soil N supply, may improve the physical properties of soils where few crop residues are returned, and provide a beneficial role in pest management.

Expanded use of animal manures is likely to be limited as well. Much of the animal manure is produced in intensive feeding operations that are not close to major horticultural production areas. With current energy prices, the high cost of transportation often makes manure a less desirable nutrient source than conventional fertilizers. While greater utilization of urban and animal by-products can provide an important, but relatively minor source of nutrients—the same nutrient cycles operate in both organic and inorganically fertilized soils (Stockdale et al., 2002).

A recent summary of P and K budgets (Fig. 2) for major crop-producing regions of the U.S. (ratio of inputs of fertilizer and manure inputs and removal by corn, soybean, wheat, and cotton) shows that *average* removal rates currently exceed the nutrient inputs (Fixen and Johnston, 2002). While many horticultural crops receive higher rates of fertilization than agronomic crops, it is clear that negative nutrient budgets are not compatible

with sustainable agricultural productivity. Regional areas of nutrient surplus should be carefully monitored, but the frequent misconception of widespread over-fertilization does not appear to be the case.

Fertilization benefits for the horticultural industry

A long history of research and experience has clearly established the beneficial response of horticultural crops to proper fertilization. These positive crop responses are commonly reflected in increased yields, improved quality, and enhanced profitability for the grower. While these benefits are well documented (e.g., Anac and Martin-Prevel, 1999), a full review is beyond the scope of this paper.

Many “quality” components of specific commodities are consistently improved when the plants are provided with proper nutrition. Although the term “quality” has multiple definitions, there is abundant literature to link improvements in many parameters to well-fertilized crops. For example, the nutritional value of food for human diets is enhanced when crops are adequately fertilized. Recent research has demonstrated the boost in phytochemicals or health-functional components in food products grown with proper nutrition. Other benefits from properly fertilized crops include enhanced disease resistance, and improved product appearance and hygiene. Future research in this area will continue to document the benefits of properly fertilized crops, regardless of the source of nutrients.

The development of the fertilizer industry has made significant contributions to the horticultural industry by improving the yield and quality of crops. Improved understanding of plant nutrition, coupled with increasing sophisticated fertilizer materials, has resulted in superior crop health. Future developments will likely include increased emphasis on fertilization for overall farm profitability in an increasingly competitive global economy—while requiring increasing levels of management to minimize adverse environmental impacts.

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Fig. 2. Ratio of phosphorus and potassium removal by major agronomic crops (corn, soybeans, wheat and cotton) and nutrient inputs (fertilizer plus manure) in the U.S. since 1960 (adapted from Fixen and Johnston, 2002).

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