Nutritional Requirements of Potatoes

D. T. Westermann

USDA-ARS, Northwest Irrigation and Soils Research Laboratory, Kimberly, ID 83341, USA
Tel: 208-423-6524; Fax: 208-423-6555; Email: dtw@nwisrl.ars.usda.gov

ABSTRACT

Plant nutrition is the practice of providing to the plant the right nutrient, in the right amount, in the right place, at the right time. This paper gives an overview of the roles that each of the 16 essential nutrients have in plant nutrition, their relative mobility as related to deficiency symptom expression, and what is generally known about nutrient responses to field applications on potatoes (*Solanum tuberosum* L.) in the USA and Canada. Maintaining high crop yields with minimum nutrient losses to the environment is and will continue to be a significant challenge to the potato producer. Additional nutritional research efforts in genetically modified plants, precision agriculture, food quality and safety, fertilizer impurities, and other management concerns should significantly help the producer in this effort.

RESUMEN

La nutrición vegetal consiste en proporcionar a la planta el nutriente correcto, la cantidad correcta, el lugar correcto y el momento correcto. Este artículo da una visión general de los roles que tiene cada uno de los 16 nutrientes esenciales en la planta, su movilidad en relación con la expresión de los síntomas de deficiencia y lo que generalmente se conoce sobre las respuestas de la aplicación en papa (*Solanum tuberosum* L.) en el campo, en EUA y Canadá. El hecho de mantener rendimientos altos con pérdida mínima de nutrientes en el suelo es y continuará siendo un desafío significativo para el productor de papa. Cualquier esfuerzo de investigación que se haga sobre nutrición adicional en plantas genéticamente modificadas, agricultura de precisión, calidad alimentaria y seguridad, impurezas de los fertilizantes y otros aspectos de manejo deben ayudar significativamente al productor.

ESSENTIAL NUTRIENTS

Only relatively few chemical elements are necessary for plant growth. To be an essential chemical element from the perspective of plant nutrition (a) it must be present for the plant to complete its life cycle, (b) its metabolic role cannot be replaced by another chemical element, and (c) it is directly involved in a metabolic process within the plant, either having a direct role in the process or as a compound component involved in the process. The 16 chemical elements that fulfill these criteria are carbon (C), hydrogen (H), oxygen (O), nitrogen (N), potassium (K), phosphorus (P), sulfur (S), calcium (Ca), magnesium (Mg), zinc (Zn), manganese (Mn), iron (Fe), copper (Cu), boron (B), molybdenum (Mo), and chloride (Cl). The plant obtains three, C, H, and O, from air and water, while the remaining 13 are obtained from soil and fertilizer sources. Nitrogen can also be obtained from the air by symbiotic organisms for use by legumes and other plants.

It is only the intent of this paper to briefly describe the role that each of the essential elements has in the plant, as they are already fully described by others (e.g., Mengel and Kirkby 1979; Marschner 1986). Carbon, hydrogen, and oxygen are components of all organic compounds. Carbon is also a critical component of the carboxylic group. Nitrogen is a primary component of all nucleic acids, proteins, and amino acids. Potassium is necessary for the activation of some enzyme systems, the translocation of carbohydrates, and for osomoregulation. Phosphorous is involved in the energy transfer process and is present in phosphorlated sugars, alcohols and lipids. Calcium functions as a structural component of cell walls, in cell division and elongation, and membrane permeability. Mag-

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nesium is a component of the chlorophyll molecule and an essential cofactor for the phosphorylation process. Sulfur is a component of selected amino acids. Zinc is a cofactor for several enzyme systems, including dehydrogenases and involved in tryptophane synthesis. Manganese is involved in the photosynthetic process and as an activator for IAA oxidase. Iron is essential in electron transfer, for heme enzymes and chlorophyll function. Copper is necessary for oxidase enzyme activity and chloroplasts. Boron plays a role in cell wall stability, cell differentiation and carbohydrate metabolism. Molybdenum is essential for nitrate reductase and nitrogenase enzyme activity. Chloride functions in the photosystem II process and as an osmoticum.

Other elements are classified as having a beneficial role in plants. These include sodium (Na), cobalt (Co), nickel (Ni), silica (Si), vanadium (V), iodide (I^-), and selenium (Se). Sodium can partially substitute for K's metabolic role in some plants, e.g., sugarbeets, and is considered to be an essential element for *Halophytes*. Cobalt is necessary for dinitrogen fixation and is a component of vitamin B_{12} in legumes. Nickel was recently shown to be a component of the urease enzyme system and necessary for ureide metabolism. Silica is necessary for the growth of diatoms and stimulates the growth of some wetland grasses such as rice. Some algae species benefit from the presence of V. Plant species that act as Se accumulators sometimes show a growth benefit from Se additions.

PLANT UPTAKE AND MOBILITY

Active and passive mechanisms are involved in moving ions from the solution contacting the roots into the plant cell. The active process moves ions against an electrochemical or concentration gradient and requires metabolic energy. The passive process moves ions along an electrochemical or concentration gradient and is generally considered to not require metabolic energy. Most essential elements are taken up by a combination of the two mechanisms, the active mechanism being more important at lower solution concentrations. Some ions are carried along with the transpirational stream.

Interactions can occur between ions during the uptake process. Competitive interactions occur between ions of similar charge and size, e.g., K^+ and NH_4^+ or NO_3^- and Cl^-, by competing for the uptake mechanism or carrier. The antagonism interaction is similar to competition, but the ions can be different such as K^+ and Mg^{++}. A synergism interaction is enhanced uptake of one ion in response to the uptake of another ion, primarily to maintain electrical neutrality within the plant. Plants will partially compensate for this effect by the production of organic ions internally or by releasing a H^+ or HCO_3^- ion into the solution surrounding the root. The latter mechanism affects the availability of inorganic ions whose solubility depends upon the pH in the rhizosphere.

Ions move to the root-solution interface by mass-flow and diffusion (Barber 1995). When ions are at a relatively high concentration in the solution, there are sufficient amounts carried by the transpirational stream to supply plant needs, such as for Cl, Ca, Mg, and NO_3-N. Mass-flow can also be important for SO_4-S and K. When ions are at a relatively low concentration (<0.5 mg L^{-1}), uptake is faster than movement by mass-flow and the concentration at the root-solution interface will be near zero. Under these conditions, movement to the soil-root interface is by diffusion down a concentration gradient. Diffusion is important for K, P, Zn, Mn, Cu, Fe, B, and Mo. Some ions are taken up by direct contact of the root with the ion on the exchange complex or soil particle. The portion of ions generally taken up by this mechanism is not large since roots contact less than 5% the soil surface area.

Two additional factors affecting ion uptake are mycorrhizae infection and the chemical, physical, and biological conditions in the rhizosphere. Mycorrhizae are mutually beneficial fungi that infect the root, extending the effective volume from which plant roots take up nutrients. This process is most important for ions that move to the root by diffusion. The degree of root infection is also important. Today's commercial potato varieties generally have a relatively low incidence of mycorrhizae infection. Infection also decreases as nutrient availabilities increase. As introduced in previous paragraphs, the immediate volume of soil surrounding the root, the rhizosphere, has an important role in nutrient uptake because nutrient solubilities are dependent upon solution pH, which may be modified by root exudates. This area is also biologically active because of carbon enrichment from cell losses and root exudates. The relative distribution of beneficial and harmful organisms in the rhizosphere and their effect on plant nutrition and health are largely unknown.

The relative mobility of the essential elements in the plant's vascular tissues affects the appearance of deficiency symptoms and nutrient application protocols. All nutrients are considered to be mobile in the xylem vessels. Xylem transport occurs in one direction, while phloem transport is bidirectional. Since there is very little cross linkage, the mobility of the nutrient element in the phloem depends upon the form and the ability of the plant to load the element into the phloem. In general, N, P, K, Mg, Cl, and S and their associated compounds are very mobile in the phloem, while Zn, Mo, and Cu mobilities are intermediate. Nutrient elements not mobile in the phloem of herbaceous plants are Ca, B, Fe, and Mn. The relative mobility of Mn, B, and Cl in the phloem is partially dependent upon the plant species.

Deficiency symptoms for phloem-mobile nutrients appear initially on the older leaves, while deficiency symptoms for the phloem-immobile nutrients appear on the immature leaves or growing tips first. Complete correction of deficiencies for phloem immobile nutrients is difficult with foliar sprays, particularly for plants with the harvestable portion below ground. Recent studies show significant B phloem mobility in plant species that form B-sorbitol complexes (Brown and Hu 1996).

POTATO NUTRIENT REQUIREMENTS

Potassium and nitrogen are found in the largest amounts in a potato plant, followed by Ca and Mg (Table 1). Most of the phloem-mobile nutrients will be in the tubers at harvest while the immobile nutrients will be in the residual vegetative portions of the plant. Total uptake amounts are site-specific since plants generally take up more nutrients than required if available. Nutrient uptake is nearly complete when the majority of tuber growth ends since little additional uptake occurs during the maturation growth stage (Westermann 1993).

Our relative ability to use a soil test to predict nutrient requirement or a plant-tissue test to determine nutrient sufficiency or deficiency in the potato plant depends upon the nutrient. In general, better information is available for plant-tissue tests than for soil tests for most nutrients (Table 1). The extremes of a nutrient deficiency can be easily determined, but the nutritional status of plants found in the transition zone between deficiency and adequacy is not always correctly determined. There are wide ranges of known documented field response data in the USA and Canada (Table 1). Known responses are well documented for N, P, and K, while those for S, Mg, Zn, and Mn are intermediate, and essentially none are available for Fe, Cl, and Mo. Only limited information is available for Ca, B, and Cu. Three states reported improved internal tuber quality from applying Ca materials, but did not report soil or plant calibration data for Ca. Limited data are also available for Mg and S. Of all the micronutrients, reliable soil and plant data are available only for Zn, with only plant data for Mn. For the others, a significant amount of information is extrapolated from other geographic areas or other crops, or sufficient nutrient concentrations are set by default because there were no responses to the applied nutrients. The response data reported in Table 1 are not inclusive as not all states responded to the information request nor was the private consulting industry contacted. As management systems continue to improve, additional nutrient deficiencies will be identified and reported. An example in another crop is a recent report of wheat responding to Cl application in Montana (Engel et al. 1998).

Emerging nutrient diagnostic technologies include the chlorophyll meter and remote sensing. The chlorophyll meter should be able to adequately assess the plant's N status if it is properly calibrated. The user will have to recognize that many factors affect the plant's chlorophyll content when using the meter. Remote sensing may eventually be a reliable diagnostic tool for the plant's real-time nutritional status, but it

TABLE 1—*The relative whole plant nutrient uptake for a 56 Mg ha^{-1} tuber yield, the general availability of a soil or plant diagnostic test for each essential nutrient, and known field data available in the USA and Canada (uptakes in parentheses are estimates; states listed in parentheses have limited data on indicated nutrient).*

Nutrient	Total Uptake kg/ha	Diagnostic Soil	Test Available Plant	Documented Responses & Calibration Data Available
N	235	yes	yes	USA & Canada
P	31	yes	yes	USA & Canada
K	336	yes	yes	USA & Canada
Ca	91	yes	yes	WI, (VA, WA, NY)
Mg	63	yes	yes	CO, ME, NY, WI
S	22	yes	yes	CO, NE, WA, WI
Zn	0.12	yes	yes	ID, OR, WA, (ME)
Mn	1.00	no	yes	OR, NY, WI
Fe	(2.0)	no	no	—
Cu	0.1	no	no	CO, WI
B	(0.2)	no	yes	ME, WA
Cl	(2-3)	no	no	—
Mo	(0.006)	no	no	—

is doubtful if it will successfully be used to predict preplant soil nutrient availabilities. The combination of remote sensing and precision farming technologies has potential to increase economic returns while protecting the environment.

Nutrients can be applied in various ways to meet the requirements for potato production (Table 2). Most nutrients can be successfully applied preplant if tilled into the rooting zone before planting. Both Mn and Fe applied preplant may oxidize to unavailable forms before plant uptake, particularly on the high pH, calcareous soils. Nutrient source, e.g., chelated and inorganic salts, also influences the application method and rate for micronutrients. Application rates can generally be lower when the chelate form is applied compared with the inorganic salt. The nutrient should also be available for a longer time interval after application when it is in the chelate form.

The greatest benefit from a starter fertilizer material occurs when it is placed above the seedpiece because roots develop at each node on the shoots above the seedpiece. Materials having a high salt index should be avoided for use as starter fertilizers. Applications made post-plant are usually done before row closure. When top-dressing, the fertilizer materials are broadcast on the surface, which could be followed by a final tillage operation, such as hilling. Side-dressed materials are usually physically injected with a shank into the soil a few inches away from the seedpiece. Foliar sprays are effective for most nutrients in correcting foliar deficiencies, but not effective to correct tuber nutritional problems if the nutrient is not mobile in the phloem. Fertigation can be an alternative practice, particularly if the nutrient is mobile in the soil. A fertigation application of a soil-mobile nutrient (NO_3-N) can be more efficient than a preplant application when the nutrient is not leached out of the plant's root zone during the process (Westermann et al. 1988). When nutrients are *fixed* by the soil, they should only be applied by fertigation when plant roots are near the soil surface. This generally occurs when the surface soil is always moist under the plant canopy. Other application problems associated with fertigation are outlined by Westermann (1993).

TABLE 2—*Recommended fertilization practices for potatoes.*

Fertilizer Application	Nutrient
Preplant	All
Starter	N, P, Zn, Mn, Ca, S
Post-Plant	
Top-dress	N, P, S, Ca
Side-dress	N
Foliar	N, P, K, S, Ca, Zn, Mn, Cu, B, Fe
Fertigation	N, P, K, C

FUTURE OPPORTUNITIES

Agriculture is listed as a major non-point source contributing to the water-quality impairment problems of U.S. streams, rivers, and lakes (USEPA 1995). Runoff from agricultural lands contains dissolved organic and inorganic ions, and suspended solids that may contribute to water-quality problems. Runoff nutrient concentrations generally increase as their availabilities in the soil increase. Maintaining high crop yields with a minimum loss of nutrients to the environment is a significant challenge. The following are selected opportunities that could improve our ability to meet this challenge.

Genetic engineering has the potential to change the nutritional relationships in the plant as known today. Potato plants with resistance to Colorado potato beetle and Roundup®-ready characteristics were being developed for public use in the late 1990s, but were then pulled from the market because of public perception. We do not know if these changes altered the plant's nutritional requirements. To fully realize their benefits and other changes, it may be necessary to know their effects on the nutritional requirements. These changes may have altered the plant's nutrient-uptake ability and/or the optimum metabolic concentration within the plant tissue, which subsequently could affect the diagnostic soil and tissue-testing concentrations used for nutrient management. Additional genetic studies/modifications are also needed to improve the disease resistance of the potato plant's root system and increase nutrient-use efficiencies. Nutrient-use efficiency would be significantly improved with more root hairs per unit of root length, increased root growth longevity and density, and plants with greater rooting depth. This improvement alone would significantly reduce the potential impact of potato production on water and environmental quality parameters, as well as reducing production costs. Nutrient-use efficiency might also be increased from improved nutrient utilization within the plant via increased translocation or recycling. Development of plants with resistance to selected diseases could also change their nutritional requirements, as there are close associations between disease resistance and nutritional adequacy (Huber and Graham 1998).

Historically, soil fertility and plant nutrition researchers have tried to eliminate all production variables except one when doing field studies. There are a few studies where complex two-way interactions were thoroughly studied while there are almost no three-way interactions fully explored. The single variable relationship can be expressed by the following equation:

$$Y = f(x) + v_{(x)} \quad (1)$$

where Y is the dependent variable (usually yield or nutrient uptake) in response to a single independent variable x (fertilizer rate or soil test concentration or nutrient concentration in the plant) with a variance of $v_{(x)}$. All other variables were assumed to be constant. This process is used by the scientist to develop soil test correlation and calibration relationships used for recommending fertilization rates or to determine the nutritional status of the plant.

Real-world production systems are much more complex than that illustrated by equation (1). Within a given field there are both spatial and temporal variations in growing conditions. This field variability is being partially addressed by site-specific or precision agriculture management practices. Ideally under this protocol, plant nutrients for crop production would be applied for the different production conditions within a field. More than one production factor varies simultaneously across a field and there is also the possibility that interactions occur between variables. The relationship expressed in equation (1) then becomes

$$Y = f(x_1) + f(x_2) + ... + f(x_i) + f(y_i) + f(x_i y_i) + v_n + ... \quad (2)$$

There is almost no information on which to base dependable nutrient recommendation rates under these production conditions. The identification and quantification of the key variables and their interactions will be necessary before the advantages of precision agriculture will be fully achieved. This will not be an easy or inexpensive task. As well as being multidisciplinary, it will require the critical application of multivariable and other advanced techniques (Mallarino et al. 1996). A creative extension of some of the concepts already available may be appropriate, e.g., DRIS (Sumner 1978) or crop-simulation models.

There is increasing concern about the nutritive value of all crops used for human consumption. Few field studies have fully evaluated the effect nutrient elements have on protein, vitamins, carbohydrates, antioxidants, phytochemicals, and digestibility of potato tubers. In addition, the potential for tubers produced in soils used for disposal of animal manures or other by-products and biosolids to carry enteric organisms harmful to humans is not known.

Large applications of fertilizers and soil amendments for potato production may cause the accumulation of heavy metals in tubers and eventually become toxic in the soil environment itself. Research activity has concentrated on cadmium (Cd) since it is contained in many fertilizer materials (Anon. 1998). In Australia, McLaughlin et al. (1997) found that fresh weight tuber Cd concentrations ranged from 0.004 to 0.232 mg kg^{-1}, with a median of 0.033 mg kg^{-1}. About 25.6% of the samples in their study exceeded the current maximum permitted concentration of 0.05 mg kg^{-1}. An earlier U.S. market survey showed a median Cd concentration of 0.028 mg kg^{-1} for 297 tuber samples (Wolnik et al. 1983). The highest trace element and heavy metal concentrations are found in sewage sludge, rock phosphate, and phosphorus fertilizer samples compared with other fertilizers or soil amendments (Raven and Loeppert 1997). Canada and Washington State have already enacted a fertilizer law limiting the application of fertilizer materials on agricultural land based on their heavy metal concentrations. Similar laws are being considered in other states and nationally (R. Stevens, WSU, pers comm). The actual solubility of heavy metals in soils and their assimilation by soil organisms and plants are urgently needed to adequately address these concerns since potato yield potentials may be limited in some production areas if fertilizer application rates are restricted by law. In addition, their tuber concentrations and availabilities to the consumer must be fully defined.

Nitrogen and phosphorus are the two major nutrients that degrade water quality. Nitrogen as nitrate in drinking water is potentially dangerous to newborn infants, causing methoemoglobinemia, resulting in brain damage or even death. A limit of 10 mg L^{-1} nitrate-nitrogen in water used for human consumption was set by EPA. Phosphorus contributes to the eutrophication of both freshwater and estuarine systems primarily through increased algae growth. As such it is usually one of the targeted components for reduction in many total maximum daily loads (TMDLs) for water-quality impaired streams on the 303(d) list.

Nitrate is highly mobile and can readily move below the crop rooting zone. Phosphorus is largely transported off-site attached to the sediment, to be later released via dissolution or made available when anoxic conditions are present. Nitrogen must normally be added to achieve maximum economic potato yields. Its efficiency may be substantially improved if it is applied as close as possible to actual plant growth needs (Westermann et al. 1988). Nitrate leaching may be reduced by improved irrigation management or a reduction in N fertilization rates. The latter may also have the undesirable effect of reducing crop yields.

Phosphorus has more potential environmental impact when the available soil P concentrations are much higher than needed for plant growth. These concentrations are normally found where manure or biosolids were applied based on the N needs of the crop being produced. Phosphorus losses are closely associated with soil erosion losses, but it can also move downward in the soil profile when the soil's sorption capacity is saturated. There is also recent evidence that higher P concentrations are found in the soil water moving in the bypass flow pores than in the bulk soil solution (Haygarth et al. 1998).

Nutrient-management plans are now mandated for most large confined animal-feeding operations because of nutrient loading and water-quality concerns. All of agricultural production may eventually be mandated to develop and follow nutrient-management plans. In most situations, these plans will contain a critical soil concentration above which no additional nutrient application will be allowed. It is imperative that sufficient data be available to facilitate development of these nutrient limits to avoid both yield losses, and negative water quality and environmental impacts.

SUMMARY

In many developed countries the historic emphasis on plant nutrition has shifted from crop production studies to minimizing nutrient losses to the environment. This shift has seriously eroded our ability to conduct the plant nutrition research that will be needed for the production needs of the next century. In many public research institutions, there were three to four scientists working in plant nutrition 10 years ago, while today there may be only one and in many cases, none devoting 100% time to these needs. Even though some of the research needs are being met by private agricultural consulting or research companies, there is still much to be done to meet the future food requirements of an expanding world human population.

Researchers must become proactive to anticipate tomorrow's needs as well as those of today. The ability to apply new advances in technology from other fields as well as networking with others will be essential skills. These individuals will also be required to do creative work with declining resources in multidisciplinary environments to solve complex and difficult problems since any new appropriate management practices must be sustainable and socially and environmentally acceptable. This will be a significant challenge for all who work in plant nutrition.

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